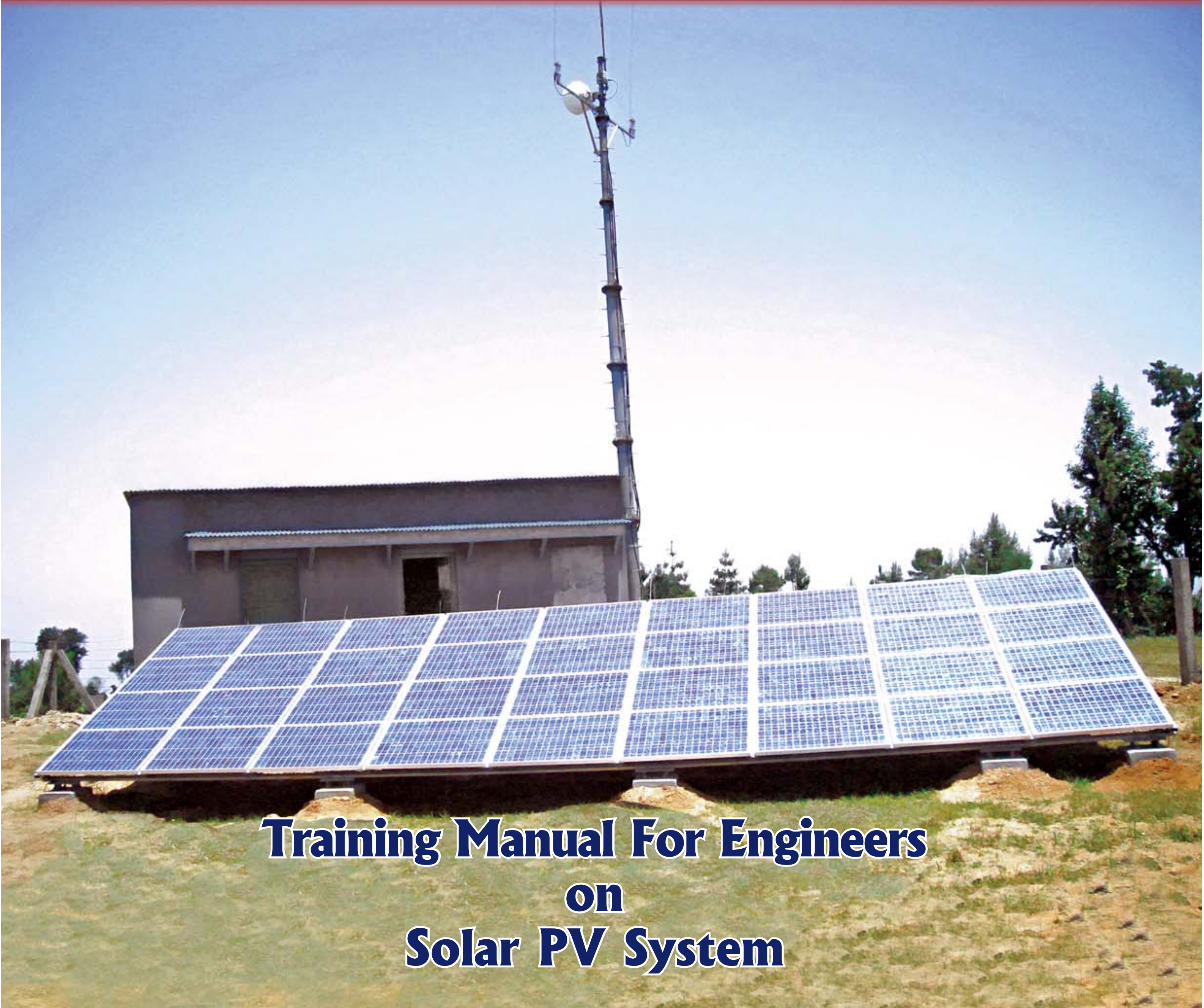




Training Manual For Engineers on Solar PV System

ALTERNATIVE ENERGY PROMOTION CENTRE (AEPC)
ENERGY SECTOR ASSISTANCE PROGRAMME (ESAP)

ALTERNATIVE ENERGY PROMOTION CENTRE (AEPC)

ENERGY SECTOR ASSISTANCE PROGRAMME (ESAP)

Training Manual For Engineers on Solar PV System

July 2011

Government of Nepal
Ministry of Environment, Science and Technology
Alternative Energy Promotion Center (AEPC)
Energy Sector Assistance Programme (ESAP)
Khumaltar Height, Lalitpur
P.O. Box: 14237, Kathmandu, Nepal
Tel: +977-1-5539390, 5543044, 5539391. Fax: +977-1-5539392
Email: ssp@aepc.gov.np
Web site: www.aepcnepal.org

Coordinated by

Ram Prasad Dhital, Sr. Energy Officer

Madhusudhan Adhikari, Solar Energy Component Manager

Team of authors

Prof. Dinesh Kumar Sharma, Dr. — Team leader and PV Expert

Er. Shree Raj Shakya, — Energy Expert

Editing Team:

Mr. Mukesh Ghimire — Energy Officer AEPC
Mr. Chaitanya P Chaudhary — Program Officer AEPC/ESAP

Preface

The Alternative Energy Promotion Centre (AEPC) was established in 1996 as an apex government body to promote the use of renewable energy technologies to meet energy needs in rural areas of Nepal. With successful completion of the first phase of the Energy Sector Assistance Programme (ESAP), AEPC has initiated second phase of the programme from March 2007 with support from Government of Denmark and the Government of Norway. The support to solar energy is one among the different programme components.

Working for promotion of the PV technology among the rural population out of access to electricity, ESAP has been carrying out different trainings for capacity building of partner organizations. As a training tool to use in Solar Design Engineers' training, a manual has been developed with effort from experts and other concerned.

This volume of ***Training Manual for Engineers on Solar PV System*** consist of technical details required for feasibility study, designing and implementation of institutional Solar Photovoltaic systems. The manual is with adequate information and guidelines to be used in training for engineers working in solar PV or with interest to work in the sector.

Authors' team of PV expert, Prof. Dr. Dinesh Kumar Sharma and energy expert, Engineer Shree Raja Shakya has put their significant effort for preparing this manual. I would like to acknowledge their effort in this endeavour.

I would like to thank SSP manager Mr. Madhusudhan Adhikari and Sr. Energy officer Ram Pd Dhital for support while preparing this manual and would like to thank AEPC Energy officer Mr.Mukesh Ghimire, SSP programmer officer Mr. Chaitanya P Chaudhary for their support in this attempt.

I further would like to acknowledge the support of all responding institution and individuals who provided the valuable information to complete this manual.

Dr. Narayan Prasad Chaulagain
Executive Director
Alternative Energy Promotion Centre (AEPC)

Table of Contents

Training manual for Engineers on Solar PV System

1. **Objective**: To provide training to the Engineers capable of working and willing to work on Solar Photovoltaic Systems.

2. **Duration**: 8 days (49 hours) + 1 day Field Visit

3. **Minimum Qualification of trainee:** Bachelor's degree in Engineering.

4. **Minimum Qualification of trainer:** Engineers or PV experts with good experience in design and installation of Solar Photovoltaic Systems.

5. **Reference materials**:
   a) Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP
   b) Solar Electricity Technical Training Manual (Level 1), AEPC/ESAP.
   c) Solar Electricity Technical Training Manual (Level 2), AEPC/ESAP.
   d) Training manual for training of Solar technician trainers

6. **Suggested course outline**:
   i. Skill standards of CTEVT and skill testing/ certification procedure.

   ii. Features requirements of certification procedure for Solar PV Technician level-1.

   iii. Features requirements of certification procedure for Solar PV Technician level-2.

   iv. History and development of solar photovoltaic in Nepal featuring history, installed capacity, users and promoting institutions, donors, future plans and programs.

   v. Basic of electrical engineering theory.

   vi. Components of solar PV systems
      a) Solar cell, module, array
      b) Storage batteries
      c) Charge regulators
      d) Inverters and converters
      e) Wiring and installation practices

   vii. Solar home system (SHS) design and installation
      a) Components of SHS
      b) Installation norms and practices of SHS
      c) Basic design of SHS

   viii. Repair and maintenance of components of solar PV systems
      a) Modules / arrays

b) DC ballast
c) Charge controllers
d) Batteries
e) DC converters and inverters

ix. Design aspects of large (institutional) PV systems – non pumping applications
a) Load calculation
b) Sizing of module/ array
c) Sizing of storage battery
d) Sizing of wires and cables
e) Installation procedures/ safety and protection

x. Design aspects of water pumping schemes
f) Load calculation
g) Sizing of module/ array
h) Sizing of storage battery
i) Sizing of wires and cables
j) Installation procedures/ safety and protection
k) Socio-techno economic feasibility study of large solar photovoltaic systems.

Training Schedule

Session	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
I	1 & 2	5.3 & 5.4	Part of 6.5, 6.6 & 7.1	7.4, 7.5 & 7.6	Part of 8.1, 8.2 & 8.3	9.1, 9.2 & 9.3	10.1, 10.2 & 10.3	Part of 11.1 - 11.4 & 11.5
II	3 & Part of 4.1	6.1	Part of 7.1	7.7, 7.8 & 7.9	Part of 8.3, 8.4 & 8.5	9.4 & 9.5	10.4, 10.5, 10.6 & 10.7	Part of 11.5
III	Part of 4.1, 4.2 & 5.1	6.2	Part of 7.1	7.10	Part of 8.6 & 8.7	Part of 9.6, 9.7 & 9.8	10.8	Part of 11.5, 11.6, 11.7 & 11.8
IV	Part of 5.1 & 5.2	6.3 & 6.4	Part of 7.1, 7.2 & 7.3	7.10	Part of 8.7	Part of 9.8	10.8	Part of 11.8, 11.9 & 11.10

The duration of each session will be 90 minutes. There will be 15 minutes break between the sessions.

Field visit should be conducted after the completion of chapter 10.

REFERENCES

1. Fraunhofer-Institute fur Solar Energiessysteme (FhG-ISE), Photovoltaic Systems, March, 1995
2. Solar Photovoltaic System Design Manual for Solar Design Engineers, Alternative Energy Promotion Center (AEPC)/ Energy Sector Assistance Programme (ESAP), 2003
3. Solar Electricity Technical Training Manual (Level 1), Alternative Energy Promotion Center (AEPC)/ Energy Sector Assistance Programme (ESAP), 2006
4. Solar Electricity Technical Training Manual (Level 2), Alternative Energy Promotion Center (AEPC)/ Energy Sector Assistance Programme (ESAP), 2006
5. Martin A. Green, Solar Cells, The University of New South Wales, Kensington, Australia, February, 1992
6. L. Stamenic; G. Ingham, Solar Photovoltaic Revolution, United power Limited, Canada, 1995
7. J. Schaeffer et.al. , Solar Living Source Book, Chelsea Green Publishing Company, Vermont, 1994
8. J.N.Shrestha, Photovoltaic Technology-Course Manual, Institute of Engineering, Tribhuvan University, 1999
9. Training Manual for Solar Electric Technician (Level-2), Alternative Energy Promotion Center (AEPC)/ Energy Sector Assistance Programme (ESAP), 2001
10. Vervaart M.R.; Nieuwenhout F.D.J, Manual for the Design and Modification of Solar Home System Components, IBRD/ The World Bank, USA, 2001
11. Status of Solar Photovoltaic Sector in Nepal, Alternative Energy Promotion Center (AEPC)/ Energy Sector Assistance Programme (ESAP), 2003
12. Schaeffer J., Alternative Energy Source Book, 7-th edition, 1992.
13. Joshi A.R., et.al., Environmental Management and Sustainable Development at the Crossroad, 2003.
14. CADEC, 2003. *Renewable Energy: Data of Nepal*, Community Awareness Development Center, Kathmandu, Nepal.
15. Piya R., Study on Quality Interventions, Product Quality and System Performance of Solar Home System in the Market of Nepal(Case study of Solar Energy Support Programme (SSP) of AEPC/ESAP), 2006
16. www.pvpower.com
17. www.pvresources.com

CHAPTER 1

Skill Standards of CTEVT, Skill Testing/ Certification Procedures

Duration: 90 minutes

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required: Brochures of Skill Testing Division (STD) of CTEVT

Procedures:

1. Instructor explains the composition of CTEVT, its aims and objectives.
2. Instructor explains the functions of Skill Testing Division of CTEVT processes involved in skill certification.
3. Q & A session, Examples

Instructor: Invited guest speaker from CTEVT – STD

Reference:

1. Skill Standards for Solar Technicians Level 1 and Level 2
2. Rules and Regulations of CTEVT – STD

Lesson Plan

Sub-chapter	**Lesson details**	**Teaching Methodology**	**Facilities required**	**Duration**	**Remarks**
1	Skill Standards of CTEVT, Skill Testing/ Certification Procedures	Lecture	Class room	90 mins.	

CHAPTER 2

Features and requirements for Skill Standard Tests and Certification procedures for solar photovoltaic Design Engineer and Technicians

Duration: 90 minutes

Materials required:
a) Solar Technicians Level 1 and Level 2 Skill Standards
b) CTEVT documents on Skill Certification for Solar PV Technicians Level 1 and Level 2
c) Solar photovoltaic Design Engineer requirements

Procedures: The instructor/s explain
a) Objective of Solar photovoltaic Design Engineer Certificate
b) Objective of Solar PV Technicians Level 1 and Level 2 Certificate
c) Processes involved in Skill Testing
d) Certification procedures
e) Q & A session

Instructor:
a) Invited guest speaker from CTEVT
b) The Trainer

Reference:
1. Skill Standards for Solar Technicians Level 1 and Level 2

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
2	Features and requirements for Skill Standard Tests and Certification procedures for Solar photovoltaic Design Engineer and Solar Technicians Level 1 and Level 2	Lecture	Class room	90 mins.	

CHAPTER 3

History of Development of Solar Photovoltaic in Nepal

Duration: 45 minutes

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required: Reference materials

Procedures: The instructor/s
a) explains the development stage of Solar PV in Nepal
b) provides updated statistics of use of Solar PV in Nepal
c) elaborates on the roles/ responsibilities of various agencies involved in the promotion of solar PV in Nepal (AEPC, ESAP, REP, CTEVT, CRE, CES, KU, etc.)

Instructor: The Trainer

Reference:
1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP
2. Solar Photovoltaic Data Book, AEPC/ESAP
3. Brochures of various institutes

Lesson Plan

Sub-chapter	**Lesson details**	**Teaching Methodology**	**Facilities required**	**Duration**	**Remarks**
3	History of development of Solar cells	Lecture	Class room	45 mins.	

Solar Energy

The energy from the sun can be exploited directly in the form of heat or first converted into electrical energy and then utilized. Accordingly the solar energy is classified into solar thermal and solar photovoltaics (PV).

Solar thermal has numerous applications like water heating, drying vegetables and agricultural products, cooking etc. In Nepal the solar water heaters are being extensively used in urban areas. The applications of solar dryers and cookers have found moderate use simply because of the low level of dissemination of these technologies.

The solar PV, on the other hand, is extensively used not only in the developing countries but also in highly developed countries. The application of solar PV is virtually unlimited. Countries like Germany, Japan and United States of America have initiated highly subsidized rooftop programs for solar PV. The level of subsidy is up to 65% of the total system cost. In Nepal solar PV is extensively used for communications, home lighting, drinking water pumping etc. The installed capacity of Solar PV in Nepal now exceeds 3.4 MWp mark and over 93,000 households are electrified using this technology. Considering the positive impact that solar PV can bring to the rural population of the developing countries like Nepal, the Government of Kingdom of Denmark has supported Energy Sector Assistance Program (ESAP) to promote alternative energy sources, including PV. ESAP target was to subsidize installation of 25,000 Solar Home Systems within a time span of 5 years. Similarly, a sizeable project with assistance from European Union (EU) is being implemented to promote institutional Solar PV in Nepal.

The solar PV can be considered the only form of electricity that can be generated any time and anywhere provided sunshine is available. The earth receives more energy from the sun in just one hour than the world uses in a whole year. The annual total amount of solar energy incident on the surface of the earth is estimated to be about 795×10^{12} MWh, which is 8300 times greater than the global energy demand in 1991. The Environmental savings from the Photovoltaic modules are highlighted in table 3.1 below:

Table 3.1 Environmental Savings from Photovoltaic Modules

Description	**Savings of one 50Wp module ***
Electricity saved per year	90 kWh
Electricity saved per life of PV module	2700 kWh
Barrels of oil saved over lifetime of PV module	4.8 barrels
Pounds of coal saved over lifetime of PV module	2700 lbs
Carbon Di-oxide kept out of the air over life of PV	4000 lbs
Sulfur Di-oxide kept out of air over life of PV	23.3 lbs

** Based on:*

Coal required to produce 1 kWh = 1 lb

Carbon Di-oxide emission = 1.5 lb/kWh

Photovoltaic (PV) Technology

Photovoltaic (PV) Technology is a process of generating electrical energy from the energy of solar radiation. The principle of conversion of solar energy into electrical energy is based on the effect called photovoltaic effect. The smallest part of the device that converts solar energy into electrical energy is called solar cell. Solar cells are in fact large area semiconductor diodes, which are made by combining silicon material with different impurities. The sand, a base material for semiconductor, is the most abundantly available raw material in the world. The ordinary sand (SiO_2) is the raw form of silicone.

The solar energy can be considered as a bunch of light particles called photons. At incidence of photon stream onto solar cell the electrons are released and become free. The newly freed electrons with higher energy level become source of electrical energy. Once these electrons pass through the load, they release the additional energy gained during collision and fall into their original atomic position ready for next cycle of electricity generation. This process of releasing free electrons (generation) and then falling into original atomic position (recombination) is a continuous process as long as there is the stream of photons (solar energy) falling onto the solar cell surface.

History of Development of PV Technology

The birth of PV technology dates back to 1839 AD when Edmund Becquerel, the French experimental physicist, discovered the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes placed in an electricity conducting solution—generation increased when exposed to light.

In 1876 William Adams and R. Day discovered that the junction of selenium and platinum also exhibit photovoltaic effect. This discovery led the foundation for the first selenium solar cell construction in 1877.

The photovoltaic effect remained theoretically unexplained until the great scientist Albert Einstein described this phenomenon in 1904 along with a paper on his theory of relativity. For his theoretical explanation of photo-electric effect, Albert Einstein was awarded a Nobel Prize in 1921.

Another breakthrough in development of PV technology was the discovery of the method for monocrystalline silicon production by Polish scientist Czohralski in 1918. This discovery enabled monocrystalline silicon solar cells production. The first silicon monocrystalline solar cell was constructed only in 1941.

In May 1954 The Bell Laboratories of USA (Researchers D. Chapin, C. Fuller and G. Pearson) published the results of discovery of 4.5% efficient silicon solar cells.

First commercial photovoltaic product with 2% efficiency was introduced in 1955 by Hoffman Electronics-Semiconductor Division. The cost of a 14 milli Watt peak power solar cell was US$ 25 (or US$ 1,785 per Watt). The efficiency of commercially available solar cell increased to 9% in 1958.

The first PV powered artificial satellite of the earth, Vanguard I, with 0.1 W of solar cell occupying an area of approximately 100 cm^2 and powering a 5 mW back-up transmitter was launched in 17 March 1958. Three more PV powered satellites were launched in the same year. The first PV powered telephone repeater also was built in Americus, Georgia, USA in the same year.

Sharp Corporation was the first company to develop the first usable PV module (group of solar cells put together in a single module) in 1963.

By 1974 the cost of PV power came down to US$ 30 per watt from US$1785 per watt in 1955. With the dramatic reduction in the cost, the PV power once affordable only in space vehicle became an alternative source of electrical energy for terrestrial applications. The fig. 3.1 below illustrates the decrease in price (US$ per peak watt) of solar PV with time.

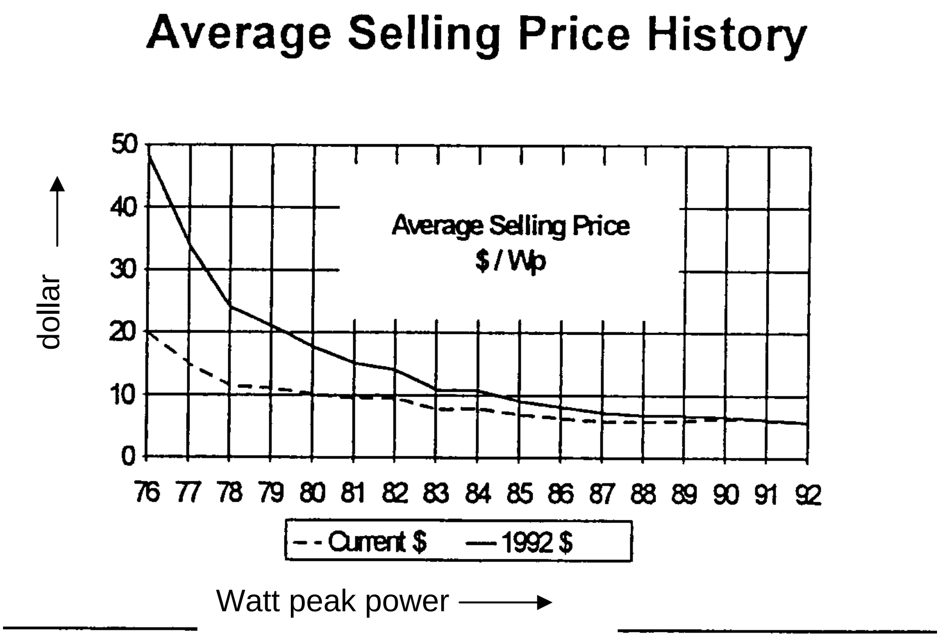


Fig. 3.1 Average selling price trend of PV modules

As the price started falling down the demand and production of the PV modules started growing. In 1980 ARCO Solar became the first manufacturer to produce PV modules with peak power of over 1 Mega Watt (MW). By 1983 worldwide production of PV modules exceeded 21.3 MW with a business volume of 250 million US$. The total installed capacity of PV modules exceeded 1000 MW worldwide in 1999. As of end of 2002, total installed capacity of PV power exceeds 2000 MW and a business volume of about 2 billion US$ (400 MW @ 5$/Wp).

Nepal could not remain in isolation with development pace of PV technology. With only 8 Solar Home System (SHS) installations in 1992/93, it increased to over 93,362 SHS by end of 2006. The fig. 3.2 below highlights the trends in growth of SHS installations in Nepal which constitute above 3414 kWp as of December, 2006. The trend of SHS installation shows a steep rise after 2000 due to the subsidy policy implemented by AEPC/ESAP. Till December 2004, 51 solar PV pumping systems have been installed, of which 28 were installed after 2000 with subsidy provided from AEPC.

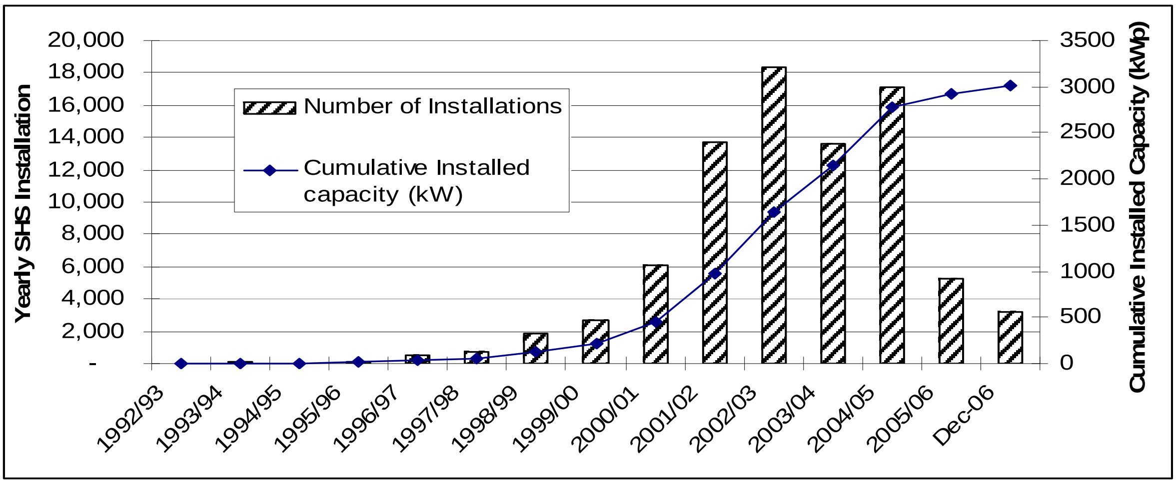


Figure 3.2: Installation of SHSs - Installed till December 2006

The estimated market potential is huge and about 4,750 kWp of photovoltaic power is currently being used in various public and private sectors (telecommunication, utility supply, stand-alone, water supply, aviation etc.) in Nepal are shown in Table 3.2.

Table 3.2: Application of PV Power by Sector

S.N.	Service	PV Power, kWp	No. of Installation
1	Telecommunications	1001	3,000+
2	Utility supply (centralised)	100	2
3	Stand-alone system	3414	93,000+
4	Water supply	120	51
5	Aviation	37	45
6	Miscellaneous	78	100+
	Total	4,750	

In near future more and more PV systems will be used for various types of services. There is a plan to install 150,000 solar home systems in areas where national grid will not reach within second phase of ESAP (March 15 2007 – March 15 2012. These facts indicate that time has come to pay special attention for PV powered systems for income generating activities.

Institutions involved in the promotion of solar photovoltaic technology in Nepal

Various institutions are involved in the development and promotion of solar PV technology. Bank and Financial Institutions like Agriculture Development Bank/Nepal (ADB/N) and local commercial banks have been playing an active role in rural energy program by financing stand-alone SHS . Non Government Organizations like Center for Self-help Development (CSD), Center for Renewable Energy (CRE), Nepal Solar Energy Society (NSES), have been successfully involved in limited banking activities and mobilizing donor assistance for the promotion, development and dissemination of SHS. Donor agencies like DANIDA/ESAP, USAID, SNV/Nepal, KfW, UNDP, UNICEF, NORAD, European Union etc. have been contributing by providing financial support in the form of grant-aid and soft loan. Manufacturer/Installers are manufacturing various components of SHS and providing quality service. Government Institutions like National Planning Commission (NPC), the Ministry of Environment Science and technology (MOEST), the Water and Energy Commission Secretariat (WECS) of the Ministry of Water Resources, the Ministry of Finance, etc., have influenced the RETs development's policies and programmes.

Applied R & D and Human Resource Development Centre/Institutions such as NAST, NARC, RECAST, CES/IOE, KU etc., are involved in different levels of applied R & D activities. Institutes like CES/IOE, CTEVT are involved in human resources development at different levels for the successful planning, designing, installation, operation and maintenance of RET projects.

RETS

In order to assure the quality of the components to be used in SHS, AEPC/ESAP has prepared and successfully implemented a standard named, Nepal Interim Photovoltaic Quality Assurance (NIPQA). In order to check and verify technical parameters of SHS components a special laboratory named as Renewable Energy Test Station (RETS) is set up and functional.

Renewable Energy Testing Station (RETS) under NAST has started to certify the various SHS components for quality assurance. An independent body like Nepal Bureau of Standard and Metrology (NBSM), can play a very important role in controlling the quality of the components/devices/systems of the SHS so that healthy competition among the suppliers can be initiated and quality assurance can be guaranteed to the users.

CHAPTER 4

Basics of Electrical Engineering

Duration: 120 minutes

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required: Reference materials

Procedures: The instructor/s
a) explains the basics of electrical power system
b) provides basic knowledge on the solar radiation

Instructor: The Trainer

Reference:
1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP
2. Solar Electricity Technical Training Manual (Level 1), AEPC/ESAP.

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
4.1	Electrical Power Supply System	Lecture	Class room	60 mins.	
4.2	Solar Photovoltaic Technology	Lecture	Class room	60 mins	

4.1 Electrical Power Supply Systems

Electrical energy is a very convenient form of energy, which can be easily generated, transmitted, stored and used. Any other form of energy can be easily converted into electrical energy. An example of this is solar electricity in which the energy from the sun (solar radiation) is converted into electrical energy by solar cells. Electricity is the branch of science that studies the theory and practices of electrical energy. Electrical engineering on the other hand is a branch of engineering that deals with generation, transmission, distribution and use of electrical energy.

Electrical energy is transmitted from one point to another by means of charged particles called electrons. There are three fundamental terminologies used in electricity: Voltage, Current and Resistance.

Voltage

Voltage or the potential difference is a force that compels the electrons to move from one point to another in predetermined manner. In water supply system analogy, the voltage can be compared with the pressure of water in the storage tank that forces the water to flow in the pipeline. The unit of measurement of the voltage is Volt and is abbreviated and symbolically represented as ‘V’.

Current

Current is the quantity of charged particles flowing in given direction per unit time. The current can be compared with the amount of water flowing in the pipeline per unit time. The unit of measurement of electrical current is Ampere and is abbreviated as ‘A’. Symbolically the letter "I" represents the current.

Resistance

Resistance is the property of the material to oppose the flow of current through it. The unit of resistance is Ohms and abbreviated as ‘Ω’. Symbolically the letter 'R' represents the resistance.

The electrical law that relates the above three fundamental parameters is called Ohm’s law. According to this law, assuming that all other parameters remain constant, the current through an electrical circuit is directly proportional to the applied voltage and inversely proportional to the resistance of the circuit:

$$I \propto V$$

$$I \propto \frac{I}{R} \qquad I = \frac{V}{R} \qquad (4.1.1)$$

The electric current is further classified into direct current (DC) and alternating current (AC). The current is called DC if the direction of flow of current does not change with time. It means the DC current always flows in one direction only. The voltage that causes the flow of DC current is referred to as DC voltage. Examples of DC voltages are the output voltages of storage batteries, DC generators etc.

If the direction of flow of current changes periodically with time then such current is called AC current. And the voltage causing the flow of AC current is called AC voltage. Examples of AC voltages are the city supply, output of AC generator etc. The rate or frequency at which the direction of current changes is termed as cycle per second or Hertz (Hz). In one cycle the current changes its direction of flow. In Nepal the frequency of AC voltage is 50 cycles per second or 50 Hz.

The other terminologies used in electrical supply systems are power, energy, active load, reactive load, power factor, crest factor, harmonics and Loss of Load (LoL) probability.

Power and Energy

Electrical power may be defined as the energy delivered by the electrical source (generator) to the load (acceptor) per unit time-

$$P = \frac{E}{t} \qquad (4.1.2)$$

where P is the power in Watts (W), E is the energy in Joules (J) and t is the time in seconds.

If the supply system is DC, then the power can be expressed as the product of voltage and current, i.e.

$$P = V \times I = \frac{V^2}{R} = I^2 \times R \qquad (4.1.3)$$

Re-writing the formula (4.1.2), we can define the energy as product of the power and time

$$E = P \times t \qquad (4.1.4)$$

Thus the energy can be defined as the power delivered to the load in given duration of time. In electrical terms the energy is expressed in Watt- Hours (Wh)

Active and Reactive loads

Depending upon the characteristics of the load it can be subdivided into active and reactive types. This classification of load type is more pertinent to AC supply than DC supply. If the load is active (i.e. it does not contain any reactive elements like inductance and capacitance) then the current through the load and the applied voltage cycling are in phase. In other words the maxima and minima of the voltage and current coincides (Fig.4.1.1).

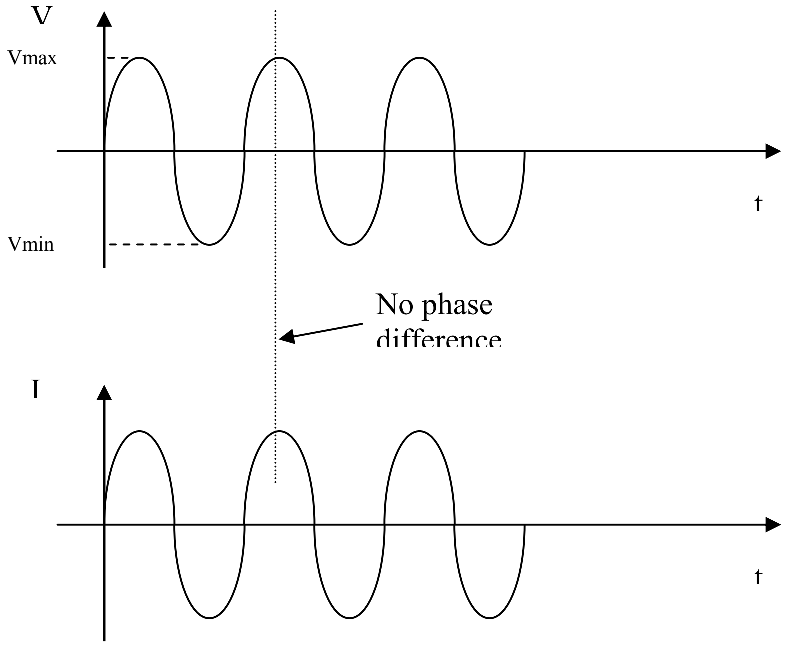


Fig. 4.1.1 Voltage and current waveforms for active load

Now if the load is either inductive or capacitive in nature then there will be phase difference between the applied voltage and the current flowing through the load (fig.4.1.2).

A purely resistive load is an example of active load. The motors, tube-lights and other loads containing reactive elements (inductance, capacitance) are the examples of reactive loads.

Real and Apparent Powers

A very important consideration for AC loads is the difference between apparent power and real power. With purely resistive loads, the current and voltage cycling are in phase with each other. This means that when the voltage is maximum, the maximum current is flowing to the load. The power delivered to the load by the source (apparent or moving in the wires and measured in VA) and consumed by the load (measured in watts) are same. This power is called real power. Thus for a purely resistive load:

$$Apparent \quad Power\ or\ moving\ power(VA) = V \times I \qquad (4.1.5)$$

$$\text{Re}\,al\ power\ or\ consumed\ power(watts) = V \times I \qquad (4.1.6)$$

Here the voltage V and the current I are Root Mean Square (RMS) average values.

However with inductive loads, such as motors, there is a “pushing backwards" by the load due to electric fields built up in the coils of the motor itself. The current cycling lags the voltage cycling, so the current and voltage are out of phase (fig. 4.1.2).

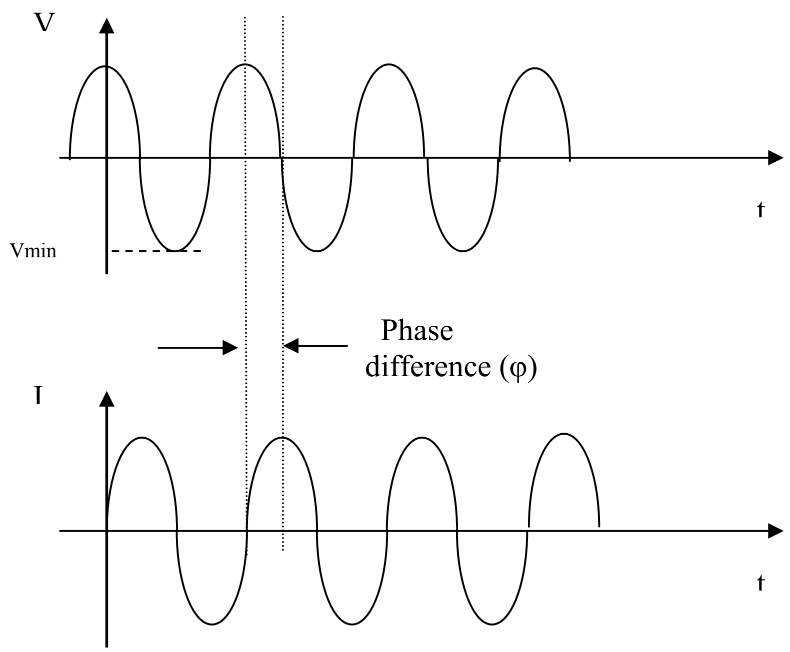


Fig. 4.1.2 Voltage and current waveforms for reactive load

The product of the average voltage and average current is now called "apparent" power flowing to the load. But the real power consumed in the load is less.

Power Factor

The amount by which the real power is less than the apparent power is related to the cosine (cos) of the phase difference (φ) between the current and voltage. The value cos φ is called the power factor. The real power, apparent power and the power factor is related according to the following expression:

$$\mathrm{Re}al\ \ power(watts) = apparent\ \ power(VA) \times \cos\varphi \qquad (4.1.7)$$

Crest Factor

The crest factor of the voltage or current waveform is defined as the ratio of peak (or maximum) value to the root mean square (rms or effective) value.

Harmonics

The AC voltage or current waveforms produced by the generator of electricity is harmonic in nature. It means the instantaneous value starts from zero, reaches maximum positive value, again drops to zero, then reaches maximum negative value and comes back to zero again making a complete cycle (fig. 4.1.1). This cycle repeats again and again as long as the generator continues to generate the power. Thus the instantaneous value of voltage or current is a function of time and mathematically can be represented as sine or cosine function of time:

$$v(t) = V_{\max}\cos(2\pi ft) \qquad (4.1.8)$$

$$i(t) = I_{\max}\cos(2\pi ft) \qquad (4.1.9)$$

here- $v(t)$ and $i(t)$ are instantaneous values of voltage and current;
$V_{\max}$ and $I_{\max}$ are maximum or peak values;
f is the frequency in Hz and t is the time in seconds.

From the above equation, it is evident that the voltage or current waveform (we will refer these waveforms as signals in further discussions) expressed mathematically as a sine or cosine function contains only one frequency. This frequency is called fundamental frequency. Now if we pass this signal through a network containing non- linearities (i.e. through a network in which the relation between the current flowing through the network and the applied voltage in non-linear), the signal (voltage or current) at the output of the network will contain more than one frequency components that were not present in the input signal. These new frequency components (sine or cosine functions with new frequency values) are called harmonics. In general the values of the harmonics frequencies are integer multiple of fundamental frequency.

Loss of Load (LoL) Probability

It is the probability that the generator of electricity fails to meet the demand of the load. When the power consumed by the load exceeds the power delivered by the source, a condition called overload occurs and the whole system will fail. LoL is an indication of the reliability of power supply system. Lower the value of LoL higher is the system reliability.

4.2 Solar PV Technology

In this chapter definitions of the terminologies used specifically in solar PV technology will be given. These terminologies are Irradiance, Insolation, radiation (global, direct, diffused), peak-sun, sun-path, seasonal variation of solar radiation, true and magnetic south, manual and automatic tracking of PV module/array etc. Other specific definitions related to system components of complete solar PV system will be given in corresponding chapters.

The Light from the Sun

The PV process converts solar radiation into useful electrical energy. Therefore it can be considered that the fuel for the generation of solar electricity is the energy received from the sun in the form of radiation.

Our understanding of the nature of light has changed back and forth over the past few centuries between two apparently conflicting viewpoints (a highly readable account of the evolution of quantum theory has been discussed very often).

- In the late 1600's, Newton's mechanistic view of light as being made of small particles prevailed.

- By the early 1800's, experiments by Young and Fresnel had shown interference effects in light beams, indicating that light was made up of waves.

- By the 1860's, Maxwell's theories of electromagnetic radiation were accepted, and light was understood to be part of a wide spectrum of electro-magnetic waves (EMW) with different wavelengths.

- In 1905, Einstein explained the photoelectric effect by proposing that light was made up of discrete particles or QUANTA of energy. This complimentary nature of light is now well accepted.

Light is referred to as the particle/wave duality, and is summarized by the equation:

$$E = hf = \frac{hc}{\lambda} \qquad (4.2.1)$$

Where,

f − frequency of light of Wavelength λ , f in H_Z and λ in meters.
E − energy of "packets" or "photons" in coming light in Joules
h − Planck's constant (6.625 x 10^{-34} J_S)
c − Velocity of light (3 x 10^8 m/sec)

In defining the characteristics of photovoltaic or "solar" cells, light is sometimes treated as waves, other times as particles or photons.

The Sun

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39 x 10^9 m and is about 1.5 x 10^{11} m away from the earth. As seen from the earth, the sun rotates on its axis about once every four weeks. However, it does not rotate as a solid body: the equator takes about 27 days and the polar regions take about 30 days for each rotation.

The sun is a continuous fusion reactor with its constituent gases as the "containing vessel" retained by the gravitational forces. The temperature of the innermost region, the core, of the sun is estimated to be around 10^7 K. The energy created by the fusion reaction is transferred out to the surface in a succession of radiative and convective process and finally radiated into the space.

Direct and Diffused Radiation at the Earth's Surface

Sun light is attenuated by at least 30% during its passage through the earth’s atmosphere. The main causes of such attenuation are:

- Rayleigh scattering or scattering by molecules in the atmosphere.
- Scattering by aerosols and dust particles.
- Absorption by the atmosphere and its constituent gases.

The degree of attenuation is highly variable. The most important parameter determining the total incident power under clear conditions is the length of light path through the atmosphere (referred to as Air Mass or AM).

The total radiation received at the earth’s surface is the cumulative total of direct radiation and diffused radiation. The figure 4.2.1 illustrates the various components of radiation received on the earth’s surface. The composition of terrestrial sunlight is further complicated by the fact that, apart from the component of radiation directly from the sun, atmospheric scattering gives rise to a significant indirect or diffuse component. Even in clear, cloudless skies, the diffuse component can account for 10 to 20% of the total radiation received by a horizontal surface during the day. For less sunny days, the percentage of radiation on a horizontal surface that is diffuse generally increases. Sun light reflected from the ground also contributes significant radiation to an inclined surface. Snow mirrors about 70% to 80% of the light it receives, while a grass field reflects only about 15 to 20%. These effects are known as "Albedo Effect".

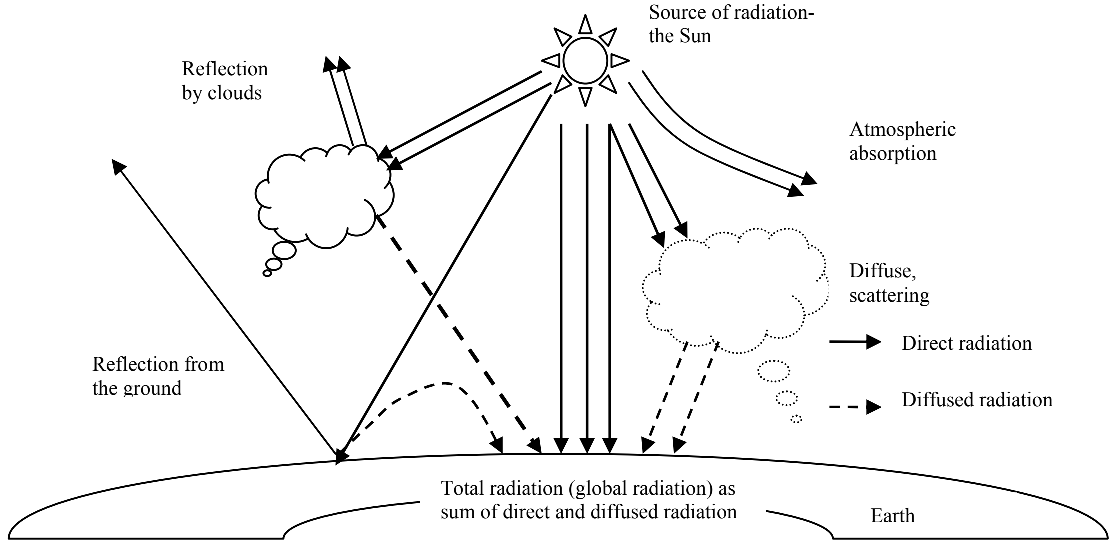


Fig. 4.2.1 Direct, diffuse and total radiation on the earth's surface

The Solar Constant

The radiation emitted by the sun and its spatial relationship to the earth result in a nearly fixed intensity of solar radiation outside the earth's atmosphere. The solar constant, Ion, is the energy from the sun per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation at the earth's mean distance from the sun outside the atmosphere. The World Radiation Center (WRC) has adopted a value of 1367 W/m^2 as the solar constant.

Irradiance

Irradiance, I, is defined as the intensity of solar radiation per unit time on a unit surface area of the earth. The unit of I is taken as W/m^2.

Insolation

Insolation is the total energy received from the sun in a day in a unit surface area on the earth. The unit of insolation is watt-hour per sq.m. per day. For Nepal the yearly average insolation can be taken around 4500 to 5500 Wh/m^2/day.

Peak Sun

Peak sun is the number obtained by division of insolation by 1000 W per sq.m. per day. In most cases, the peak sun or the insolation is treated as a single parameter because they are interrelated by a constant coefficient.

Air Mass

Although radiation from the sun's surface is reasonably constant, by the time when it reaches the Earth's surface it is highly variable due to absorption and scattering in the Earth's atmosphere.

When skies are clear, the maximum radiation strikes the Earth's surface when the sun is directly overhead, and sunlight has the shortest path length through the atmosphere.

This path length is usually referred to as the "Air Mass" through which solar radiation must pass to reach the Earth's surface. The condition when the sun is directly overhead, the distance through which the sunrays penetrate the atmosphere is shortest and is referred to as Air Mass 1 or AM1.

AM1.5 (equivalent to a sun angle of 48.2º from overhead or 41.8º from horizontal plane) has become the standard for photovoltaic standards. The air mass can be estimated at any location using the following formula:

$$AM = \sqrt{\left(1 + \left(\frac{s}{h}\right)^2\right)} \qquad (4.2.2)$$

Where s is the length of the shadows cast by a vertical post of height h.

Locating the Sun’s Position

In PV system it is very important to face the modules/array in such angle to the horizontal surface that permits the sunlight to fall into the module surface for maximum possible duration and intensity. The angle at which the module is inclined is called tilt angle. To determine the optimum tilt angle it will be necessary to locate the position of the sun from the given site on the earth.

The earth's daily rotation on its axis and the annual rotation of the tilted earth around the sun both affect the angle at which sunlight passes through the atmosphere as seen from any point on the earth. The position of a site on earth with respect to the sun is determined by two continuously changing angles, namely: the sun's hour and declination angles, and by one fixed angle that specifies a site's location on earth, namely the latitude.

The sun's hour angle for a particular location depends on the momentary position of the earth in its axial rotation. Since the earth makes a complete 360^0 rotation in 24 hours, the hour angle changes 15^0 every hour. The hour angle is measured from the local meridian, or the sun's highest point in the sky at solar noon (not necessarily 12:00 hours), with angles between sunrise and solar noon being positive and angles after noon being negative.

The sun's declination angle is the angular position of the sun at its highest point in the sky with respect to the plane of equator it depends on the momentary position of the earth in its revolution around the sun. Changes in the declination angle are caused by a simple fact: the earth's axial tilt of 23.34^0 remains constant and in the same direction during the earth's entire orbit around the sun. In the northern hemisphere, the declination angle reaches its most northern and positive peak of $+23.45^0$ on June 21st (the summer solstice) and drops to its most southerly and negative peak of -23.45^0 on December 21st (the winter solstice).

The apparent motion of the sun is indicated in fig. 4.2.2 for an observer at latitude 28^0 north.

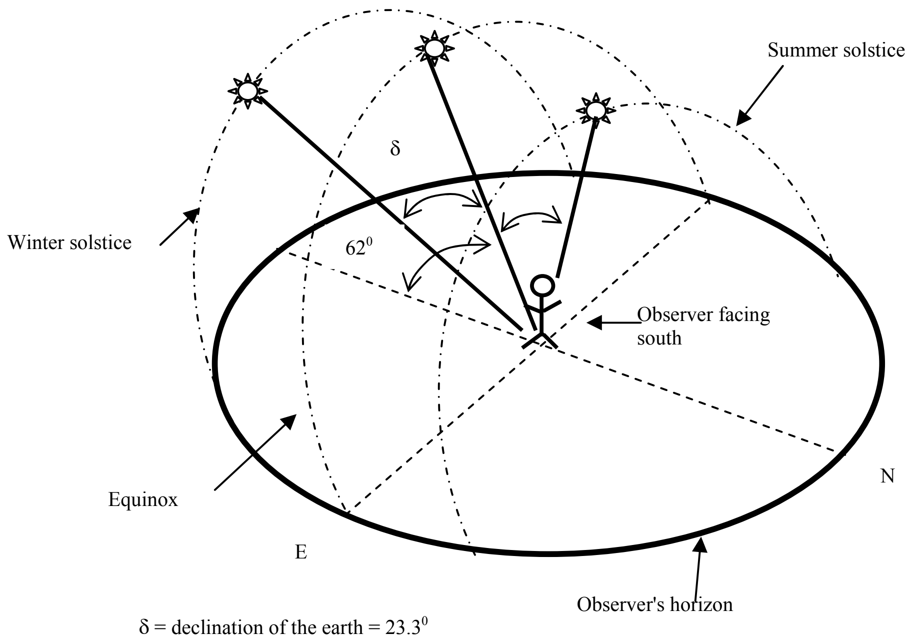


Fig. 4.2.2 Apparent motion of the sun

An area facing due south at a tilt angle that equals to the site's latitude would obtain the average optimum amount of direct-beam solar radiation over the entire year. But if the designer wishes to maximize the solar energy received during the winter months, the surface should approximately be equal to the latitude angle plus 11^0, while the best orientation during the summer months is the site's latitude minus 11^0.

The optimal tilt angle of a PV array at any given time equals the latitude angle minus the declination angle, the angle that the sun makes at solar noon with respect to the plane of the equator. The declination angle changes throughout the year. It can be calculated by the following trigonometric equation (formula 4.2.3):

$$\text{Declination angle of sun} = 23.45 \times \sin\left[360 \times \frac{(284+N)}{365}\right] \qquad (4.2.3)$$

Where,

N is the day number in the year (N=1 for January 1 and N=365 for December 31).

Using the above equation, the optimal array tilt angle can be determined for monthly adjustments, or for adjustments any time. The optimal tilt angle will be latitude minus the declination angle (considering the sign of the angle).

True and Magnetic South

The orientation of array/module towards true south (for northern hemisphere) and true north (for southern hemisphere) is essential to ensure that maximum amount of sunlight falls on the array surface throughout the day. It would have been optimal solution if the array could track the sun path: facing east in the morning, south in the noon and west in the afternoon. Although such tracking systems are available in the market, they cost money and consume power. Therefore for fixed orientation of array permitting optimal incidence of sunlight, it has to be oriented towards true south.

North-south direction is along any meridian (a line approximating the surface of the earth, from the north pole to south pole and connecting points of equal longitude) and east-west is along any parallel (a circle approximating the surface of the earth, parallel to the equator and connecting points of equal latitude), because of the way the graticule has been defined. These lines are perpendicular except at the poles of the earth. The direction determined by the orientation of the graticule is called geographical or true direction. True south is therefore the direction towards the south geographical pole.

The direction indicated by south (or north) seeking magnetic needle (compass) is influenced only by earth's magnetic field. The direction of the magnetic pole is not usually parallel to the meridian. The difference between true north (south) and magnetic north (south) is called magnetic declination.

Therefore the south direction indicated by the compass has to be corrected by magnetic declination to find the true south direction.

Manual and Automatic Tracking Systems

Although fixed mounting structures of module/array oriented towards true south and tilted at fixed angle are simple and worry free, modules do not get good exposure in the morning and evening hours of the day. By mounting the modules on tracking structure, gains in total daily output of power of 30% or greater can be achieved because the modules are facing the sun directly during all the sun shine hours.

Trackers can be motor driven (powered by the battery) or solar powered themselves. The solar powered design involves two tubes of Feron and oil on either side of the modules. Each tube is partially shaded by mask. As the sun moves, one tube becomes more exposed than the other. The Feron expands and either pushes a piston of transfers oil to the other side which causes the structure to move to follow the sun. Motor driven trackers also use two light sensors on either side of the module. Depending upon the difference in the outputs of two sensors, the motor drives the structure in either direction to follow the sun (fig. 4.2.3).

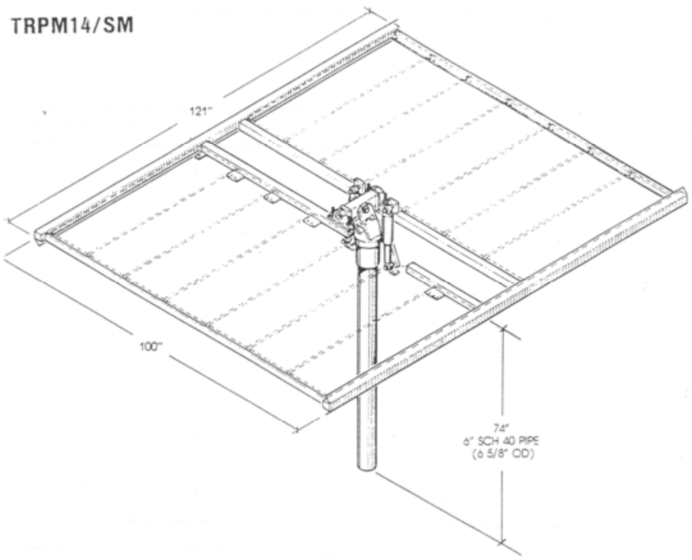


Fig. 4.2.3 Sketch of PV array with tracking system

Trackers can follow the sun along only one axis (east-west) or can have dual axis (east-west and tilt angle) for complete seasonal compensation.

Manual tracking along east-west axis is not practical, as the orientation has to be changed manually from east to west at fixed interval. Therefore, this type of tracking is generally automatic. The tilt angle adjustments to compensate seasonal change in sun-path could be accomplished manually once every three months.

Large utility scale PV systems have the modules mounted on dual axis trackers, to maximize module output and minimize average costs. But for small scale array/modules use of trackers is an economical issue. The gain provided by the tracker (in terms of reduced number of modules for given load) has always to be compared with the investment and maintenance cost of the tracker. However, manual seasonal adjustment of tilt angle is advisable to all the PV installations.

Review Questions

1. The unit of measurement of electric current is

   a. Volts
   b. Ohms
   c. Ampere
   d. Watts

2. In an electric circuit with fixed resistance, the current flowing through the circuit …… if the applied voltage is doubled.

   a. decreases
   b. remains unchanged
   c. doubles
   d. increases four times

3. The power factor is the ratio of

   a. voltage to the current
   b. energy to the power
   c. real power to apparent power
   d. peak to rms value

4. The intensity of solar radiation per unit time on a unit surface area of the earth is called

   a. Irradiance
   b. Insolation
   c. Solar constant
   d. Air mass

5. The yearly average insolation in a given locality is 6500 Wh/m^2/day, the peak sun value is

   a. 6500
   b. 650
   c. 65
   d. 6.5

6. The value of air mass in standard test condition of PV modules is

   a. AM1
   b. AM1.5
   c. AM2
   d. AM0

7. Yearly average optimum amount of direct beam radiation in northern hemisphere can be achieved if the tilt angle is equal to

   a. site latitude
   b. site latitude plus 11^0
   c. site latitude minus 11^0
   d. 90^0

8. The angle that the sun makes at solar noon with respect to the plane of the equator is called

   a. solar constant
   b. true south
   c. magnetic south
   d. declination angle

9. Calculate the optimum tilt angle of the PV array for a site located at the latitude of 30^0 in northern hemisphere for 20-th May.

10. A one-meter long rod erected vertically produces shadow of 0.8 m. Calculate the value of air mass.

CHAPTER 5

Fundamentals of Solar Photovoltaic

Duration: 195 minutes

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required: Reference materials

Procedures: The instructor/s

a) explains the basic principles of photo-electric conversion, basic parameters of a solar cell, generations of solar cells, basics of solar photovoltaic technology
b) explains the construction and parameters of solar modules and solar arrays.

Instructor: The Trainer

Reference:

1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP
2. Solar Electricity Technical Training Manual (Level 1), AEPC/ESAP.
3. Solar Electricity Technical Training Manual (Level 2), AEPC/ESAP.

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
5.1	Basic principles of photovoltaic effect	Lecture	Class room	55 mins.	
5.2	Solar cells	Lecture, demonstration	Class room	50 mins	
5.3	Solar Modules	Lecture, measurements and demonstration	Class room and open sunlight area	60 mins	
5.4	Solar Array	Lecture	Class room	30 mins	

5.1 Basic Principles of Photovoltaic Effect

Solar Cells are devices, which convert solar energy directly into electricity.

The most common form of solar cells is based on the photovoltaic (PV) effect in which light falling on a two-layer semi-conductor device produces a photo voltage or potential difference between the layers. This voltage is capable of driving a current through an external circuit and thereby producing useful work.

To have a deeper understanding of PV effect, it is essential to become familiar with the principles of construction and operation of a two-layer semiconductor device popularly known as PN junction.

It is well known from the first course of physics that all mater is made of atoms which consist of a small dense nucleus containing positive and neutral particles (protons and neutrons) a surrounding “cloud” of fast moving negatively charged particles (electrons). The outer most electrons (valence electrons) seem to be arranged in symmetrical elongated shells or orbitals, like stretched out clouds. Neighboring atoms share outer electrons, forming “bonds”. These bonds where electrons are shared between atoms is what holds all mater together. The valence electrons play very important role in defining the electricity conducting capacity of a material.

As defined in earlier chapter, the electric current is the flow of free (un-bonded) charged particles (electrons) in a matter. An electron can take part in conduction of electric current if it is loosely bonded with the atoms. In all metals, the valence electrons are loosely bonded with the atom and with some minimal external energy applied (in the formal thermal energy) they become free and ready to take part in conduction of electric current. In metals each atom can release one electron to become free. Therefore the number of free electrons available in metals is very high (in one cubic meter of matter there are about 10^{29} atoms; each atom releasing one electron to become free results in about 10^{29} free electrons in metals) resulting very good conduction capacity (very low resistivity) by the metals. On the other hand, materials classified as insulators have valence electrons tightly bonded with atoms. Great deal of external energy is required to let these electrons free. At normal temperature, the insulators have virtually no free electrons to contribute for electricity conduction. That is why the conduction capacity of insulating materials is extremely low (very high resistivity).

There is another group of material whose conductivity (or say resistivity) lies between that of conductors and insulators. This group of materials are called semiconductor. These semiconductors are basic building blocks of all the electronic components and the solar cells. Silicon and Germanium are the examples of semiconductor materials. A silicon atom has 4 outer electrons. Crystalline silicon consists of orderly bonding of each silicon atom with 4 neighboring silicon atoms. Such a highly ordered structure of atoms is also called a crystal lattice. Each of the four outer electrons of one atom is shared by surrounding four atoms to form an effect of 8 outer electrons (the most stable condition) for each atom. The bond that binds each outer most electrons together is called covalent bond (fig. 5.1.1).

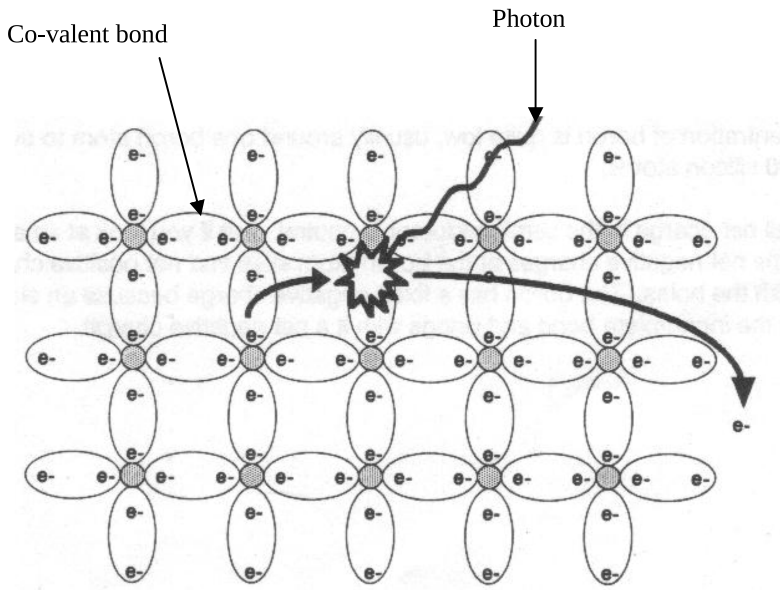


Fig. 5.1.1 Crystalline structure of semiconductor material

At the atomic level, light acts as a flux of discrete particles called photons. Photons carry momentum and energy but are electrically neutral. When semiconductor material is illuminated by light, photons of light actually penetrate into the material, traversing deep into the solid. Photons with enough energy can collide with bonded electrons and knock them out of their original position. During the collision the photon disappears and its energy is transferred to the dislodged electron. The newly dislodged electron now becomes free and can wander around the semiconductor material as conduction electron. This free electron carries a negative charge and usable energy. It is at this moment of releasing the electron that sunlight energy has been converted into electrical energy. And this effect of converting light energy into electrical energy is called photovoltaic effect.

Whenever an electron is freed, it leaves a vacant position in its original position in the covalent bond. Such an incomplete bond (with missing electron) is called a "hole". A nearby electron with higher energy level can jump from its bond into the hole and fill it, but this leaves a hole where the electron came from. In this way the hole moves in the material. But wherever the hole is, an electron is missing, so there is a localized net positive electrical imbalance there. The atom with a hole is referred to as positive ion. Therefore the hole appears to be a positive charge moving in the solid, although it is really an absence of an electron moving about. Overall, the net charge of the material is neutral.

In the absence of any external electrical field, newly freed electrons wander for a short time and then recombine with a wandering hole. During recombination, the energy gained by the freed electron is released and converted into heat. The key idea of producing usable output current is to sweep the freed electrons out of the material before they recombine with the holes. This task of sweeping the free charge carriers is accomplished by creating internal electric field in a junction of two different types of semiconductors.

In pure silicon, the number of freed electrons is always equal to holes. Adding impurities in it can increase the conductivity of pure or intrinsic silicon. The impurity is referred to as dopant and the process of adding dopant is called doping. Depending upon the type of dopant used, the impure or extrinsic semiconductor is called P type or N type semiconductor. By joining these two types of semiconductors, it is possible to create internal electric field to sweep freed electrons out of the material and force them to produce usable current.

P Type Semiconductor

Boron is a type of semiconductor material having only three valence electrons. If we add boron to intrinsic semiconductor, then each boron atom will bond with three atoms of silicon leaving one covalent bond of silicon half complete (fig.5.1.2).

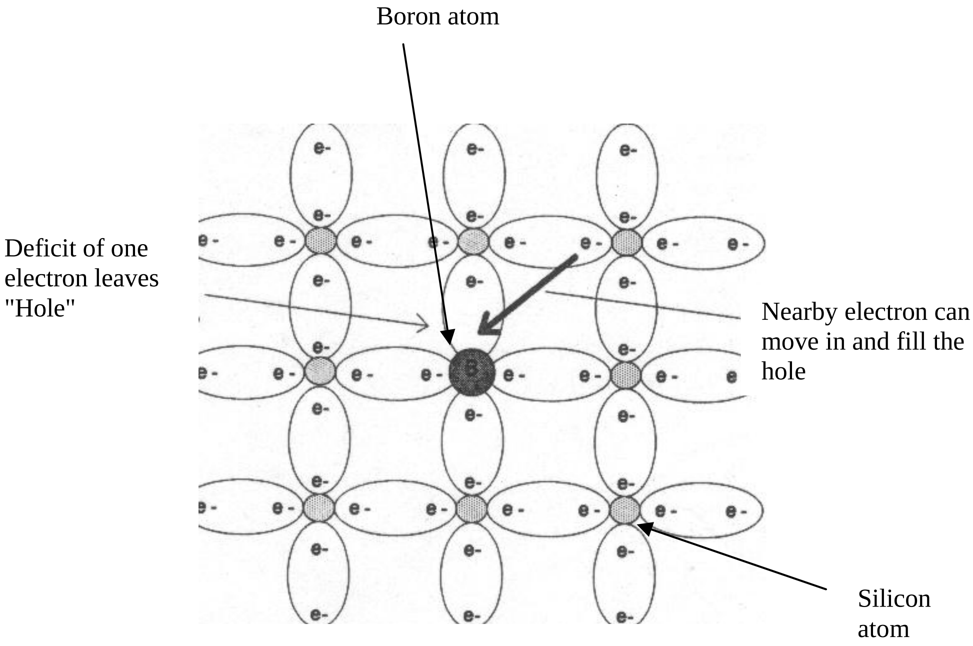


Fig.5.1.2 P-type semiconductor

The half complete bond represents a hole. The nearby electron can vibrate and jump into this hole leaving a hole in its original position. So there exists in the semiconductor structure a wandering absence of an electron. In other words, each doped boron atom will create absence of electrons (in other words- the holes) with net positive charge. That is why the extrinsic semiconductor doped with trivalent impurity is called P type or positive type semiconductor. The concentration of boron is quite low, usually around one boron atom to every 10^6 silicon atoms. The overall net charge in the semiconductor is neutral. But in the small regions, the boron atom has net negative charge because one extra electron has fallen in the empty bond. And the silicon atom from where the electron ran away remains positively charged because one electron is missed from the bond.

N Type Semiconductor

Now if penta-valent impurity (e.g. phosphorous) is added to intrinsic semiconductor, the four outer electrons of dopant make covalent bond with four silicon atoms (fig. 5.1.3).

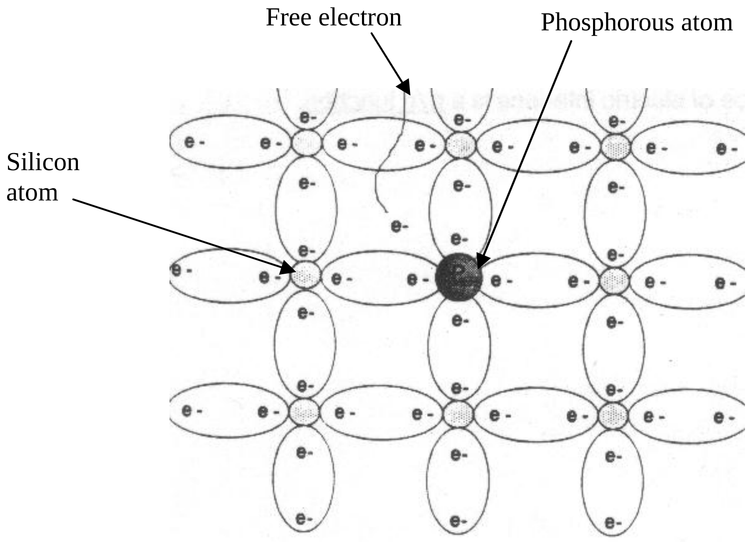


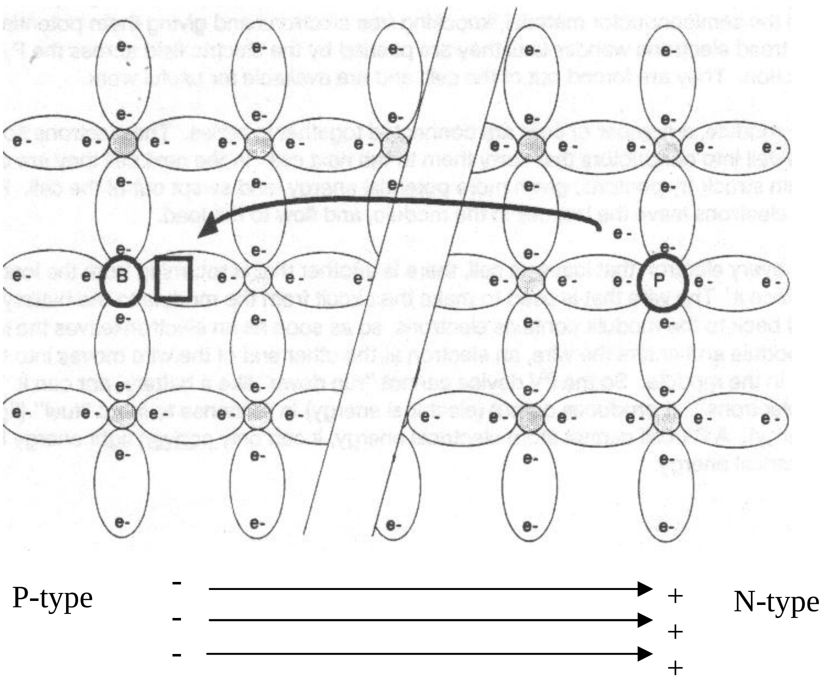
Fig. 5.1.3 N-type semiconductor

The fifth electron of dopant atom breaks away easily as there is no bond to hold it. This free electron moves around the material carrying negative charge. Since there exists localized excess of negative charge, the extrinsic semiconductor is called N type semiconductor.

The concentration of phosphorous atoms is again quite low, but typically greater than the boron concentration, usually around one impurity atom for every 10^3 silicon atoms.

The PN Junction or Internal Electric Field

Regions of P type and N type semiconductors are created adjacent to another to form a PN junction (fig.5.1.4). Immediately after creation of the adjacent regions, free electrons from N type semiconductor cross the junction and permanently fall into the holes of P region. As this cross over continues, every boron site that contributed a hole becomes permanently negatively charged.



Permanent internal electric field and lines of force

Fig. 5.1.4 PN Junction and internal electric field

And every phosphorous atom that gave up an electron becomes permanently positively charged. Two equivalent but oppositely charged regions grow on the either side of the PN interface or junction, creating an electric field. This internal electric field, also called, potential barrier, is oriented to push electrons in one direction, towards the N type region. Any holes are swept by this field toward the P type region. Any stray charges that enter the zone of influence of the electric filed are immediately swept out of that zone, so the zone is also called depletion region.

The Solar Cell

The solar cell is nothing but a large area PN interface or junction. It is the internal electric field of the PN junction that sweeps electrons out of the cell. When light penetrates into the semiconductor material, knocking free electrons and giving them potential energy, the freed electrons wander until they are pushed by the electric field across the PN junction. They are forced out of the cell, and are available for useful work.

The electrons with higher energy level flow out of the cell through the wire to the load. After releasing the excess energy into the load these electrons return back to the cell and fall into the holes. So as soon as an electron leaves the cell from one side and enters the wire, an electron at the other end of the wire moves into the cell. So the solar cell cannot "run down" like a battery, nor can it "run out of electrons". It produces output (electrical energy) in response to the input "fuel" (light energy). A solar cell thus cannot store electrical energy; it can only convert light energy into electrical energy.

5.2 Solar Cells

In this section discussion will be made on various aspects of a solar cell: various types (generations) of solar PV cell technologies, electrical parameters, effect of temperature spectral response etc.

Types of Solar Cells

The solar cell technology has evolved dramatically; from the crystalline structure cells to thin film (ribbon) cells to the cells based on Carnot principle. Accordingly, the PV cells are classified into generations. The first generation of cell technology is based upon bulk crystalline structure of various semiconductor materials. The second-generation solar cells are thin film type cells. The third generation cells are based on entirely new principle.

- ***First Generation Solar Cells***

  Mono-crystalline silicon (where the atoms align into a large single crystal) remained predominant cell production technology for last 40 years. At the time being silicon is almost the only material used for solar cell mass production. As the most often used semiconductor material it has some important advantages:
  - In nature it can be easily found in large quantities;
  - Silicon oxide forms 1/3 of the earth's crust;
  - It is not poisonous, and it is environment friendly, its waste does not represent any problems;
  - It can be easily melted, handled, and it is fairly easy formed into monocrystalline form;
  - Its electrical properties endurance of 125^0 C allows the use of silicon semiconductor devices even in most harsh environment and applications.

  In process of manufacturing silicon based solar cell, wafers of pure silicon are produced in first place. Then by doping appropriate impurities, large area PN junction is formed.

  In techniques, pure silicon is the only widely used chemical element produced so pure. The percentage of pure silicon (semiconductor grade silicon) in material is at least 99.9999999%. Metallurgical grade silicon (98-99% purity) is produced from silicon di-oxide by reduction in specially designed furnace at 1800^0C. By using more complex process the metallurgical grade silicon is further purified.

Monocrystalline silicon is produced from pure silicon by utilization of Czochralski (Cz) method. In this method the silicon is extracted from melt in induction oven with graphite lining at the temperature of 1415^{0}C. Silicon crystal of defined orientation (called seed) is placed on a rod. In the melt, spinning the rod makes the crystal grow. The rod spinning speed comes to 10 to 40 turns per minute, whilst the movement at length comes between 1 micrometer and 1 millimeter per second. It allows production of monocrystalline rods (called ingots), which measure 30 cm in diameter and several meters in length. Individual round wafers of required thickness are sawed from the cylindrical ingot by using diamond saw. If the sides of the cylinder are cut first, making a long block, then when the wafers are cut they are square.

Monocrystalline silicon based solar cells have excellent efficiency (up to 13% in standard test conditions- STC) in converting light energy into electrical energy. The limitations of this technology are high production cost associated with wastage of precious pure silicon during sawing (almost 40-50% of the material is converted into dust) and slow process of growing the ingot.

Another method of creating a block of silicon is to melt purified silicon rocks in a rectangular block shaped mold. When the silicon is cooled slowly, it solidifies into the block shape. But in the solidifying process, the atoms do not align into large single crystal as in the Cz method. Small regions of single crystal structure form next to each other, forming a **polycrystalline** block of different grains.

At the boundaries between the grains, it is possible for defective atomic bonds to interfere with the current flow, and typically a slightly lower output is produced compared to equivalently processed single crystal cells. As with Cz cells, polycrystalline wafers are produced by slicing the large block. The typical efficiency of polycrystalline cell is around 10-12%.

The solar cell made of a single type of semiconductor material is called homojunction cell. Example is the silicon cell where the junction is formed by doping the silicon material with different impurities. The other PV cell materials and designs employ a heterojunction structure in which the junction is formed between two different semiconductors that have different energy band gaps. The examples of heterojunction PV cells are amorphous silicon alloy (a-Si:H), Copper Indium Diselenide (CIS), Cadmium Telluride (CdTe), Gallium Arsenide (GaAs) etc.

Independent of the methods of manufacturing the individual wafers, the solar cells based on bulk wafers have the structure as shown in fig. 5.2.1.

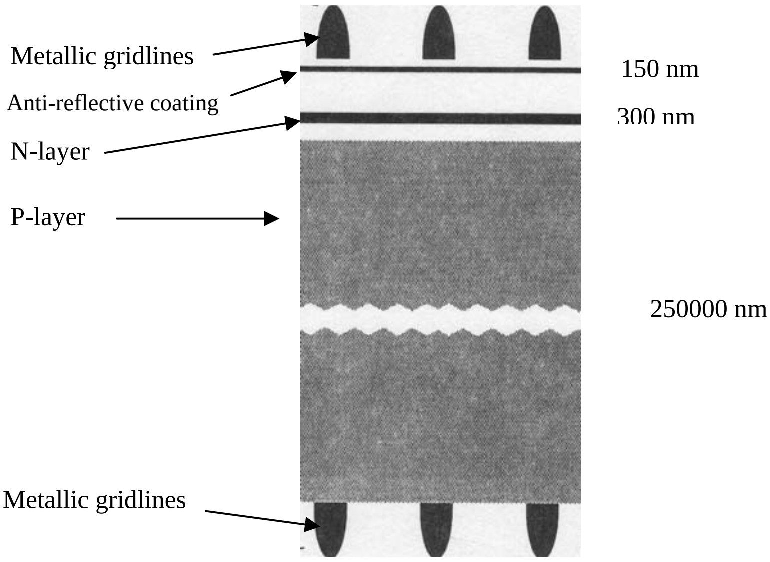


Fig. 5.2.1 Structure of traditional (Bulk) Solar Cell

The typical solar cell consists of a P type wafer of about 250000 nm thicknesses with rear end of the surface covered by metallic gridlines for external connections. An extremely thin layer (about 300 nm thick) of N type silicon is grown by diffusion method on top of the P type wafer to produce the PN junction. Anti-reflective conductive coating of around 150 nm thicknesses is applied to the N layer. Finally, metallic grid connection is applied for external connections. In this way an individual cell is manufactured.

- ***Second Generation Solar Cells***

The slicing process in the previous two methods is wasteful. This is because the wafers are around 250000 nm thick, and the saw blade is about this thickness as well.

One method of producing wafers avoids most of this waste by growing a **thin ribbon** from the melted silicon. The ribbon is either pulled sideways off the top of the melt, or pulled up through a die. Very fast growth rates are possible, but the speed results in polycrystalline structures. However, if pulling is done very carefully and slowly, near single crystal structure is possible. As the ribbon thickness is same as that of wafer thickness, no sawing is necessary. The ribbon sheet is simply scribed and broken to produce rectangular wafers of required size.

However the surface of the wafer is not typically flat, and often bulges or waviness in the surface makes further manufacturing steps and interconnection difficult. The efficiencies of the ribbon silicon cells are similar to polycrystalline silicon cells. As with bulk cells, the materials used in thin-film cells could be amorphous silicon, CIS, CdTe, Cu_2S, GaAs etc.

- ***Third Generation Solar Cells***

The third generation PV technology is a new concept based on different conversion principles that allow the solar energy conversion value to be more closely approached Carnot value.

Since the early days of terrestrial PV, a common perception has been that "first generation" silicon wafer based solar cells would be replaced by a "second generation" of lower cost thin film technology, probably also involving a different semiconductor. Historically, Cds, a-Si, CIS, CDTe and now thin film Si have been regarded as key thin-film candidates. Since any mature solar cell technology must evolve to the stage where costs are dominated by those of the constituent materials, be it silicon wafers or glass sheet, it is argued that PV must evolve, in its most mature form, to a "third generation" of high efficiency thin-film technology with energy conversion values double or triple the 15-20% range presently targeted from the first and second generation technology.

Unavoidable entropy production associated with light absorption that limits solar energy conversion efficiency to 86.8%. To reach this efficiency, converters must be perfectly absorbing but re-emit light with a specific spectral content. The chemical potential associated with spontaneous emission for each photon energy must have a particular value and be constant throughout the absorption volume.

Several advanced conversion approaches are theoretically proved to be capable, in principle, of meeting these requirements (tandem, hot carrier, multiple band cells). Others are bound by a slight low energy conversion efficiency of 85.4% (thermophotovoltaics). A third group (multiple electron-hole pairs) has intermediate bounds (85.9%), while the impurity photovoltaic effect has the efficiency bound 77.2%. All are appreciably higher than the bound for conventional cells (40.7%).

Tandem cells are now in commercial production with triple junction cells based on GaInP/GaAs/Ge have been developed for use on spacecraft with terrestrial efficiencies approaching 30%. Quadruple junction devices with efficiencies approaching 40% are presently under development in various parts of the world. Besides other methods are still under the research and development for commercial production.

The cost of the module based on the "third generation" PV is initially higher than conventional one at present, but due to the overall higher efficiency the operation (electricity generation) cost will be drastically reduced. The latest development in this sectors shows that there is a great prospect for the cheaper production of "third generation" PV cells within next decade.

Spectral Response

It is well known fact that white light is the combination of light sources of various colors of different intensities. Therefore different sources of light may appear equal in brightness to an observer (human being) but will contain different amounts and intensities of colors. For example, fluorescent light is typically stronger in blue tint than incandescent lights. Also throughout a day, there is difference in the spectral content of morning, noon, and evening sunlight, as can be seen by looking at the sky.

Light (here we refer to visible light only) is just a narrow range of all electromagnetic radiation that is emitted by the sun. Radiation is a moving electric-magnetic field, and the field vibrates regularly at a very rapid pace. The speed at which the field propagates is equal to the speed of light i.e. 3 $x10^8$ meters per second. The distance the electromagnetic wave travels during one complete cycle of vibration is called the wavelength of radiation. The visible light (fig.5.2.2) is radiation between approximately 400 nanometers (violet color) and 800 nanometers (red color).

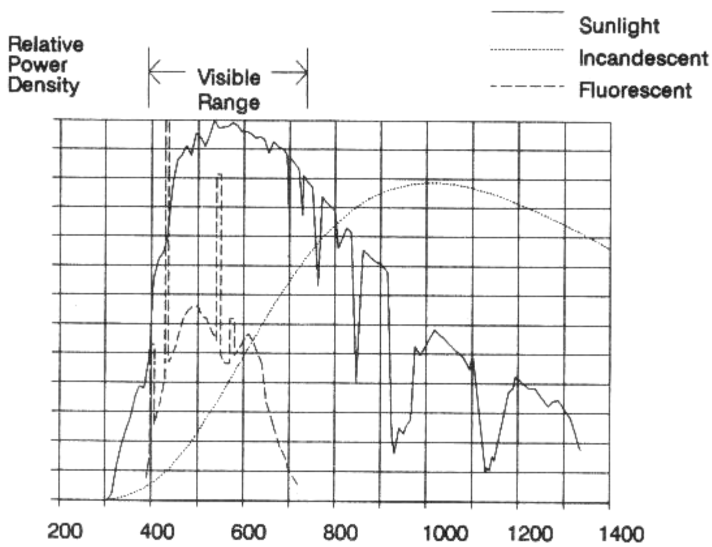


Fig. 5.2.2 Light Spectra from Common Sources

The spectral response is a measurement of the “response” (measured by generated current) when a solar cell is exposed to a spectrum or range of light. A 100% response would mean for 100 photons of a certain wavelength that are absorbed, 100 electrons would be freed and swept out for use.

Light of the same color or wavelength will produce different amounts of current in different semiconductor devices. The spectral response of a typical Cz silicon cell begins about 350 nm, peaks around 800 nm and falls off rapidly beyond 1100 nm. The response range spans the entire visible spectrum and reaches into near infra-red. The fig. 5.2.3 provides general picture of spectral responses of various semiconductor materials used to manufacture the solar cell.

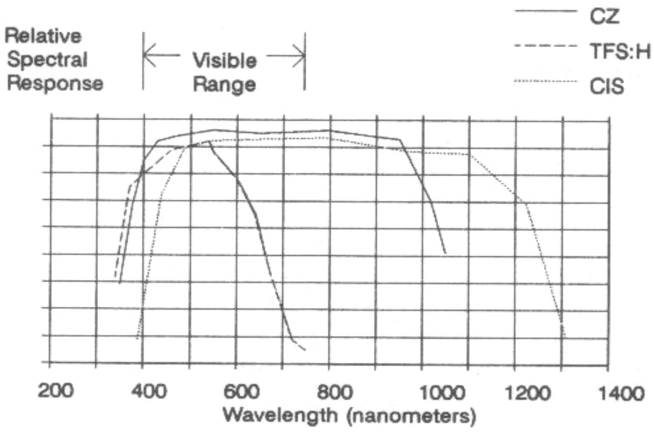


Fig. 5.2.3 Spectral Response of Solar Materials

Because a cell's response to light depends on the wavelength of that light, just knowing the total energy of the light is not enough information to predict cell output. Also, two light sources can appear to be similar in brightness to the human eye, but one may emit a great deal of extra radiation beyond the visible range where our eye will not notice but to which the solar cell will respond significantly. A standard "typical outdoor spectrum" has been defined as the spectrum from the sun that filters through 1.5 AM (Air Mass).

Electrical Parameters of a Solar Cell

The graphical representation of the relation between the current and voltage produced by a solar cell is the standard form of representing the output of the cell. This graphical representation is called current-voltage curve (I-V curve). The I-V curve (fig.5.2.3) represents the snap-shot of all the potential combinations of current and voltage possible from a cell under specified environmental conditions like irradiance, air mass and surrounding temperature.

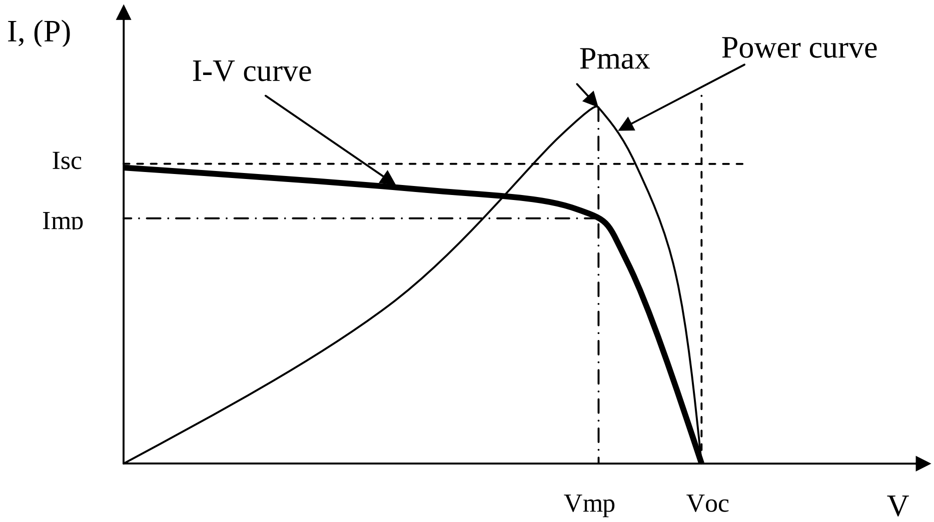


Fig. 5.2.3 I-V curve of a solar cell

The key terminologies used in the above curve are:

Short Circuit Current (Isc) – It is the maximum current (in A or mA) produced by the cell under given conditions of irradiance and surrounding temperature. Isc is the current when the load is short-circuited, i.e. the output voltage is zero. The output power at this point is essentially zero.

Open Circuit Voltage (Voc) – It is the maximum voltage generated by the cell under given conditions of light and temperature. Voc is the voltage when the load is open-circuited, i.e. the output current is zero. The output power at this point is again essentially zero.

Maximum Power (Pmax) – It is the maximum power that can be delivered from the cell under specific environmental conditions. The point at I-V curve at which the maximum power is attainable is called Maximum Power Point (MPP).

Current at Maximum Power (Imp) – It is the current that results in maximum power. Imp is also called the "Rated" current of the cell.

Voltage at Maximum Power (Vmp) – The voltage that results in maximum power output is called Voltage at maximum power. Vmp is also called "Rated" voltage of the cell.

Fill Factor (FF) – The fill factor is a figure of merit that indicates the "squareness" of the I-V curve. It is the ratio of the actual maximum power Pmax to the unattainable but ideal power that would result from operating at Isc and Voc.

Total Area Efficiency – It is the ratio of electrical power output (typically the Pmax) to the total light power incident on the entire cell area including frames (if applicable), interconnects and pattern lines on the surface.

The above parameters are equally applicable to the modules and arrays.

Mathematically, some of the above parameters can be expressed as:

$$P_{\max} = I_{mp} \times V_{mp} \tag{5.2.1}$$

$$FF = \frac{(I_{mp} \times V_{mp})}{(I_{sc} \times V_{oc})} \tag{5.2.2}$$

Example 5.2.1

Suppose a certain model of the solar PV module has the following parameters:

Peak Power (Wp)-	35 Watts
Open Circuit Voltage (V_{oc})-	20.8 V
Maximum Power Voltage (V_{mp})-	16.4 V
Short Circuit Current (I_{sc})-	2.3 A
Maximum Power Current (I_{mp})-	2.14A

The maximum or peak power according to formula 4.2.1 is:

$P_{max} = V_{mp} \times I_{mp} = 16.4 \times 2.14 = 34.99$ W

This value is equal to the Peak Power value (35 Wp) indicated by the manufacturer of the module.

Theoretically achievable maximum power is :

$P_{ideal} = V_{oc} \times I_{sc} = 20.8 \times 2.3 = 47.84$ W

The Fill-factor of the module is therefore (formula 4.2.2):

FF = 34.99/47.84 = 0.73

The voltage at maximum power point (MPP) of a single solar cell is approximately 0.5 volt under full sunlight. This voltage varies with the exact semiconductor materials used and is slightly affected by the temperature. The most important fact is that this voltage does not depend upon the area (or size) of the cell.

On the other hand, the current produced by a cell is the function of cell area, intensity of light, the semiconductor material used and the surrounding temperature. The larger the surface area, the more light will enter the cell and more current will be released. The typical value of Imp for a Cz monocrystalline cell is about 30 mA per square centimeter and for a Amorphous cell it is about 9 mA/cm.sq.

Solar Cell Models

The simplest solar cell model (fig. 5.2.4) consists of diode and current source connected in parallel.

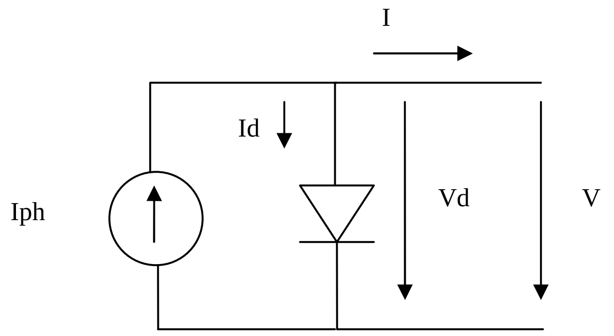


Fig. 5.2.4 Ideal Solar Cell Model

The magnitude of the current source is directly proportional to the solar radiation. Diode represents PN junction of a solar cell. Equation of an ideal solar cell, which represents the ideal solar cell model, is:

$$I = I_{ph} - I_s\left\{\left[\exp\left(\frac{v}{m \times V_t}\right)\right] - 1\right\} \qquad (5.2.3)$$

Where is:

I_{ph} – photocurrent (A),

I_s – reverse saturation current (A) (approximately in the range of $10^{-8}/m^2$), v- diode voltage in volt,

V_t – thermal voltage in volt (25.7 mV at 25^0C),

m – diode factor.

The thermal voltage V_t for given temperature can be calculated with the following equation:

$$V_t = \frac{kT}{e} \qquad (5.2.4)$$

Where is:

k- Boltzmann constant = 1.38 x 10^{-23} J/K,

T- temperature (K),

e - charge of electron = 1.6 x 10^{-19} Columbs.

The real solar cell model (fig 5.2.5) consists of serial resistance (Rs), parallel resistance (Rp) to reflect the voltage drops and parasitic currents and the load resistance (Rl) to determine the operating point in the I-V curve.

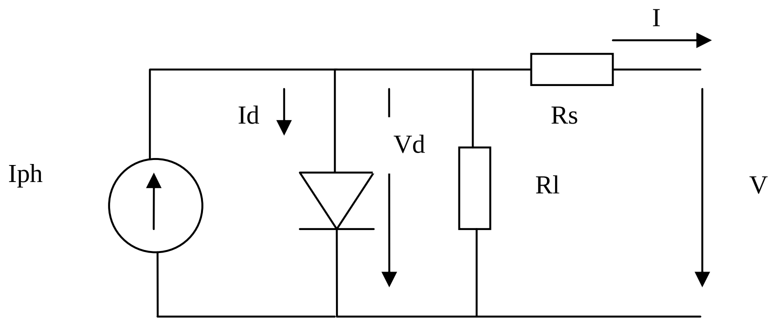


Fig. 5.2.5 Real Solar Cell Model

Effect of Environment on Output of the Cell

The I-V curve of a solar cell is really just a “snap-shot” view of the potential out put under static environmental condition (solar radiation and temperature). If these parameters are changed, the output (voltage and current) of the device will change.

As the intensity of light changes, so does the number electrons released. So the direct result of a change in light intensity is a change in the output current in all voltage levels.

The short circuit current Isc of a cell is directly proportional to the light intensity. The standard value of Isc is provided by manufacturer at the intensity of light of one sun or peak insolation that equals to 1000 W/sq.m (100 mW/sq.cm). If the value of Isc is known for Standard Test Condition –STC (light intensity = 1000 W/sq.m; cell temperature = 25^0C and Air mass = 1.5), then the magnitude of Isc at other light intensity can be calculated using the following relationship of direct proportionality:

Isc (at given light intensity) = Isc (at STC) x (given light intensity/ 1000 w/sq.m) (5.2.5)

Example 5.2.2

If the magnitude of Isc for certain cell at 1000 W/sq.m is 2 A, then at the light intensity of 800 W/sq.m would be:

Isc (800 W/sq.m) = 2 x 800/1000 =1.6 A

The open circuit cell voltage (Voc), on the other hand, varies more slowly in a logarithmic relationship with light intensity.

When the cell temperature rises (due to rise in ambient temperature), the main effect is to reduce the voltage available at most currents. There is slight rise in current at very low voltage. The change in voltage is directly proportional to the rise in temperature. The proportionality coefficient is called temperature coefficient and measured in terms of +/- V per ^{0} C or +/- mA per cm.sq. per ^{0}C. Sometimes the proportionality coefficient is expressed in terms of percent change per degree change in temperature. The typical values of temperature coefficients for Voc and Isc for various cells are given in table 5.2.1.

Table 5.2.1 Temperature Coefficient of various cell types

Cell type	**Voc**	**Isc**	**Remarks**
Cz (monocrystal)	-0.0023 V/deg.C *or* -0.37% /deg.C	+0.004 mA/cm^2/deg.C *or* +0.01 mA/cm^2/deg.C	Applicable to Voc and Isc only, but can be applied to give approximate values for Vmp and Imp as well
Amorphous Silicon	-0.0028 V/deg.C *or* -0.32% /deg.C	+0.013 mA/cm^2/deg.C *or* +0.10mA/cm^2/deg.C	Applicable to Voc and Isc only, but can be applied to give approximate values for Vmp and Imp as well

The fall in voltage and slight rise in current at very low voltage results in overall reduction in maximum power by 0.5% per deg.C in Cz cells and 0.3% per deg. C in amorphous cells.

5.3 Solar Modules

A single Cz solar cell of size 4 sq. inch (≅ 105 sq.cm) will produce around 3.05 A of Imp and 3.36 A of Isc at STC. Assuming Vmp to be 0.5 V, the maximum power generated by the cell would not exceed 1.52 Wp (Watt peak). This is too low power for any practical applications. In fact, increasing the size of the cell can increase the power, but there are practical limitations of cell size. Therefore, numbers of cells are connected in series and parallel to increase the current, operating voltage as well as the output power.

When two cells are connected in series the voltage doubles (or the total output voltage is the product of voltage produced by individual cell and the numbers of cells connected in series). But the current through the series connected cells will be equal to the current produced by a single cell.

Example 5.3.1

If 36 cells with Vmp = 0.5 V and Imp = 3 A are connected in series then:

The Vmp for 36 series connected cells = 0.5 V x 36 = 18 V, and
Imp 36 series connected cells = current produced by the single cell = 3A

The total power (at MPP) in this case would be :
Pm = Vmp x Imp = 18 x 3 = 54 Wp.

The I-V curve with series connected cells will now have the voltage axis shifted 36 times.

Now if we connect number of cells in parallel, the total output voltage will not change but the total current will be equal to the product of current produced by one cell and number of cells connected in parallel.

Example 5.3.2

If 36 cells with Vmp and Imp as in previous example are connected in parallel, then:

Vmp for 36 parallel connected cells = Vmp of single cell = 0.5 V, and

Imp for 36 parallel connected cells = Imp (of a single cell) x 36 = 3 x 36 = 108 A.

The total maximum power in this case will be again

Pm = 0.5 V x 108 A = 54 Wp.

The I-V curve with parallel-connected cells will now have the current axis shifted 36 times.

From above two examples it can be concluded that the power will be multiplied by number of cells no matter how these cells are connected (in series or in parallel).

A solar module is nothing but number of cells connected either in series (in most of the cases it is the series connection that makes a module) or in parallel and encapsulated in a single frame. In other words, a solar module is a collection of cells connected in series and sometimes in parallel to produce a basic building block with enough voltage to do useful work. In most common load for a solar PV application is a 12V storage battery. To charge a 12 V battery fully, the charging voltage needs to be not less than 14-15 V. So most modules are made of enough cells in series to produce at least 14.5 V at MPP, to be able to efficiently charge the batteries. To achieve this voltage, 30-36 Cz cells or 24-28 thin film silicon cells are connected in series. The I-V curve for a single cell is added along the voltage axes 36 times.

If the main application for the modules were not 12 V battery charging, then some other number of cells might be more appropriate. Therefore the ultimate application voltage determines the number of cells needed in series. The most common market for large power photovoltaic modules is still 12 V battery charging, so that is why most manufacturers produce modules with around 30 to 36 Cz cells in series.

The parameters of a module are same as that of a cell- the open circuit voltage (Voc) which now depends upon the number of cells connected in series, the short circuit current (Isc) which is equal to the short circuit current of a single cell, Vmp, Imp and Pmax at MPP. A typical I-V curve of a solar module is shown in figure 5.3.1 below.

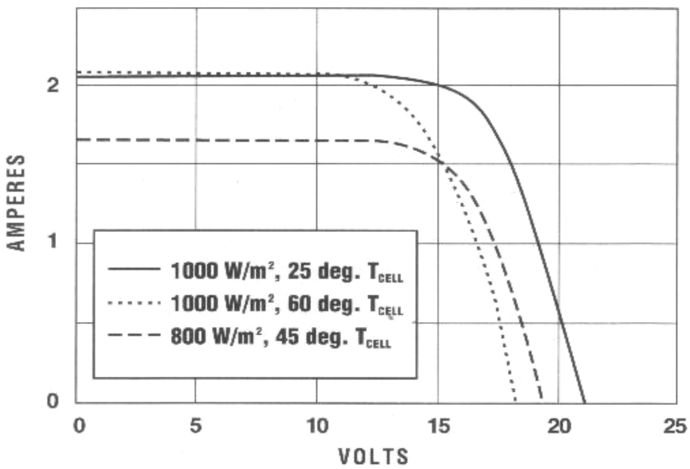


Fig. 5.3.1 Typical IV curve of a module

The process of manufacturing a module is as follows. The individual cells are first connected in series in back to front fashion by using thin tin plated copper ribbons. The interconnected cells are carefully placed over a rear support plate ensuring optimal packing density. Encapsulation is the next step of module manufacturing. Encapsulation is required to protect the cells from the environment and to support them in module. The two most common encapsulants are transparent silicon rubber and ethylene vinyl acetate (EVA) plastic. Usually a top cover of plastic or tempered glass is added to offer better protection against the elements. Glass covers are more scratch-resistant and remain transparent longer, but they do not flex as much as plastic covers. Finally aluminum frame is attached to the encapsulated module to offer support for installations.

Bringing the electrical wires out of the module requires careful design. The electrical connectors are a pair of contacts that protrude from the back of the module and are sometimes encased in a small junction box (JB). The external wires can be screwed to the terminals of the junction box that are marked as positive and negative terminals. Some low power modules do not incorporate JB in their design; instead two different colored wires of fixed lengths are extended directly from the back of the module. The point from where the wires protrude is hermetically sealed. The modules are finally tested in the laboratory under simulated STC.

Blocking Diode

The blocking diode is a low forward voltage drop semiconductor device that blocks the flow of current in reverse direction. During the day when there is sufficient sunlight, the solar module acts as a generator of electricity. It means during the day the current flow from the module to the storage battery. But during nights the module IV curve is shifted downwards to zero current level (fig. 5.3.2).

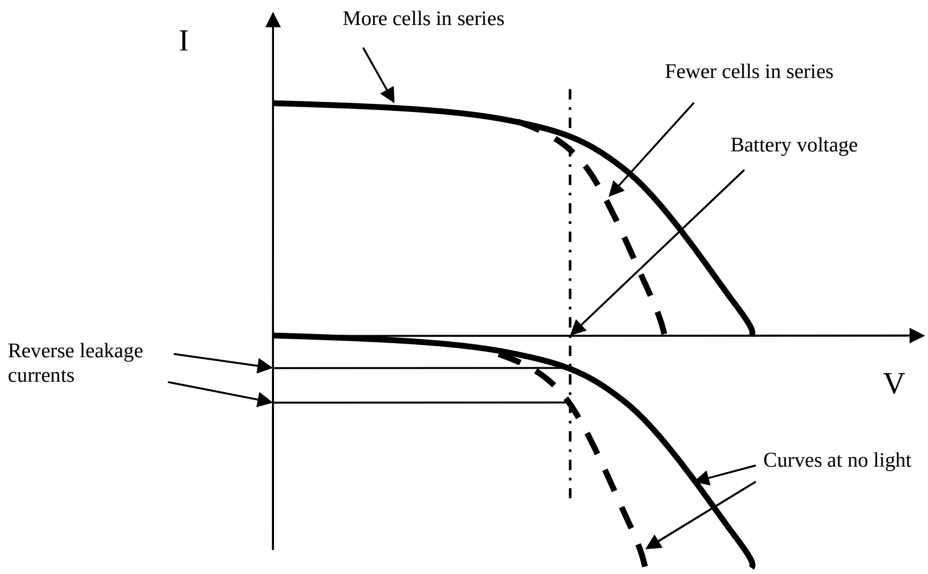


Fig. 5.3.2 Reverse Leakage Current through the module

At this moment the battery voltage will see the module as a drain (i.e. the module will be seen as a load) and current will start flowing from the battery to the module, thus losing precious energy gained during the daytime. The amount of reverse leakage current will depend upon the battery voltage and the shape of IV curve. Poorer the IV curve (i.e. the current drops rapidly at lesser voltage level and this is the case of fewer cells connected in series), higher will be the reverse leakage current. The magnitude of this current for a 36 cell Cz module is around 50 mA at the voltage level of fully charged 12 V storage battery. Though the leaking current will not harm the module but if precautions are not taken, the current stored in the battery will leak to the module and converted into heat during dark hours.. Therefore to reduce the leaking current a diode is connected in the path between the module and the battery in such a way that during the day it is forward biased from module point of view and during the night it remains reverse biased from battery point of view. The figure 5.3.3 illustrates the function of a blocking diode.

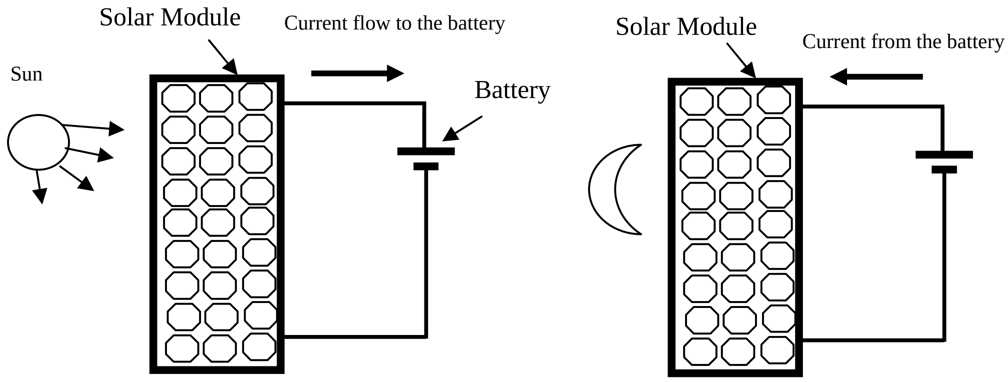


Fig. 5.3.3 a Module connected to the battery without blocking diode

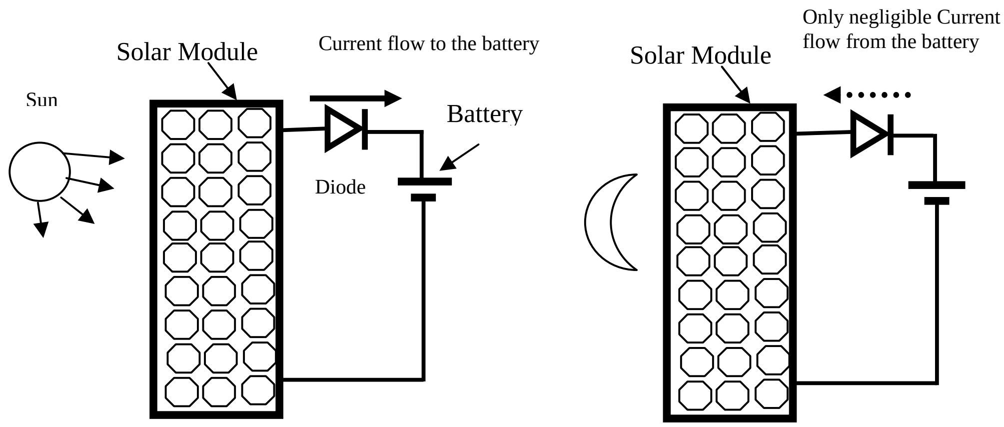


Fig. 5.3.3 b Module connected to the battery with blocking diode

With the blocking diode, the leakage current is limited to the reverse saturation current of the diode (normally in the range of micro Amperes). The penalty for using the blocking diode is the forward voltage drop in it during the daytime charging of the battery. This drop is about 0.7 V for silicon diodes and 0.3 V for low forward drop Schottky diodes or germanium diodes. Even if the module does not incorporate a blocking diode, it has to be inserted during the wiring of the system. In most cases a charge regulator has the blocking diode in it. If the load of a PV module is not a storage battery, then blocking diode can be omitted.

By-pass Diode

Another critical component of a module is the by-pass diode. When part of a PV module is shaded, the shaded cell will not be able to produce as much current as the unshaded cells. Since all the cells are connected in series, the same amount of current must flow through every cell. The unshaded cells will force the shaded ones to pass more current than their new Isc (with lower light intensity). The only way the shaded cells can operate at a current higher than their Isc is to operate in a region of negative voltage: that is to cause a net voltage loss to the system. The current times this negative voltage gives the negative power produced by the shaded cells. In other words, the shaded cells will dissipate power as heat and cause “hot spots”. And the shaded cells will drag down the overall IV curve of the group of cells or module. Figure 5.3.4 below explains the effect of shaded cells on over all IV curve of the module.

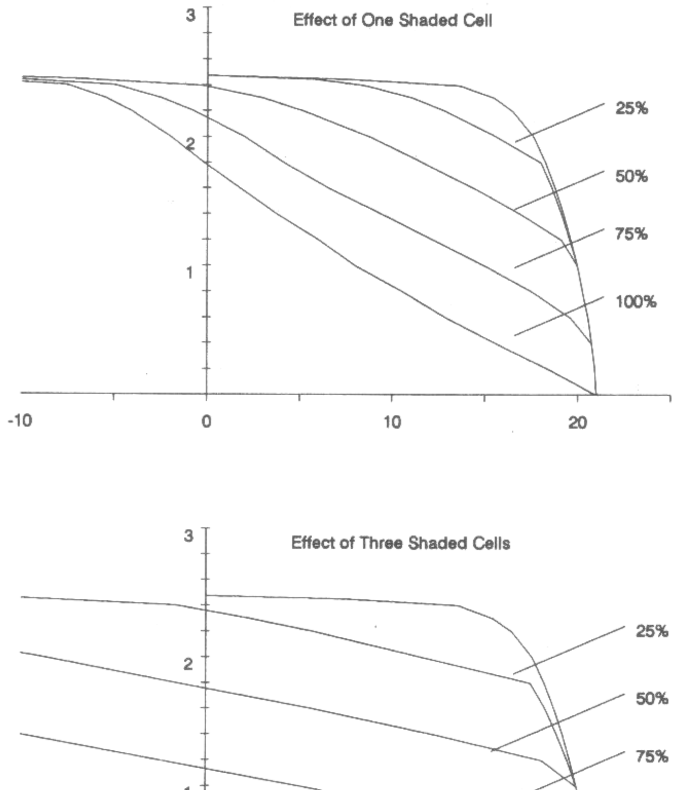


Fig. 5.3.4 Effect on IV curves from the cells shaded in different level

As seen from the first graph, even with only one cell 50% shaded, there is a significant drop in current in the voltage range of battery charging. One cell completely shaded is even worse. But note that the module is not completely “turned off” by one completely shaded cell. For a module with three cells shaded the impact is of course worse still. But it is worthwhile to notice that the effect of 25% shading on the three cells is not as bad as 75% shading on one cell, the same total area of shading. Having the shading spread over many cells is not as sever as having all the shading located in one or a few cells. This is why special precautions are to be taken while selecting the location for installing the module. Moreover, frequent cleaning of the module is required to avoid shading of the cells by bird shit.

Figure 5.3.5 below best illustrates the loss in power and heating effect due to the shading of cells.

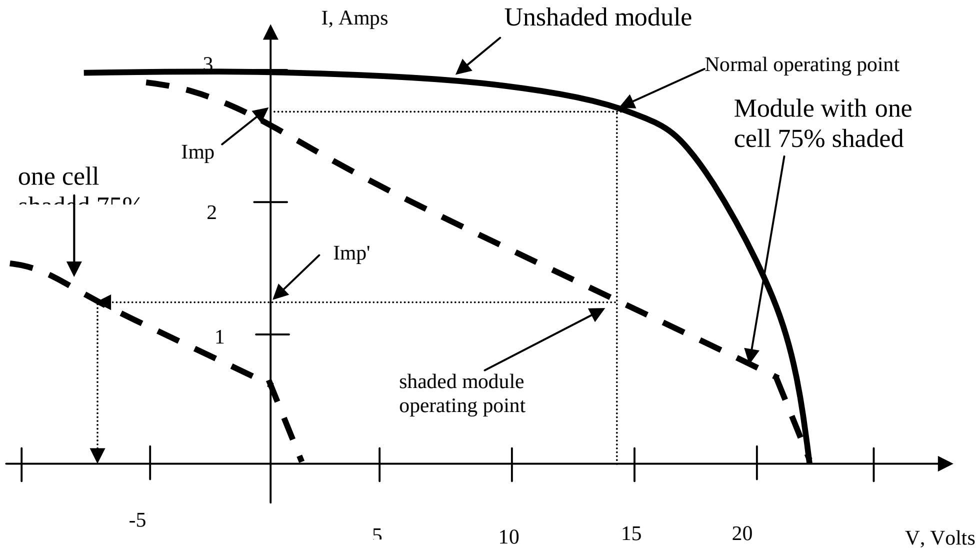


Fig. 5.3.5 Effect of Partial Shading of Cells

As it can be seen from the above figure at normal battery charging voltage of around 14 V, the shaded module output current is about 1.2 A as against nominal operating current of 2.6 A of unshaded module. Without shading the module would have produced 2.6 x 14 = 36.4 W. With one cell 75% shaded, the output power is just 1.2 x 14 = 16.8 W. The shaded cell (as well as other cells in the module) must pass 1.2 A of current, but in order to do this it must operate in its reverse voltage range at a net voltage drop of about –7 Volts.

This means it is dissipating power in the form of heat at the rate of - 7 x 1.2 = - 8.4 W. If a standard single cell was producing 2 W of power in normal condition, the shaded cell is absorbing and wasting more than 3 times its nominal output. The reduction in module output current with shaded cell will result in less energy delivered to the battery and perhaps eventually result in system failure due to inadequate battery charging. The effect of shading will be more sever, if the operating voltage is lower (cell will be forced to operate in higher negative voltage).

It would have been better if the shaded cells were taken out temporarily to limit the amount of local heating and to prevent damage to the plastic and stress to the cells. This can be done by installing diodes in parallel with group of cells in the module. These diodes are called by-pass diodes. As seen from the fig. 5.3.5 above, for the currents greater than the new Imp' of shaded cell, the cell is in reverse polarity (i.e it is consuming power). For the current less or equal to Imp', the shaded cell, along with other unshaded cell are in normal polarity (generating power). Now if a diode is connected parallel to the cell, then an effect of by-passing the difference current (difference between normal Imp and the shaded cell Imp') by the diode to other unshaded cells can be observed (Fig. 5.3.6). The Imp' is passed by the shaded cell itself to other cells.

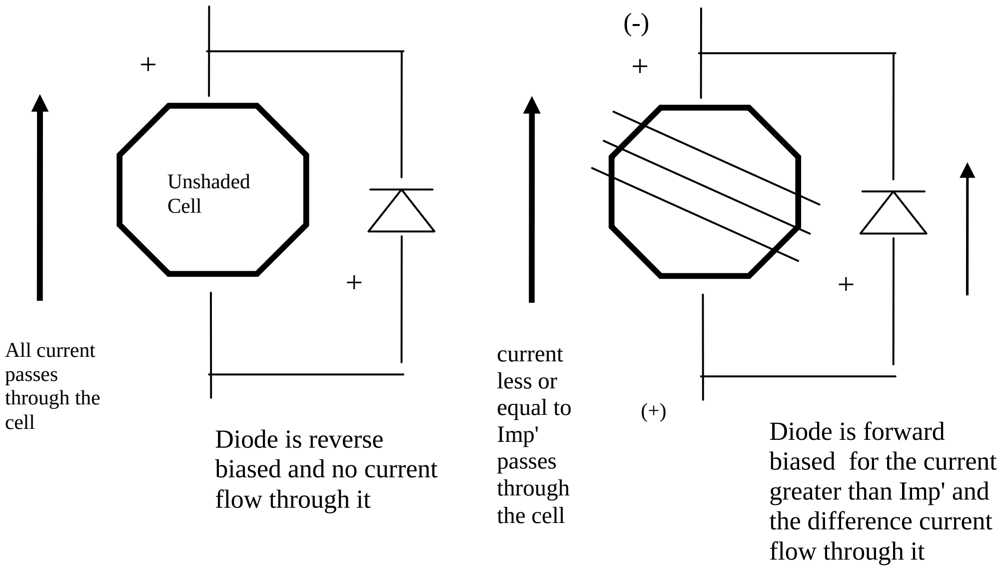


Fig. 5.3.6 Operation of the By-pass Diode

The by-pass diode for the current above Imp' becomes forward biased (as the polarity of the cell reverses for the current above Imp'). In this case the diode will pass the difference current to other cells, thus reducing the heating effect to the shaded cell and increasing the module power even with shaded cell in series with other cells. In normal condition (unshaded cell) the cell is in its normal polarity and therefore the diode is reverse biased. All the cell current passes through the cell it self. The price paid for adding a by-pass diode is the forward voltage drop of about 0.7 V in it.

It is impractical to add a diode to each cell. Instead the cells in the module are divided into three strings of equal cells and by-pass diodes (two numbers) are inserted between each string. Example of insertion of by-pass diodes in a module with 36 cells is shown in Figure 5.3.7.

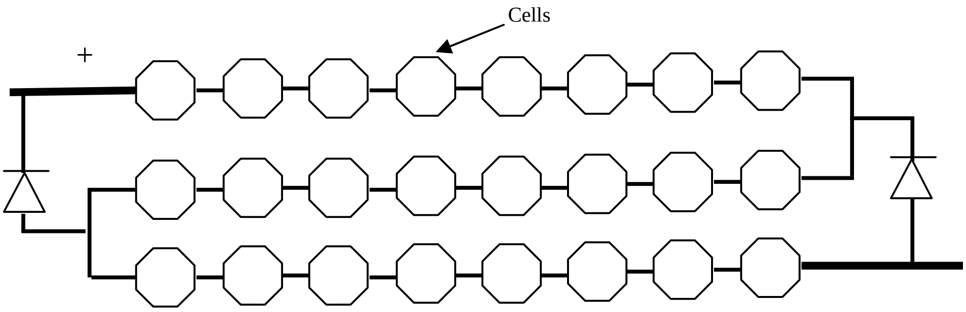


Fig. 5.3.7 By-pass diodes in Module

In above figure each string of cells is considered as a single cell, making an equivalent of three cells connected in series. The by-pass diodes will operate in the manner explained previously. Most of the large modules incorporate field replaceable by-pass in the junction box. The smaller modules without junction box may not contain the by-pass diodes at all.

5.4 Solar Array

Solar array is a group of similar modules connected in series and parallel to increase the power delivered by the PV system. As in case of series and parallel connection of cells, series connection of modules increases the final array voltage. In this case the current supplied by the array is equal to the current produced by a single module. Parallel connection of modules increases the output current keeping the voltage level at par with the voltage produced by the single module. In both cases the total power of the array will be equal to the product of power of single module times the number of modules used in connection. The array configuration (i.e. the number of modules connected in series or parallel) is dictated by the required system voltage. The peak reverse voltage that a module can withstand also governs the number of series connected modules in an array.

The parameters of an array are same as that of a single cell or single module. The only difference is in their magnitudes.

The input to configuring an array is the final required system voltage. For example if the load is a 24 V DC pumps, only two modules are to be connected in series to produce 24 V nominal outputs. Strings of two modules connected in series further can be connected in parallel to obtained required power levels. The figure 5.4.1 below is the suggestive array configuration for a 24 V DC system.

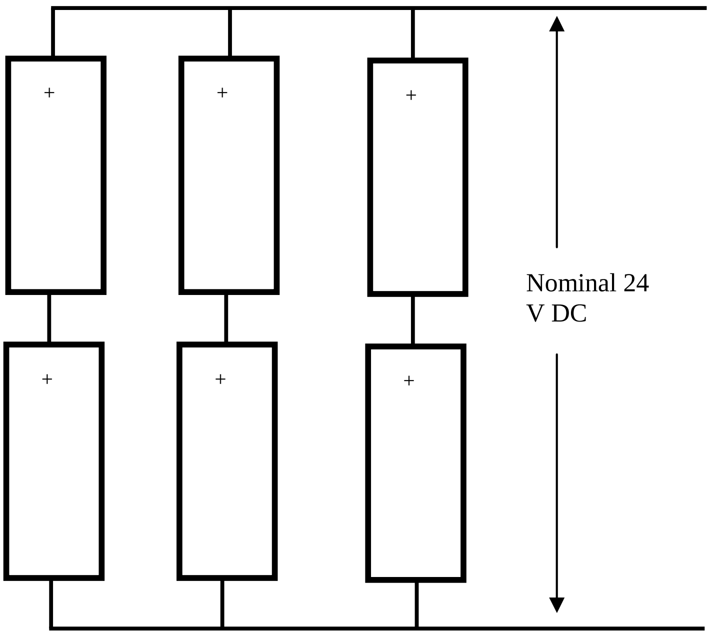
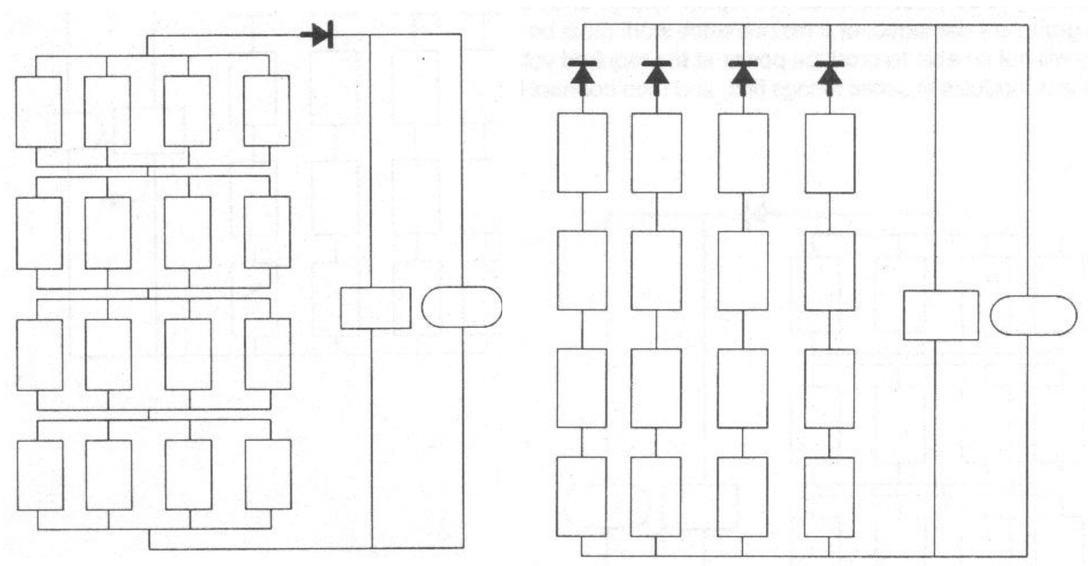


Fig. 5.4.1 Example of an array configured for 24 V DC applications

If the system requirement is 48 V batteries bank charging then four modules are to be connected in series. Number of these strings can further be connected in parallel to increase the total power. Suppose 16 modules of 40 Wp capacities are to be configured in an array to charge the bank of 48 V batteries. The array configuration can be performed in two distinct ways. In first method (parallel-series) four modules can be connected in parallel to produce a string, and four of these strings connected in series to produce 48 V nominal output (fig. 5.4.2a). In second method (series-parallel) four modules are first connected in series to make a string and finally four of these strings are further connected in parallel to obtain required power level.

In both cases the system voltage will be 48V and will deliver the same power to the battery bank.

The first method (figure in the left) has the draw back. If one string is removed for any reason (e.g. replacement of module), then the array is required to reconfigure or there will be no power available for the load. In second method (right figure), any string can be just removed and the array will still be supplying the reduced power at the same voltage level. Therefore the second method is considered more preferred method of array configuration.



a b

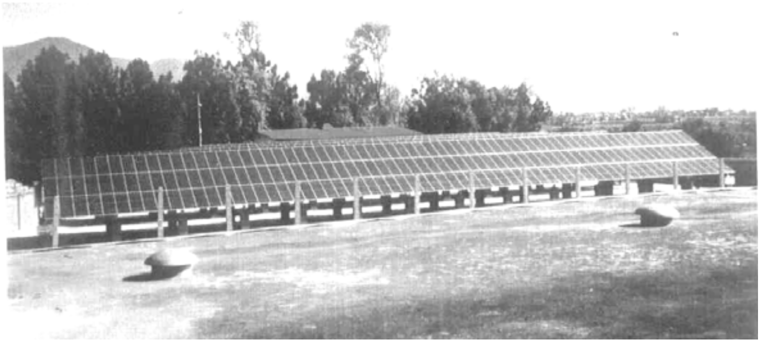
Fig. 5.4.2 Methods of configuring an array (a) parallel-series (b) series-parallel

Isolation Diode

If one string becomes severely shaded, or if there is short circuit in one of the modules, the diode connected in series with each string (see fig. 5.4.2 b) prevents the other strings from loosing current backwards down the shaded or damaged string. By use of these diodes the shaded or damaged string is "isolated" from the others, and more current is sent to the load. These diodes perform the same function as the blocking diodes, but because they isolate the damaged or shaded string, they are also called isolation diodes. Note that in case or parallel-series connection of modules only one diode at the one end of the output is used as blocking diode (fig. 5.4.2 a).

Large size arrays are also in use in Nepal. The largest is the array installed in Bode, Bhaktapur for water pumping purpose. It has the total installed power of 40,000 Wp.

The Zero Energy House (ZEH) at the Center for Energy Studies, Institute of Engineering, uses a 6.5 kWp array to power its facilities.



A 40 kWp array at Bode, Bhaktapur

Array used for water pumping at Ghorahi, Dang

Array used at Zero Energy House, Institute of Engineering

Review Questions

1. The electrical conductivity of semiconductor is

   a. very high
   b. same as that of copper
   c. very low
   d. same as that of glass

2. An atom with a 'hole' is

   a. neutral
   b. positively charged
   c. negatively charged
   d. not charged

3. When the intrinsic semiconductor is doped with tri-valent material, the resulting extrinsic semiconductor is called

   a. PN junction
   b. intrinsic semiconductor
   c. N type semiconductor
   d. P type semiconductor

4. Purity of semiconductor grade silicon is about

   a. 98%
   b. 99.9999%
   c. 99.9999999%
   d. 100%

5. The current at maximum power point of a solar cell is

   a. less than 1 A
   b. less than short circuit current
   c. greater than short circuit current
   d. equal to short circuit current

6. The maximum power that can be delivered from the module is the product of

   a. short circuit current and short circuit voltage
   b. open circuit voltage and open circuit current
   c. current at maximum power and open circuit voltage
   d. current and voltage at maximum power point

7. The open circuit voltage of a solar module

   a. decreases with rise in cell temperature
   b. increases with rise in cell temperature
   c. does not vary with temperature
   d. increases logarithmically with rise in temperature

8. There are at least…….. by-pass diodes in a module

   a. 36
   b. 18
   c. 9
   d. 2

9. 24 cells with Vmp =0.6 V and Imp = 1.2 A each are connected in series to form a module. Calculate the Vmp and Imp of the module.

10. The short circuit current of a module at light intensity of 100 mW/sq.m is 4.6 A. Calculate the short circuit current of the module when the light intensity is 600 W/sq.m.

CHAPTER 6

Components of a Solar Photovoltaic System

Duration: 330 minutes

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required:
a) Reference materials
b) Samples of various types and catalogues of batteries, charge regulators, lamps, DC-DC converters and DC-AC inverters, wire-size tables, PV standards and a calculator.

Procedures: The instructor/s
a) exposes to the operating principles, constructions and parameters of the components of solar PV system like battery, charge controllers, lamps and other loads, DC-DC converters and DC-AC inverters, wiring.
b) provides an overview of the installation practices

Instructor: The Trainer

Reference:
1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
6.1	Batteries	Lecture and demonstration	Class room	90 mins.	
6.2	Charge Controllers	Lecture and demonstration	Class room	90 mins	
6.3	Lamps and other loads	Lecture and demonstration	Class room	45 mins	
6.4	DC-AC inverters	Lecture and demonstration	Class room	45 mins	
6.5	DC-DC converters	Lecture and demonstration	Class room	30 mins	
6.6	Wiring and installation practices	Lecture and demonstration	Class room	30 mins	

6.1 Batteries in Solar PV Systems

Electrical storage batteries are usually used in PV systems, as the demand for energy does not always coincide with its production. The primary functions of a storage battery in a PV system are as follows:-

(a) **Energy Storage Capacity and Autonomy**: to store electrical energy whenever the PV modules produce it and supply energy to electrical loads as needed.
(b) **Voltage and Current Stabilization**: to supply power to electrical loads at stable voltages and currents by suppressing or "smoothing out" transients that may occur in the PV system.
(c) **Supply Surge Current**; to supply surge or high peak operating currents to electrical loads or appliances.

Battery Types and Classifications

Generally electrical storage batteries could be categorized into two main groups-Primary and secondary batteries**.**

Primary batteries can store and deliver electrical energy; but they cannot be recharged. Example of primary battery is dry cell used in radio, torchlight, watches etc.

Secondary batteries can store/deliver electrical energy as well as can also be recharged by passing a DC current through it in an opposite direction to the direction of discharge current. General examples of such batteries are common lead acid batteries used in automobiles and PV systems.

Battery Design and Construction

Battery manufacturing is an intensive heavy industrial process involving the use of hazardous and toxic materials. Some common components of the lead acid batteries are as follows (fig. 6.1.1):

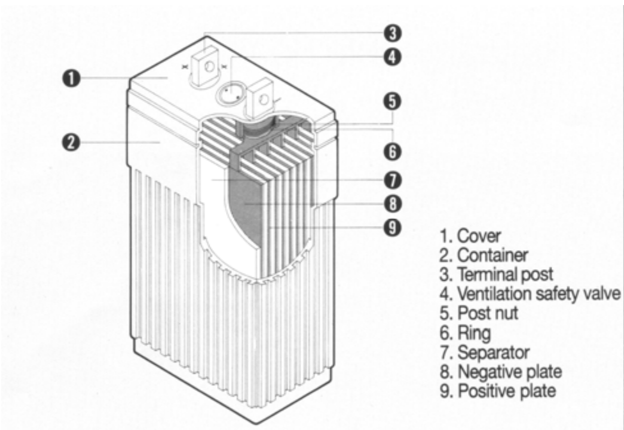


Fig.6.1.1 Construction of Battery

- *Cell*
  The cell is the basic electrochemical unit in a battery consisting of a set of positive and negative plates divided by separators; which are immersed in an electrolyte solution enclosed in a case. In a typical lead-acid battery each cell has a nominal voltage of about 2.1 Volts. Therefore a 12-volt battery consists of 6 cells in series connection.

- *Active Material*
  In lead-acid batteries the active materials are lead dioxide (PbO_2) in the positive plates and metallic sponge lead (Pb) in the negative plates. The amount of active material in a battery is generally proportional to the capacity that a battery can deliver.

- *Electrolyte*
  An electrolyte is a conducting medium, which allows the flow of current through ionic transfer between plates in a battery. In a lead acid battery the electrolyte is a diluted sulfuric acid solution, either in a liquid (flooded) form, gelled or absorbed in glass mats. In flooded nickel-cadmium batteries the electrolyte is an alkaline solution of potassium hydroxide and water.

- *Grid*
  In a lead –acid battery the grid is typically a lead alloy framework that supports the active material on a battery plate; and which also conducts current. Antimony and calcium are also used as alloying agents to strengthen the lead grids, which impart characteristic effects on battery performances such as cycle performance and gassing. Some grids are made of long spines of lead with the active material plated around them forming tubes; which are called as tubular plates.

- *Plate*
  A plate, sometimes called as an electrode consists of grid and active material. A pasted plate is made by coating a mixture of lead oxide, sulfuric acid, fibers and water on the grid. The thickness of the grid and plate very much affect the deep cycle performance of a battery. Thin plates are generally used in automotive batteries, whereas thick plates are used in deep cycle batteries.

- *Separator*
  A separator is a porous insulating divider between the positive and negative plates in a battery, which prevents the plates from coming into electric contact and short-circuiting; but allows the flow of electrolyte and ions between the positive and negative plates. Separators are generally made of micro-porous rubber, plastic or glass-wool mats.

- *Element*
  An element is a stack of positive and negative plate groups and separators assembled together with plate straps interconnecting the positive and negative plates.

- *Terminal Posts*
  Terminal posts are the external positive and negative electrical connections to a battery. A battery is connected in a PV system and to the electrical loads at the terminal posts. In lead-acid batteries the terminal posts are generally made of lead or lead alloy.

- *Cell Vent*
  Cell vents allow the escape of gases produced inside the battery during charging process or permit addition of water if required. Each cell of a complete battery has some type of cell vent.

- *Case*
  The plates, separators and electrolyte in a battery are contained in a typically enclosed case, generally made of plastic or hard rubber. Clear battery cases or containers allow easy monitoring of electrolyte levels and battery plate conditions.

Lead-Acid Battery Chemistry

During discharge cycle the battery is connected to an electrical load and current flows from the battery to the load. In this process the active materials are converted into lead sulfate ($PbSO_4$) as given by the following chemical equation:

Positive Plate Electrolyte Negative Plate Positive Plate Electrolyte Negative Plate

$PbO_2 + 2H_2SO_4 + Pb \rightarrow PbSO_4 + H_2O + PbSO_4$

During battery charging the direction of chemical reaction is reversed as follows:

Positive Plate Electrolyte Negative Plate Positive Plate Electrolyte Negative Plate

$PbSO_4 + 2H_2O + PbSO_4 \rightarrow PbO_2 + 2H_2SO_4 + Pb$

As the battery is discharged the active materials PbO_2 and Pb in the positive and negative plates respectively, combine with the sulfuric acid solution to form $PbSO_4$ and water. The dilution of the electrolyte has important consequences in terms of specific gravity and freezing point of the electrolyte.

- *Formation*
  Formation is the initial process of battery charging during manufacture, when lead oxide (PbO) on the positive plate grids are changed to lead dioxide (PbO_2) and lead on the negative plates into metallic sponge lead (Pb). The need for additional cycles

in the field to achieve the rated capacity of the battery depends upon the extent to which the battery has been formed during manufacturing

- *Specific Gravity*
  Specific gravity is defined as the ratio of the density of a solution to the density of water. Specific gravity is typically measured by a hydrometer. By definition water has a specific gravity of one. In a fully charged lead-acid battery the electrolyte consists of about 36% sulfuric acid by weight or 25% by volume; and the rest is pure water. Specific gravity of the electrolyte is related to the battery state of charge, which depends upon the design electrolyte concentration and temperature.

According to the manufacturers of "VOLTA" brand deep cycle lead-acid batteries the specific gravity of electrolyte of such batteries should be in the range of 1.240 to 1,250 at 25°C. The state of charge and specific gravity of such batteries are tentatively as follows (Table 6.1.1):

Table 6.1.1 Specific gravity of cell and status of charge for Lead-acid battery

S.No.	Specific Gravity of Cell	Status of Charge
1.	1.250	Fully charged.
2.	1.190	50% Charged
3.	1.100	Fully discharged

Specific gravity very much depends upon the temperature of the electrolyte. For every rise of 10°C above 25°C an amount of 0.007 should be added to the specific gravity reading at 25°C as temperature correction factor. Similarly for every fall of 10°C below 25°C a temperature correction factor of 0.007 should be deducted from the standard specific gravity reading at 25°C. The following table 6.1.2 explains this phenomenon.

Table 6.1.2 Variation of specific gravity with temperature

S.No.	Temperature	Specific Gravity Reading
1	15°C	1.243
2	25°C	1.250
3	35°C	1.257

An electrolyte having a specific gravity reading of 1.250 at 25°C will show a reading of 1.243 at 15°C or will give a reading of 1.257 at 35°C.

While the specific gravity can be used to assess the state of charge of a lead acid battery, low or inconsistent specific gravity readings between series connected cells in a battery may indicate sulfation, stratification or lack of equalization between cells. In some cases a cell with a low specific gravity may indicate a cell failure or internal short-circuit within the battery. Therefore the measurement of specific gravity could be a valuable aid in the routine maintenance and diagnosis of battery problems in solar PV systems.

- *Sulfation*
  Sulfation is a normal process that occurs in lead acid batteries resulting from prolonged operations at partial state of battery charge. During sulfation lead sulfate crystals grow up on the positive plates, and reduce the chemically active area and thus capacity of the cell. During normal battery discharge the active materials of the plates are converted into lead sulfate. The deeper the discharge is, the greater the amount of active material that is converted into lead sulfate. During recharge the lead sulfate is converted into lead dioxide and sponge lead on the positive and negative plates respectively. If the battery is recharged soon after being discharged, the lead sulfate converts easily back into active material.

  However if a lead-acid battery is left at less than full state of charge for prolonged period (say days or weeks) the lead sulfate crystallizes on the plate and retards the conversion back to active material during recharge. The crystals essentially "lock away" active material and prevent it from reforming into lead and lead dioxide; which consequently reduces the available total capacity of the battery. If the lead sulfate crystal growth is too large, plates could be physically damaged. Sulfation also causes higher internal resistance within the battery making it more difficult to recharge.

  Sulfation is a common problem experienced with lead-acid batteries in PV systems. To minimize the sulfation of lead-acid batteries the PV array should be designed to recharge the battery bank on the average daily conditions during the worst insolation month of the year

- *Stratification*
  Stratification indicates the condition of a flooded lead-acid battery in which the specific gravity/concentration of the electrolyte increases from the bottom to the top of the cell. Undercharging or not providing enough overcharge to gas and agitate the electrolyte during finishing charges can cause stratification. Prolonged stratification can result into the bottom of the plate being consumed, while the upper portion remaining in relatively good shape. This ultimately leads to the reduction in the capacity and life of the battery. Periodic equalization charges can prevent stratification problem.

Battery Terminology and Performance Characteristics

- *Ampere-Hour (Ah)*
  An ampere-hour is equal to the transfer of 1 amp over a period of 1 hour and is equal to 3,600 coulombs of charge. For example a battery, which delivers 7 Amperes for a period of 10 hours is said to have delivered 70 Ampere-hours.

- *Capacity*
  Capacity refers to the ability of a battery to store or deliver electrical energy. It is commonly expressed in Ampere-hours. Usually the capacity of a battery in Ah is

given for particular discharge rate. Slower the discharge rate, higher will be the capacity of the battery. The capacity of a battery depends upon the following factors:

(a) Design factors such as the quantity of active material; the number/design/physical dimensions of plates; the specific gravity of electrolyte, etc.
(b) Operational Factors such as discharge rate, depth of discharge, cut-off voltage, temperature, age, cycle history of battery, etc.

Lower operational temperature generally reduces the rated capacity of a battery.

The graph in fig. 6.1.2 relates the battery capacity correction factor for different temperatures.

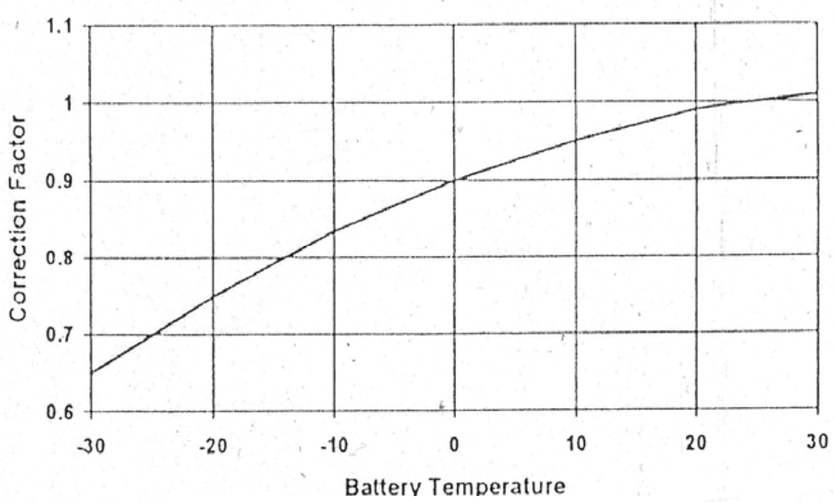


Fig. 6.1.2 Battery capacity correction

- *Open Circuit Voltage*
  Open circuit voltage is the voltage of the battery at rest or in steady state and which is not in the charge or discharge cycle. Depending upon the design, specific gravity and temperature of the battery the open circuit voltage of a fully charged battery is about 2.1 volts per cell.

- *Cut-off Voltage*
  Cut-off voltage is the lowest voltage, which a battery system is allowed by the manufacturer to reach in operation. Manufacturers often rate battery capacity to a specific cut-off or end-point voltage at a defined discharge rate.

- *Terminal Voltage*
  Terminal voltage is the voltage between the positive and negative terminals of a battery either during charge or discharge cycle.

- *Cycle*
  Cycle refers to a discharge to a given depth of discharge followed by a complete recharge. Life of the battery is measured in number of cycles.

- *Rate of Charge/Discharge*
  The rate of charge or discharge of a battery is expressed as a ratio of the nominal battery capacity to the charge/discharge time period in hours. For example, a 5-Ampere discharge for a nominal 100 ampere-hour battery would be considered as a C/20 discharge rate.

- *State of Charge*
  The state of charge (SOC) refers to the amount of energy in a battery expressed as a percentage of the total energy stored in a fully charged battery. A battery that has been discharged 60% is said to be at 40% state of charge.

- *Depth of Discharge*
  The depth of discharge (DOD) is the percentage of capacity that has been withdrawn from a battery compared to its total fully charged capacity. By definition the depth of discharge and the state of charge of a battery total 100 percent.

- *Allowable Depth of Discharge*
  The maximum percentage of full rated capacity that could be withdrawn from a battery is known as its allowable depth of discharge. Allowable DOD depends upon the design cut-off voltage and discharge rate. In stand-alone PV systems the low voltage load disconnect set point of the battery charge controller dictates the allowable DOD limit at a given discharge rate. Depending upon the type of battery used in a PV system the design allowable DOD may be as high as 80% for deep cycle batteries or as low as 15% to 25% for SLI batteries.

  The allowable depth of discharge also depends upon the autonomy of battery bank, i.e. upon the capacity required to operate the system loads for a given number of days without energy input from the PV modules. The higher the discharge rate or current withdrawal the lower is the capacity that can be withdrawn from a battery to a specific allowable DOD or cut-off voltage. Higher discharge rates also result in the terminal voltage to be lower than that with lower discharge rates, sometimes affecting the LVD set point.

  The maximum allowable DOD is also a function of ambient temperature (fig.6.1.3). With decrease in temperature the level of allowable DOD decreases substantially.

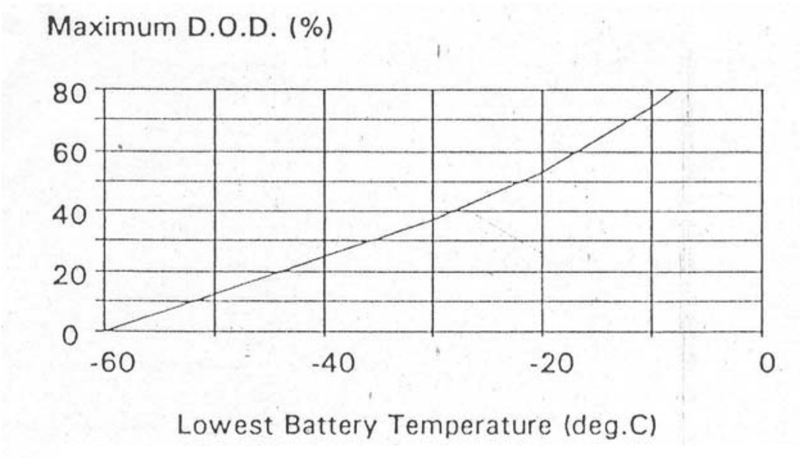


Fig. 6.1.3 Maximum DOD as a function of temperature

- *Autonomy*
  In a stand-alone PV system autonomy refers to the time a fully charged battery can supply required energy to the system loads when there is no energy supplied by the PV modules. For common and less critical PV systems the autonomy period ranges from two to five days.

- *Self-discharge Rate*
  Even in open circuit mode (i.e., without any charge or discharge cycle) a battery undergoes reduction in its state of charge primarily due to the internal mechanisms and losses within the battery itself. Different types of batteries have different self-discharge rates. Higher temperatures generally contribute to higher discharge rates particularly for lead-antimony type of batteries.

- *Temperature Effects*
  Higher operating temperatures accelerate corrosion of the positive plate grids causing greater gassing and electrolyte loss in the battery. Lower operating temperature generally increases the battery life; however the battery capacity is significantly reduced at lower temperatures, particularly for the lead-acid batteries. Whenever severe variations in the operating temperatures exist, batteries should be located in an insulated enclosure to minimize the battery temperature swings.

- *Corrosion*
  Immersion of two dissimilar metals in an electrolyte or in direct contact of the dissimilar metals cause one material to undergo oxidation or lose electrons and at the same time cause the other material to undergo reduction, i.e., gain electrons.

  Corrosion of grids supporting the active material is naturally an on-going process and may finally dictate the useful life of a battery. Battery terminals also undergo corrosion due to the action of electrolyte gassing from inside the battery. Therefore flooded type lead-acid batteries generally require periodic cleaning and tightening of the terminal posts

- *Battery Gassing*
  Gassing takes place during recharging when the battery is nearly fully charged. At this point the cell voltage rises sharply. In flooded type lead-acid batteries the gasses are releases from the cell vents and contribute to water loss. In sealed or valve regulated (i.e. maintenance-free) batteries however an internal recombinant process causes the reformation of water from the hydrogen and oxygen gasses generated under normal charging condition; as such no electrolyte maintenance is required. All gassing reactions consume a portion of the charging current, which cannot be delivered on the subsequent discharge, thereby reducing the efficiency of battery charging. Some degree of gassing is required to agitate and prevent stratification of the electrolyte, particularly in flooded type lead-acid batteries. When a flooded lead-acid is charged heavy particles of sulfuric acid form over the surface of the plates; and afterwards fall to the bottom of the battery. Over time the electrolyte stratifies and develops greater concentration of the acid at the bottom of the battery than at the top. If left unmixed the reaction process could be different from the bottom to the top of the plates. By gently gassing the flooded batteries the electrolyte is thoroughly mixed, thereby preventing the stratification of the electrolyte. However excessive gassing and overcharging could result in the break-up of active material from the grids, consequently reducing the life of the battery. Excessive gassing could also cause higher temperature leading to accelerated corrosion of the grids and thereby shortening the battery life.

  Recommended typical charge regulation voltages (at 25°C) are given below (Table 6.1.3); however specific battery manufacturers should be consulted for their suggested values.

Table 6.1.3 Recommended Charge Regulation Voltages

	Flooded Lead-Antimony Battery	Flooded Lead-Calcium Battery	Sealed Valve Regulated Lead-Acid Battery
Per cell	2.40 – 2.47	2.33 – 2.40	2.33 –2.40
Per nominal 12 Volt battery	14.4 – 14.8	14.0 – 14.4	14.0 – 14.4

The fig. 6.1.4 below illustrates the cell voltage, specific gravity, Ampere-hours delivered to load and drawn from the battery during the charging and discharging process of a lead-acid battery.

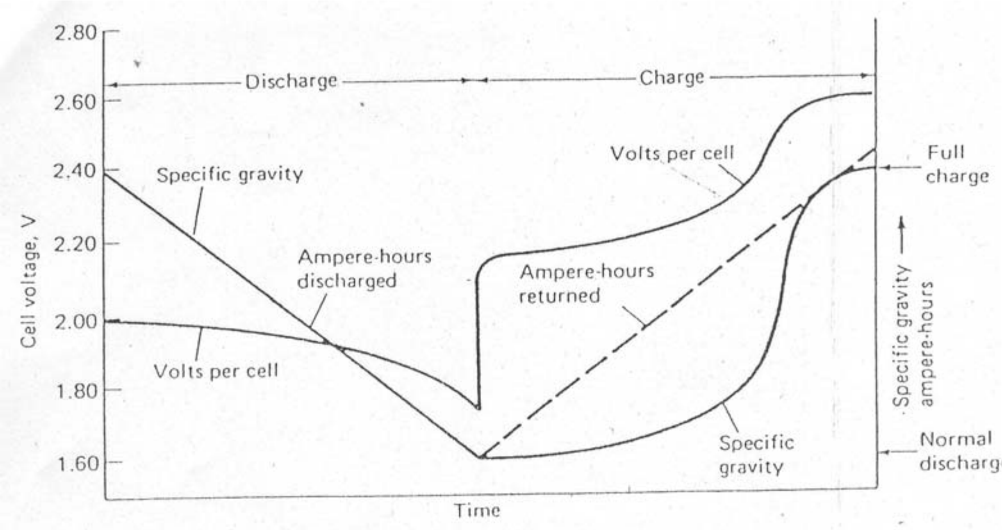


Fig. 6.1.4 Typical voltage and specific gravity characteristics of a lead- acid battery

- **Battery Charging**

  Battery manufacturers often refer to the following the modes of battery charging: -

  Bulk or Nominal Charging

  Bulk or nominal charging is the initial portion of a charging cycle, performed at any charge rate, which does not cause the cell voltage to exceed the gassing voltage. Such charging takes place generally between 80% and 90% of the state of charge.

  Float or Finishing Charging

  Once a battery has been nearly fully charged most of the active material in the battery will be converted into its original form. Then the voltage and/or current regulation are generally required to limit the amount over overcharge supplied to the battery. Finishing charges are generally conducted at low charge rates.

  Equalizing Charge

  Equalizing charges are periodically conducted to maintain consistency among the individual cells of a battery. Such charge generally consists of current-limited charge to higher voltage limits than set for the float charge; and is generally maintained until the cell voltages and specific gravities remain consistent for a few hours. For batteries deeply discharged on a daily basis an equalizing charge is recommended in every 1 or 2 weeks. For other types of battery discharges it could be conducted every one or two months depending upon the nature and depth of the battery discharge.

General Classification of Lead-Acid Battery

Many types of lead-acid batteries are used in PV systems, each having specific design and performance. Generally they are one of the following three categories.

- ***SLI Batteries***
  Starting, lighting and ignition (SLI) batteries are lead-acid batteries primarily designed for shallow cycle services and mostly used to power automotive starters. The large number of plates per cell of such battery enables it to deliver high discharge currents for short periods. However they are not suitable for long life under deep cycle services. In developing countries SLI batteries are sometimes used in PV systems, where only one type of locally manufactured battery is available or when the difference in the up-front cost of the deep cycle battery and SLI battery is very high. Although generally not recommended in most PV applications, SLI batteries may provide 2 or more years of useful services in small stand-alone PV systems, where the average daily depth of discharge (DOD) is limited to 10% to 20% and the maximum allowable DOD is limited to 40% to 50%.

- ***Motive Power or Traction Batteries***
  These batteries are designed for deep discharge cycle services as generally required in electric vehicles or forklifts, etc. Such batteries have a fewer number of plates per cell than SLI batteries, however the plates are made much thicker and constructed more durably. These types of battery are also very popular in PV systems due to their deep cycle capabilities and longer life cycles

- ***Stationary Battery***
  Stationary batteries are used commonly in un-interruptible power supplies (UPS) to provide back-up power to computers, telecommunication equipment, etc. These batteries are designed for deep discharge and limited cycle service; and they are commonly float charged continuously.

Captive Electrolyte Type of Special Lead-Acid Battery

- ***Valve Regulated Lead-Acid Battery***
  Valve regulated lead-acid (VLRA) batteries are captive electrolyte type of lead-acid batteries where the electrolyte is immobilized by means of specially designed pressure regulating mechanism on the cell vents; and the battery is sealed under normal operating conditions. Electrolyte cannot be generally replenished on these types of battery; therefore, they should not be subjected to excessive overcharge

- ***Gelled Battery***
  In gelled lead acid batteries the electrolyte is specially ”gelled” by adding silicon dioxide in the electrolyte. Cracks and voids develop within the gelled electrolyte during the first few cycles, which provide path for gas movement between the positive and negative plates, facilitating the recombinant process.

- ***Absorbed Glass Mat Batteries***
  In absorbed glass mat (AGM) type lead-acid batteries the electrolyte is absorbed in glass mats, which are sandwiched in layers between the plates. Under condition of controlled charging the pressure relief vents in AGM batteries are designed to remain closed, preventing the release of any gasses and water loss.

The above mentioned batteries are costlier than the flooded lead-acid batteries; and are used in special applications only, for example as a battery bank in low temperatures to avoid freezing of the electrolyte as found in flooded type lead-acid batteries.

Modern Rechargeable Batteries

- ***Nickel-Cadmium Rechargeable Battery***
  In nickel cadmium rechargeable batteries nickel oxyhydroxide (NiOOH) is generally the active material in the charged positive plate and cadmium metal is the active material in the charged negative plate of the battery. The primary cell voltage is commonly 1.2volts. These batteries have found diverse applications in consumer and electronics market. For the same capacity range they are quite costlier than the similar lead-acid batteries; although they have a longer life cycle and higher allowable DOD. The main disadvantages of nickel cadmium batteries are the following aspects:
  (a) It has got memory effect.
  (b) It is environmentally hazardous as it contains toxic material viz. cadmium.

- ***Nickel Metal Hydride Rechargeable Battery***
  The basis of this latest metal hydride technology is the ability of certain metallic alloys to absorb the smaller hydrogen atoms in the interstices between the larger metal atoms. As in nickel cadmium battery generally nickel hydroxide is used as positive electrode and aqueous potassium hydroxide is used as electrolyte. But in place of cadmium metal hydride alloys as used as active material for the negative electrode of the cell. The primary cell voltage is 1.2 Volt. As compared to Ni-Cd batteries NiMH batteries are initially costlier; but their energy density is about 20% to 30% higher than similar NiCD batteries; and they have longer life cycles. These batteries do not have memory effect and are considered as environmentally friendly. They do not pose any serious disposal problem. If fact these batteries are now rapidly replacing the market of Ni-Cd batteries.

- ***Lithium Ion Battery***
  Lithium ion batteries use lithium compounds and are rechargeable. They have a higher energy density than even NiMH batteries; and posses a primary cell voltage of about 3.7 Volts. They have a lower self-discharge rate and are quite environmentally friendly. But as compared to any other type of rechargeable batteries they are still costlier.

The table 6.1.5 below provides quick reference to the merits and demerits of different types of batteries used in solar PV system.

Table 6.1.5 Comparison of different types of batteries

Type of battery	Merits	Demerits
Flooded Lead-Acid battery (LSI type)	• Widely available • Low cost • Good for automotive use	• Shallow cycle • Heavy weight • Very poor cycle life • Contains toxic element
Flooded Lead-Acid battery (Modified LSI type)	• Deep cycle • Good for use in solar PV system and electric traction vehicles	• Heavy weight • Poor cycle life • Costlier • Contains toxic element
Flooded Lead-Acid battery (Tubular plate type)	• Improve deep cycle • Better for use in solar PV system and electric traction vehicles	• Heavy weight • More costlier • Contains toxic element
Nickel Cadmium battery	• Long cycle life • Deep cycles • Withstand harsh environment	• Expensive • Memory effect • Contains toxic element
Nickle Metal Hydride battery	• Prolonged cycle life • Deep cycles • Better performance in cold climate • Light weight • Lower operating cost • Non-toxic • No memory effect	• Up-front cost very high

- **Methods of Battery Charging**
  Charging lead-acid or any other types of secondary batteries is a matter of replacing the energy depleted during the discharge cycle. Charging may be accomplished by various methods; but the objective of driving current through the battery in the direction opposite to that of the discharge remains the same.

- ***Constant –Current Charging***
  In constant current charging the charger provides a relatively uniform current regardless of the state of charge or temperature of the battery. Constant current charging assists to eliminate any charge imbalance in the battery, especially when several cells/batteries are charged in series.

- ***Constant-Voltage Charging***
  Constant voltage/potential charging is the most common method of charging secondary batteries. In this mode of battery charging the charger voltage is held uniform regardless of the battery state of charge. The charge current is initially greater; but as battery gets recharged the charge current declines or tapers down. PV modules basically act as constant- voltage chargers.

- ***Charge Acceptance***
  Charge acceptance (i.e., efficiency) is the term used to describe the efficiency of the battery. No battery is 100% efficient. A 90% charge acceptance means that for every one ampere-hour of charge introduced into the battery or cell, the battery or cell will be able to deliver 0.9 ampere-hour of current to the load during discharge cycle. The charge acceptance of lead-acid batteries may be higher than 85%. Charge acceptance is affected by a number of factors including cell temperature, state of charge, age of cell, charge current, method of charging, etc.

Battery Auxiliary Equipment

- ***Enclosures***
  Batteries should be preferably installed in suitable enclosures that are insulated or could have passive heating/cooling devices to protect the batteries from excessive temperatures. If the enclosure is located above ground some type of shading should be provided.

- ***Ventilation***
  Batteries often produce gases namely hydrogen. Passive ventilation techniques such as vents or ducts should be provided.

- ***Catalytic Recombination Caps***
  A substitute for standard vent caps on lead acid battery is the catalytic recombination caps (CRC) whose main function is to reduce electrolytic loss from the battery. CRC contains particles of platinum or palladium, which absorbs hydrogen generated from the battery during finishing or overcharge cycles. The hydrogen is again combined with oxygen in the CRC to form water, which drains back into the battery.

Battery Test Equipment

- ***Hydrometer***
  Hydrometer is used to measure the specific gravity of electrolyte of lead-acid batteries. As mentioned earlier the specific gravity of electrolyte is closely related to the state of charge of the battery. Hydrometer should be calibrated preferably at 25°C. If possible properly calibrated and tested battery hydrometers only should be used in PV systems. When measurements are taken from the electrolyte at other temperatures a correction factor as described above must be applied.

- ***Voltmeter***
  Analog or digital type voltmeter (or multimeter) is generally used to measure the terminal voltages of batteries.

- ***Load Tester***
  A battery load tester is an instrument, which draws current from a battery with an electric load, while recording the voltage. Although not designed for measuring capacity it may be used to determine the general health or consistency among the

batteries in a system. Load test data generally express a discharge current over a specific time period.

Battery Maintenance

The maintenance requirement for lead-acid batteries varies significantly depending upon the type, design and application of the battery. Maintenance recommendations provided by the specific battery manufacturer should be properly studied and followed. Maintenance considerations should include cleaning of cases, terminals and cables, tightening terminals, coating of terminals by petroleum jelly, water addition and performance checks. Water should be distilled or de-mineralized or de-ionized, having a pH value of 6.5 to 7 and a conductivity of 2 to 6 micro-siemens (μs). Performance checks may include recordings of specific gravity, temperature measurements, cell voltage readings or even a capacity test.

Battery Safety Considerations

- ***Handling Electrolyte***
  Sulfuric acid of the electrolyte can destroy clothing and burn the skin. For these reasons protective clothing such as acid-proof apron, and face shields should be worn by personnel working with the battery, If required acid should be poured slowly into the water while mixing. The water should never be poured into the acid. Appropriate non-metallic funnels and containers should be used when mixing electrolyte solution.

  To neutralize sulfuric acid spills or splashes on clothing, the spill should be rinsed immediately with a solution of baking soda and water. If electrolyte is accidentally splashed in the eyes, the eyes should be forced open and flood with clean water for at least 15 minutes. If necessary a doctor should be consulted.

- ***Personnel Protection***
  When performing battery maintenance, personnel should wear protective clothing such as aprons, ventilation masks, goggles or face shields and acid-proof gloves to protect from acid spills or fumes. Jewelry on the hands and wrists should be removed and properly insulted tools should be used to protect against inadvertent battery short-circuits.

- ***Dangers of Explosion***
  During operation batteries may produce explosive mixture of hydrogen and oxygen gases. Keep spark, flames, burning cigarettes, kerosene lamps or other ignition sources away from the batteries at all times. While making or breaking connections to a battery from a charging source or electrical load, it should be checked and ensured that the charger or load is switched off so as not to create sparks or arcing during the connection.

Battery Disposal

Batteries are considered as hazardous item as they contain toxic materials such as lead, acids and plastics that can harm human beings and the environment. If recycling facilities exist, deliver the complete battery with electrolyte to the recycling organization or to their scrap dealers. Under no circumstances should the batteries be disposed off in the landfills or near the water springs and resources. The electrolyte should not be allowed to seep into the ground and the battery should not be burned.

6.2 Charge Controllers/Regulators

Charge regulators (also called charge controllers) are the electronic gadgets used to protect the storage batteries from being over charged or over discharged. The basic function of the charge regulator (CR) is to disconnect the module or array from the battery when the battery is charged to a preset level and disconnect the load (which is connected to the battery) when the battery is discharged to the preset level. Advanced CR also senses the battery temperature and adjusts the charging current accordingly. Another, but less important, use of the CR is as a meeting point of all the cables coming from module to battery and battery to load. In other words the CR also serves the purpose of junction box. As the PV cell costs continue to fall, the battery in a stand-alone PV system becomes an increasingly large part of the system cost. The life of the battery now has the greatest impact on the economic viability of a small PV system. The CR in small PV system is the primary driver of system reliability and battery life. A good regulator will affect the system performance more than any other component, and an improved regulator can potentially reduce 20-year system costs by 20 to 40 percent because the battery needs to be replaced less often.

CR may not be the part of the solar PV system where the module or array output is directly connected to the load other than the battery.

Basic Principle of Operation

The state of the charge of a battery is proportional to its open circuit terminal voltage. Therefore the terminal voltage of the battery can be taken as the reference to assess its state of the charge. The electronic circuitry of CC continuously monitors the battery voltage and depending upon the preset voltage levels, disconnects the array from the battery or battery from the load. The CR is broadly subdivided into two categories: the shunt regulator (SHR) or the series regulator (SR).

- **The Shunt Regulator**

The SHR bypasses the module or array current through an active load (other than the actual load). In this case the bypass load is connected parallel to the module (fig. 6.2.1).

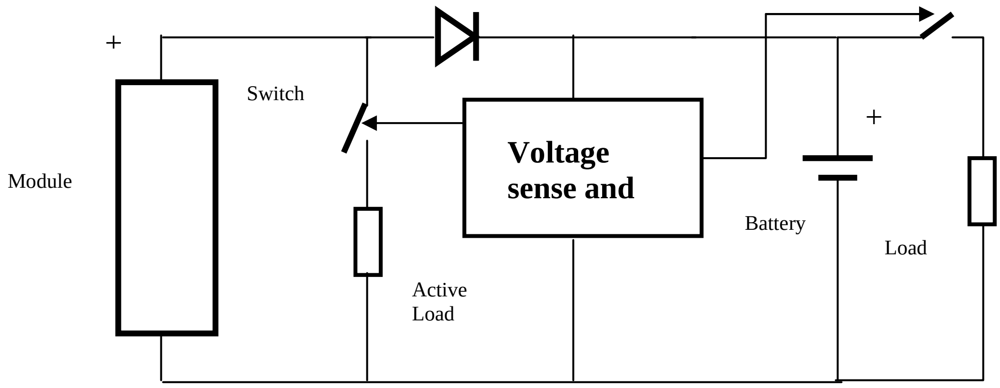


Fig. 6.2.1 Operation of a Shunt Regulator

In normal charging mode, i.e. when the battery is not fully charged, the switch is in OFF position and the entire module current is passed to the battery via blocking diode. When the state of the charge of the battery reaches pre-determined level, as indicated by the voltage level of the battery, the control circuit turns ON the switch. In this case the entire module current is passed to a very low resistance active load, which dissipates all the module power. In fact the active load could be any other usable device or the second set of battery that needs charging. When the battery charge level drops below module reconnect level, the control circuit turns the switch OFF and the module current is again passed to the battery. Note that when the switch is in ON position, the current from the battery does not flow to the active load because of the blocking diode. Hence the blocking diode has two-fold application in case of use of shunt regulators.

The SHR are simple in design, cost effective but are not suitable for large power applications. In large power application, the active load has to dissipate large power as heat. Therefore for small PV applications, like solar home systems, shunt regulators are preferred over series regulators.

- **Series Regulators**

Series regulators (SR) operate in entirely different principle that the shunt regulator. In SR the path between the module and the battery is simply disconnected by a switch when the charge level of the battery is over the preset level (fig. 6.2.2).

In normal charging condition the switch is in ON position and the current from the modules is passed to the battery through the blocking diode. When the state of charge of the battery reaches the pre-set level, the control circuit turns the switch OFF blocking passage of current to the battery. SR is more suitable for large power PV application as there is no need to dissipate the module power in the form of heat. The module is simply disconnected and remains idle. The circuitry of the SR is more complex that that of SHR. The only remarkable drawback of SR is the loss of energy in switching element. This loss depends upon the internal resistance of the switching element.

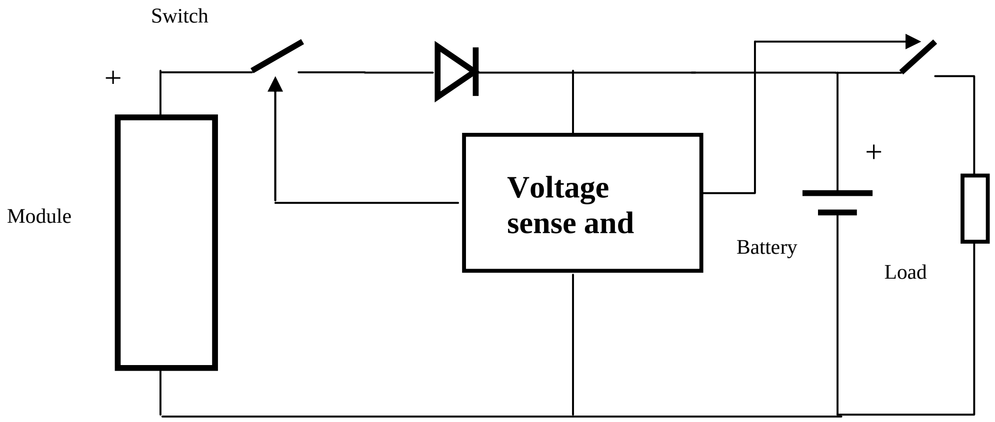


Fig. 6.2.2 Operation of a Series Regulator

The CR also disconnects the load from the battery when the discharge level is below the set point. The control circuit senses the battery voltage level and when it falls below certain set point, the circuit turns OFF the switch (load switch) inserted in series between the battery and the load. When the battery state of charge is increased by charging, the load switch is turned ON by the circuit and power is available for use by load.

In earlier designs, the switches used in both of the versions were mechanical switches (relays) controlled by control signal. These mechanical switches have limited life span and are prone to mechanical as well as electrical failure. In more recent design the mechanical switches are replaced by electronic (semiconductor) switches. These electronic switches (Bipolar transistors, MOSFETs, SCRs) can handle large current and operate reliably.

Parameters of CR

The basic parameters of a CR are:

- *Low Voltage Disconnect* (LVD) – This is the voltage level of battery at which the load is disconnected from the battery to protect it from over discharge. The LVD level depends upon the type of battery used and the type of load. If the load is critical (e.g. vaccine refrigerator) then LVD is set to very low. For non-critical loads like laps or TV the LVD level can be set at relatively higher side to ensure higher life cycle of the battery.
- *Low Voltage Reconnect* (LVR) – This is the voltage level of the battery at which the load is reconnected after being disconnected due to LVD. LVR value is higher than the LVD value. For example for a 12 V lead acid battery the LVD level could be 11.8 V (corresponding to 50% discharge level). The LVR in this case may be 12 V or greater. The difference between LVR and LVD is called hysteresis. Provision of LVR is required to avoid toggling of the load between on and off.

- *High Voltage Disconnect* (HVD) – This is the voltage level of the battery at which the module is disconnected from the battery to protect it from over charging. The HVD level again depends upon the type of battery used, the battery temperature and the ambient temperature. The HVD set pint for lead acid battery is around 14.2 – 14.8 V. In general HVD set point corresponds to 100% state of charge (SOC) of the battery type used.
- *High Voltage Reconnect* (HVR) – This is the voltage level of the battery at which the module is reconnected to the battery after being disconnected at HVD. The HVR is applicable to the CR based on simple ON-OFF design. For PWM based CR, the HVR has no significance.
- *Voltage drop across CR while charging* – It is the permissible voltage drop in CR while charging the battery. For shunt type CR, it is the drop in blocking diode only. In case of series CR, it is the total drop in blocking diode and the switch element.
- *Voltage drop across CR while discharging* – It is permissible voltage drop in CR while discharging the battery through the load. It is basically the voltage drop in series load switch for both types of regulators. Normally the permissible total drop (charging and discharging) is less than 5% of the system voltage.
- *Maximum charge current capacity* (I_{cmax}) - It the maximum charging current in Amperes that CR can handle safely. Note that it is not the peak charging current which can occur due to surge or other interference.
- *Maximum load current capacity* (I_{lmax}) - It is the maximum current in Amperes that CR can deliver to the load safely.
- *System Voltage*- It is the voltage for which the CR is designed.
- *Self consumption (or quiescent) current* - It is the current in mA that the CR draws from the battery for its operation.
- *Level of Radio Frequency Interference (RFI)* – It as indication of the level of interference caused by the CR to other electronic devices (e.g. radio, TV).
- *Reverse Leakage Current* - It is the current that is passed from the battery to the dark module through the CR. Usually the blocking diode is used to limit this current in shunt regulators. In series regulators this value depends upon the type of switch used, provided no blocking diodes are used.
- *Reverse Polarity Protection Level* - It is the type of protection incorporated in the CR design to avoid the damage to the CR, module or battery from the wrong sequence of polarity of module and battery connected to the CR. Generally the protection level shall be such that nothing is damaged by connecting the module and/or the battery in wrong polarity sequence.

Other parameters may include permissible environmental conditions for safe operation of CR, enclosure characteristics, labeling etc.

Methods of Charging the Battery by CR

Independent of the basic type of CR (shunt or series) the technique used to charge the battery may vary from CR to CR. In this sub-section brief overview of various techniques will be discussed.

- ***Simple ON-OFF Method***

The early design of CR used simple ON-OFF regulation mechanism. The regulator interrupts charging early in the cycle when the HVD set point is reached. To prevent instability, a hysteresis of 1 V (i.e. HVR is less than HVD by 1 V)is generally used to reconnect the module or array, and this causes the battery voltage to drift down for a period of time before charging can start again (fig 6.2.3).

Research has shown that the batteries charged with standard set points will typically average between 55% and 60% SOC for a period of years. This causes stratification of the electrolyte and sulfation of battery plates, thus increasing internal resistance, which further reduces charge efficiency. Because of these problems ON-OFF charge regulators are replaced by more advanced Pulse Width Modulation (PWM) regulators.

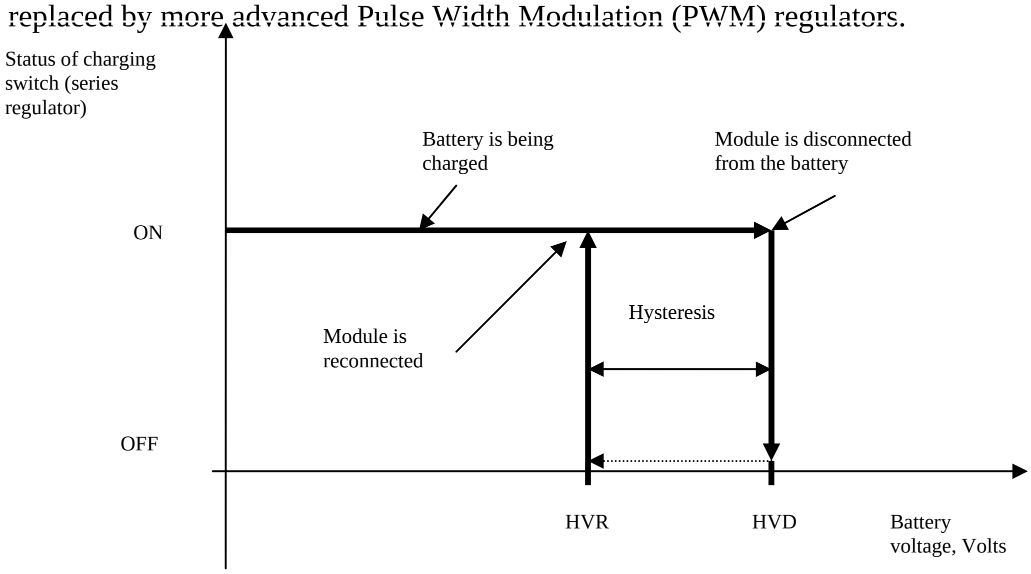


Fig. 6.2.3 ON-OFF charging algorithm

- ***PWM Method***

The better algorithm to charge the battery is Pulse Width Modulation (PWM). While in ON-OFF method the module was disconnected from the battery during the last part of charging cycle, in PWM the module is switched on and off with the certain frequency. Normally the voltage level of the most of the batteries goes down when the charging device is removed. By connecting and disconnecting the charging device with a duty cycle, charging can go on much longer and the battery will reach a much higher state of charge. The duty cycle is defined as the ratio between ON time and OFF time of the charging current. In PWM method the ON time of charge current (or the ON time of the series switch) is gradually decreased (the OFF time gradually increased) as the battery SOC increases. When the battery reaches its 100% SOC, the series switch is completely turned OFF. The figure 6.2.4 below illustrates the charging algorithm with PWM method.

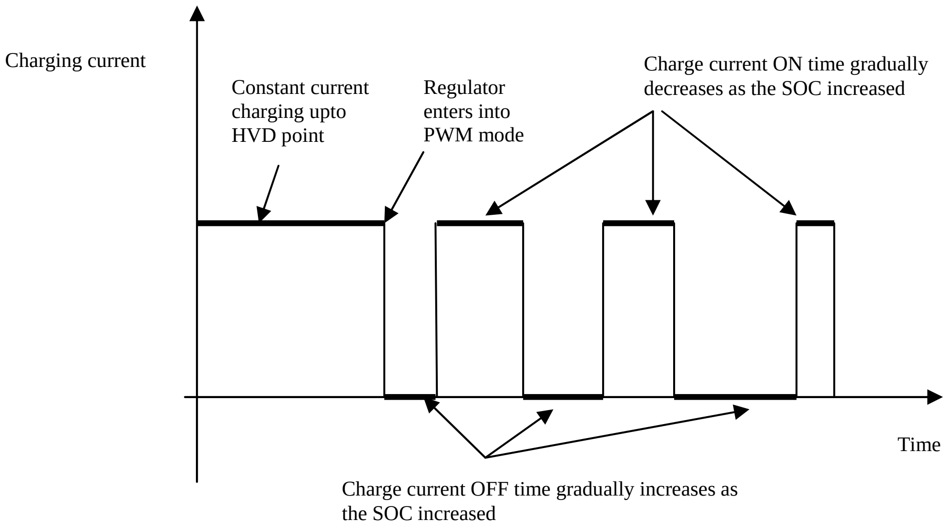


Fig. 6.2.4 PWM charging algorithm

- ***Three Stage (or Trickle charge) Method***

In this method the battery is charged with maximum constant current (Imax) till the battery voltage reaches some preset value (normally 2.3 Volt per 2 V cell). After this point, the battery is charged with a constant voltage (from this point the current drawn by the battery starts decreasing). When the battery reaches its (almost) full state of charge, i.e. when the charge current accepted by the battery is around 20% of Imax, maintenance charging is applied by limiting the magnitude of charging current to very low level. The figure 6.2.5 illustrates the charging algorithm of three stage method.

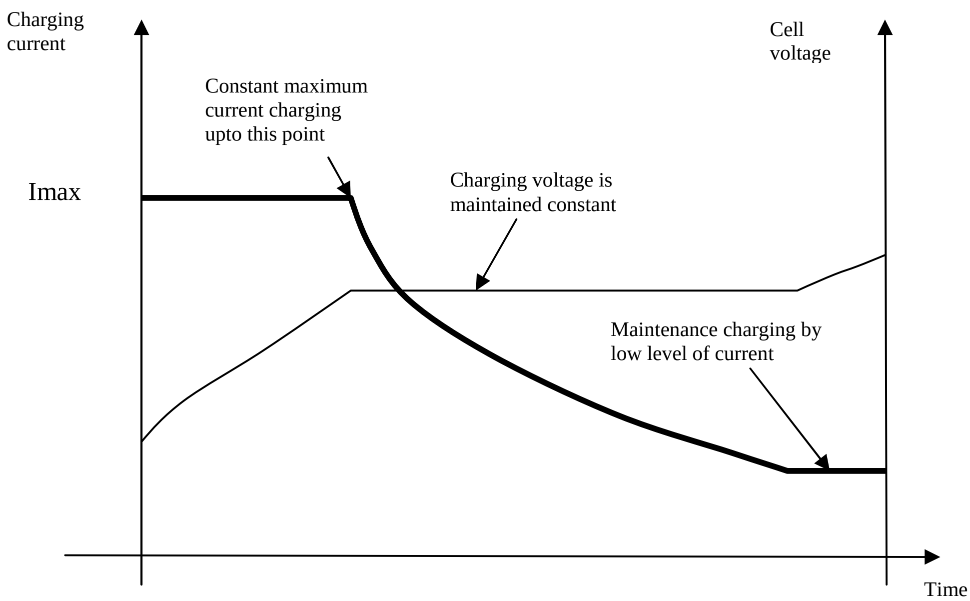


Fig. 6.2.5 Three stage charging algorithm

While ON-OFF regulators stop the whole charging process when the cell voltage is at its maximum (HVD set point), trickle charging continues maintenance charging until the battery reaches its full state of charge. When the cell voltage just reaches its maximum value, the actual state of charge is only 60%. With maintenance charging the SOC could be increased to 100%. In PWM regulators there is no such term as maintenance charging. The regulator continues charging the battery until the duty cycle is zero. If there is self discharge of the battery, a low duty cycle charging will again be initiated. This process can be considered as maintenance charging.

The advantage of PWM regulators with controlled pulses compared to other methods are:

- Compact lead sulfate can be broken up to improve battery capacity and charge acceptance.
- Charge efficiency can be improved and effects of aging can be reduced.
- Operating life of the battery can be increased.
- Higher voltage pulses can punch through resistive coating between the grid and active materials on the plates.
- The opportunity for a gas bubbles to form can be reduced, and
- Down pulses further improve charge efficiency and reduce gassing.

The recent advancement in CR design has helped to produce intelligent regulators which senses the battery temperature and adjust the maintenance charging current to suite the given temperature, adjusts the HVD, HVR set points depending upon the life of the battery and the battery temperature, displays the SOC of the battery and total Ah drawn from the battery etc. These intelligent CR are microprocessor based and relatively costlier than conventional simple design regulators.

- **Battery temperature consideration in CR**

The end of charge voltage (or the HVD level) used by the CR to switch off module/array current or to switch into a trickle charge mode should be allowed to vary according to the battery temperature. As the battery internal temperature decreases, the chemical reactions all proceed slower. In order to fully charge the battery, the voltage must be allowed to rise more for a colder battery, so that the chemical reaction can proceed to completion. The nominal final charge voltage at 25^0 C is about 14.5 V for a 12 V lead –acid battery. As the battery temperature drops, the voltage for final charge must increase, and conversely as the battery heats up, the final charge voltage must be reduced. This phenomenon is handled by an option in many CR designs and called "temperature compensation" or TC. The temperature compensation coefficient for a 12 V lead –acid battery can be taken as 30 mV/^{0}C (this value is often given in battery specification sheet).

For example, if a 12 V battery were at 15^0C, the final charge voltage should not be 14.5 V (set for 25^0C) but should be almost 14.8 V. conversely, if the battery is in hot climate, and the battery temperature is 30^0C, the final charge voltage should be reduced to about 14.35 V.

With temperature compensation, or TC, built into the CR, batteries in cold climates will receive the full charging they require, and batteries in hot climates will not be overcharged and experience excessive gassing.

- **Boost charging option**

All batteries require some overcharging now and then to reverse sulfation and reach full charge. Gassing in the battery, which is initiated by some small overcharge, cleans the internal plates. If this is done once every three weeks, it will reduce battery deterioration and increase deep recharge capacity. The process of overcharging the batteries beyond their final end of charge voltage is called boost charging. While boost charging the HVD set points are temporarily increased to higher value. Some CR incorporate the function of this "boost charging". The biggest difference between the various types of CR is the timing when the boost charging takes place. Some CR only boost charge the battery when it is connected for the first time, just after installation. This cost more in electronic circuits, while the boost function is not very effective. Others apply the boost charge function every time the LVD set point is reached. In this way, the extra sulfation is removed shortly after it is formed on the plates. However, overcharging too frequently also is not recommended, because this will shorten the battery life. The optimum situation seems to be to make boost charge possible about once every three weeks.

6.3 Lamps and Other Loads

All loads possible to be connected to the grid electricity supply system are applicable to the PV system as well. The only limiting factor is the available power to drive the load. As the PV electricity is considered to be precious, specially designed low power consuming loads are considered for PV applications. Vast majority of the load type used in PV system are lights, radio/cassette, television, computers and water pumps. In this chapter overview of some of the common types of loads is provided.

Lights

Lighting is a basic necessity with a very high priority in households all over the world. When electricity first arrives in a village, lighting is by far the most common application. In conventional rural electrification with grid extension, there are few incentives to apply energy-efficient lighting. Consumers lack the knowledge of alternatives and the usually low electricity tariff does not provided strong incentive to consider an optimum choice of lighting source. However, when solar PV provides the electricity for rural lighting, the situation is completely different. The high electricity cost per unit stimulates careful selection of the right type of lamp.

Lights can be categorized into four groups with regards to their use in household application:

- general lighting – illuminates the whole room or large area
- localized lighting – illuminates part or localized area of the room only

- task lighting- used to illuminate a table or working area
- orientation lighting – illumination level sufficient only to recognize shapes

The duty of Solar PV designer is to select appropriate light type as per deemed application.

Basic technical parameters of lights are:

- *Luminous Flux*

Luminous flux is the term used to measure the light output of a lamp in all directions as perceived by the human eye. Its measurement unit is Lumen (lm), which takes into account that the eye is more sensitive to some colors than others. Lights with a lumen output less than about 20 lm are not meant for general lighting, but usually function as orientation lights only.

- *Illuminance*

Illuminance is the measure of the amount of light that falls on the given surface. The unit of measurement of illuminance is Lux. For reading, a minimum illuminance of about 50 Lux is required. For general lighting 20 to 25 Lux is sufficient, and for orientation lighting 10 Lux or even lower can be sufficient.

- *Luminous Efficacy*

Luminous efficacy is a term used to measure the efficiency of lights to convert electrical energy in to light. It is measured in lumens per watt. Higher the efficacy, more light is produced for given input electrical power. Luminous efficacy is also measured in lumen per watt. But since measurement of lumen requires expensive set-up, more preferable measurement term is Lux per watt. A Lux meter is readily available in the market at reasonable price. The standard practice is to measure Lux output of a lamp at a distance of one meter from the light source. While selecting the light for solar PV application, efficacy of the lamp has to be considered as a major factor.

The fluorescent tubes (FT) or also called tube lights (TL) with a reflector appear to be especially optimal in combining a high level of illuminance with a high luminous efficacy. The efficacy of FT without reflector is in the range of 2-5 Lux/W, while that of incandescent lamps is generally below 1 Lux/W. Adding a reflector in TL produces an approximate three fold increase in efficiency: up to 12 Lux/W. The highest efficacy is of white light emitting diode (WLED) clusters, around 14 Lux/W, but their illuminance is very low. Compact fluorescent lamps (CFL) have the efficacy level almost at par with FT or sometimes slightly higher.

Basic Lamp types used in PV applications

- Fluorescent Lamps

Till to day, the fluorescent tubes (FT) and Compact fluorescent lamps (CFL) remains dominating type of lamps in the solar PV systems. Generally, 6 to 11 Watt lamps are used for home system applications but higher watt lamps (40 W and over) are also in use for other lighting applications. The FT or CFL is a high efficiency light source in which electrical energy is converted into light without great loss of energy as heat as it happens in incandescent lamps. In incandescent lamps, the tungsten filament is first heated to very high temperature by the electrical supply. The glow from the heated filament is the actual light output produced. In this way great deal of electrical energy is converted into heat energy in incandescent lamps.

A schematic diagram of a FT construction is shown in figure 6.3.1.

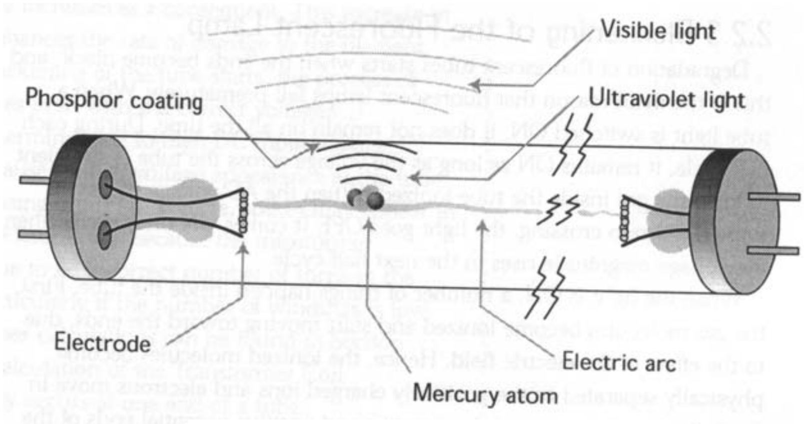


Fig. 6.3.1 Construction of FT

The glass tube is coated with fluorescent (Phosphor) paint and filled with mercury vapor. When an electric current passes through the mercury vapor, the molecules absorb kinetic energy and are ionized. When an ionized atom recombines with an electron, and the electron drops back to its original energy level, the mercury atom radiates ultraviolet (UV) light. Ultraviolet light is not visible to the human eye. So a fluorescent material is painted on the inner surface of the tube that converts the ultraviolet radiation into visible light. AC voltage of sufficient magnitude is required to initiate ionization of mercury vapor. Therefore all the FT or CFL operate only with AC source. However, in solar PV systems, DC supply is pre-dominant and therefore fluorescent lamps require well-designed ballasts (an electronics gadget that convert 12 V DC from the battery into high frequency AC voltage suitable to turn the fluorescent lights on) to ensure that the tubes will operate for more than 5,000 hours and will not interfere with radio or television reception. The ballasts, in most of the case of solar PV applications, have been the most problematic component of the system.

- Incandescent (Filament) Lamp

These are the least efficient lamps for solar PV applications. However, considering their low cost, low watt 12 V DC incandescent bulbs can substitute lights to be used for orientation purpose. Although not efficient, halogen lamps can be used in the places where localized high illumination level is required (e.g. operation theaters, health posts, projectors etc.).

- White Light Emitting Diode (WLED) Cluster Lamp

WLEDs are semiconductor devices like the PV cell itself. In ordinary PN junction, when a free electron falls into hole they release additional energy in the form of heat. It is well known fact that heat is also a form of electromagnetic radiation like the light. Now if the impurities (dopants) are properly chosen, the released energy during recombination can be obtained in the form of visible lights. The light emitting diode (LED) operates in the above principle. Depending upon the type of material used different light colors (red, green, yellow etc.) can be emitted. But these coloured LEDs have no significant application in lighting, where white light color is preferred. Adding appropriate impurities, the PN junction can be constructed to emit nearly white light. Those LEDs emitting white lights are called white LEDs (WLED). Recent development in the WLED technology has produced high intensity (upto 8-10 Candela, Candela is also a unit of luminous intensity).

The very promising aspect of WLED is that they are compact, have high luminous efficiency and extremely durable. The power consumed by a single WLED is about 100 mW. The mean time between failures of WLED is 100,000 burning hours. In other words a WLED can operate safely for over 40 years if operated 6 hours daily. WLEDs operate directly from DC supply and therefore complicated electronics (like ballast for FTs) is omitted, thus increasing system reliability.

The illumination level produced by a single WLED may not be sufficient for general lighting, though a torchlight made up of a single WLED is more than illuminating than kerosene wicked lamp. Therefore numbers of WLEDs are clustered in a enclosure for high illumination level. The number of WLEDs to be clustered will depend upon required illumination level. One example of clustered WLED lamp designed by Nepalese designers is a lamp named "Tukimara". This lamp consists of cluster of three WLEDs and is powered by three dry cells of 1.5 V each (Fig. 6.3.2).

Fig. 6.3.2 Tukimara Lamp

Other Loads

Knowledge of the parameters of the load to be used with the solar PV systems is very critical for designing the PV system. The parameters include power consumed by the load; type and magnitude of supply voltage required and for AC operated loads, the power factor and frequency.

The most common types of loads, apart from the lights, are radio/cassette players, Television sets (Black and white; color), computers (desk-top as well as lap-tops), printers (Laser as well as ink jet), scanners, fax machines, cordless telephones, Satellite receivers, vaccine refrigerators etc. The parameters of these loads are briefly discussed below.

- ***Radio***

Portable radios consume very low power, less than 1 W and are operated from 3-4.5 V DC. If these radios are to be powered from PV system, then a special device called DC-DC converter is required. The converter down converts 12 V DC from the battery to required voltage level.

- ***Cassette Players***

These gadgets come in various power ratings and supply voltage requirement. Most common type players consume 10-50 watts and can be operated from 12 V DC directly. Smaller units operate from 4.5 to 9 V DC and consume upto 5 watts of power. High music power players operate from AC only.

- ***Television***

Power consumed by a TV set depends upon its type (Black and White or Color), the size of the screen and the technology used to manufacture them. Traditional tube based B/W television of the screen size 12-14" consume around 15-20 Watts and can be operated both from AC or 12 V DC.

The tube based color television consumes far more power than their B/W counterpart. The 12-14" color television will consume around 40-60 watts of power. Higher screen size color television consumes proportionally more power. The supply requirement for most of the color televisions is AC. Limited brands of color television with smaller screen size also operate with 12 V DC.

Recent development in Liquid Crystal Display (LCD) technology has made possible manufacturing of color televisions based on this technology. The LCD television sets are flat in design, light weight and consume extremely low power. A 14" LCD color TV will consume less than 15 W of power. Moreover, these LCD TVs operate from 12 V DC supply directly, thus eliminating the need for costly DC-AC inverters.

- ***Computers***

A desktop computer with 14-17" color monitor may consume around 150 W of power and can be operated from AC supply only. The laptop computers come with LCD screen and consume relatively low power – in the range of 20-30 W. The laptop computers also cannot be operated directly from 12 V DC supply. A small capacity inverter may suffice to charge the internal battery of the laptops.

- ***Printers***

There are three basic types of printers available for home/office computer applications: dot matrix, ink-jet and laser. All these commercially available printers operate from AC only. Among these, the Laser printer is most power consuming type of printer. In print mode it consumes around 1000 W of power. The least power-consuming printer is ink-jet printer; it consumes around 30 W in print mode. The dot-matrix printer consumes around 200 W in print mode.

- ***Scanners***

These devices consume less than 10 W and operated by AC through an adapter.

- ***Fax Machines***

Fax machines are generally operated from AC. They consume about 500 W of power in transmit/receive mode. The stand-by power consumption is low (around 10 W).

For power and supply voltage requirements of other appliances, the designer is advised to refer the technical brochure of the device.

6.4 Inverters

Inverter is an electronic device that converts DC voltage into AC voltage of required magnitude and frequency. In solar PV applications inverters are used to power the equipment/devices that operate from AC source. The DC to AC conversion is required as the solar PV system generates and stores energy in the form of DC voltage and current only. The inverters are some time called DC-AC converters.

Basic Principle of operation of inverters

The basic idea behind DC-AC conversion is to turn ON and OFF the DC supply voltage (e.g. 12 V) at a regular interval (as governed by the frequency of the required AC signal; e.g. 50 Hz) and boost the magnitude of switched voltage to required level (e.g. 220V). The graphical representations shown in figure 6.4.1 below illustrate the basic principle of the conversion.

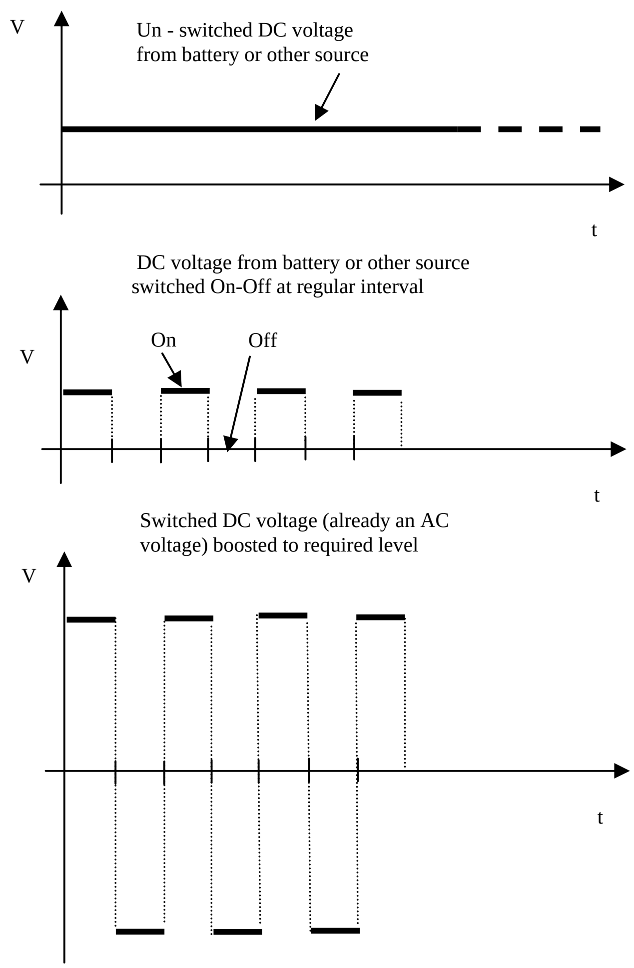


Fig. 6.4.1 Basic Principle of DC-AC conversion

Functionally, the block diagram of the simplest inverter would be as shown in fig. 6.4.2.

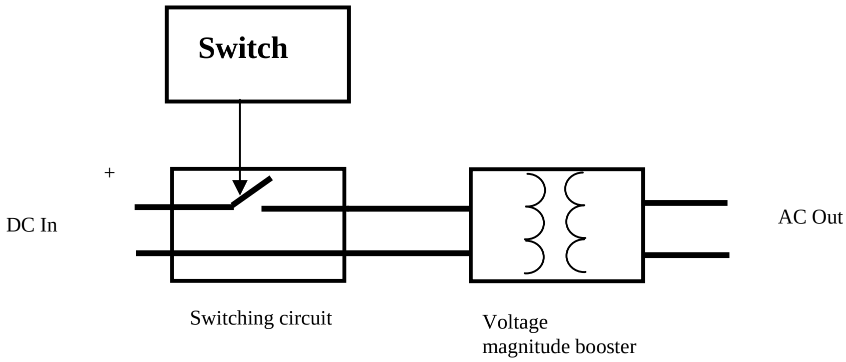


Fig. 6.4.2 Functional diagram of DC-AC conversion

The DC input supply, say 12 V, is fed to a switching circuit, which makes and breaks the current path on a fixed regular interval. The switch On-Off time is controlled by the switch control circuit. The output of the switching circuit now is rather quasi AC than DC. By the term quasi, it is to be understood that the AC is not the type of AC in which the flow of current reverses periodically. In the present case, the current either flow in one direction or do not flow at all. In technical terms, this AC is shifted in voltage axis by a level equal to its negative swing. Now if this quasi AC voltage is passed through an electronic component (capacitor) that blocks the DC voltage level, AC voltage in true sense is obtained. Thus obtained AC voltage magnitude does not exceed the input DC level. Voltage boosting circuit (transformer) is further used to increase the magnitude of the AC voltage to required level.

Parameters of an Inverter

The basic parameters of an inverter are as follows:

- ***Rated Output Power***

This parameter indicates the continuous power that an inverter can deliver in normal operating condition. The unit of rated output power is VA. The power is expressed in VA, because the inverter can also be used to power loads with reactance like motor.

- ***Nominal output voltage***

It is the magnitude of output voltage (RMS value) that the inverter produces steadily. This voltage is specified with fixed level of deviation like 200V +/- 10% for given range of fluctuation of input DC voltage.

- ***Nominal Frequency***

It indicates the frequency of the output voltage or current waveform and expressed in Hz. As with the voltage, the value of frequency is also specified with tolerance level, generally about 2% from the nominal value of 50 Hz.

- ***Efficiency***

Efficiency of an inverter is an indication of the losses of energy occurred during the conversion from DC to AC. Efficiency is the ratio of output power delivered to the nominal load (i.e. the maximum load for which the inverter is designed) and the total input power drawn from the DC source. The efficiency is expressed in percent and is specified for the upper limit of load. Typical efficiency of good inverter exceeds 80% range.

- ***Maximum Quiescent Current***

It is the current drawn by the inverter from the DC source in idle (no load) condition.

- ***Surge Capability***

It is an indication of the capability of the inverter to deliver the power beyond its nominal power for a very short period of time. This capability is very important where the load takes large surge current for a short period time and then draws nominal rated current rest of the time. Examples of such loads are color television, motors, refrigerators etc. The surge capability is usually defined in percent of its nominal capacity for given duration (e.g. 150% of rated capacity for 2 seconds).

- ***Total Harmonic Distortion (THD)***

The AC supply from the grid line has sinusoidal waveform containing a single frequency component called fundamental frequency. In other words, if the waveform of the grid supply is perfectly sinusoidal, it will contain the frequency component of 50 Hz only, i.e. no other frequency components are present in that waveform. But if the waveform is other than sinusoidal (e.g. rectangular or square), it will contain the frequency components that are integer multiple of fundamental frequency. These additional frequency components are called harmonics. The total harmonic distortion (THD), expressed in percent, is the ratio of power contained in all other frequency components to the power contained in the fundamental frequency only. The THD is the measure of similarity between the real waveform and the ideal sinusoidal waveform. The THD of ideal sinusoidal waveform is essentially zero.

Other additional parameters may include operating environmental conditions (temperature and humidity levels), safety measures (electric shock protection, reverse polarity protection, over-load protection, low input voltage warning etc.), noise levels etc.

Types of Inverters

Inverters are classified into different groups based on the following criteria:

- **Output Power Rating**

According to this rating, inverters are in low power (upto 500 VA), medium power (upto 5000 VA) and high power (above 5000 VA) inverters.

- **Output Waveform**

As per this criterion, the inverters are sub divided into sinusoidal, quasi-sinusoidal and square wave types (fig. 6.4.3). The output of a sinusoidal (or sine wave) inverter is sinusoidal in shape and thus it has very low or negligible THD value. It is the most preferable type of inverter as it produces the waveform identical to the waveform available in grid supply. This type of inverter has low efficiency and cost more. Quasi sine wave inverter has the waveform resembling the sinusoidal waveform. This type of inverter has higher THD value than the sine wave inverter but is more efficient and cost effective. The square wave inverters are simple in design, have highest efficiency, low cost but have highest THD value. It is the challenge of the designer to select the most appropriate inverter based on the cost, application and quality of the waveform.

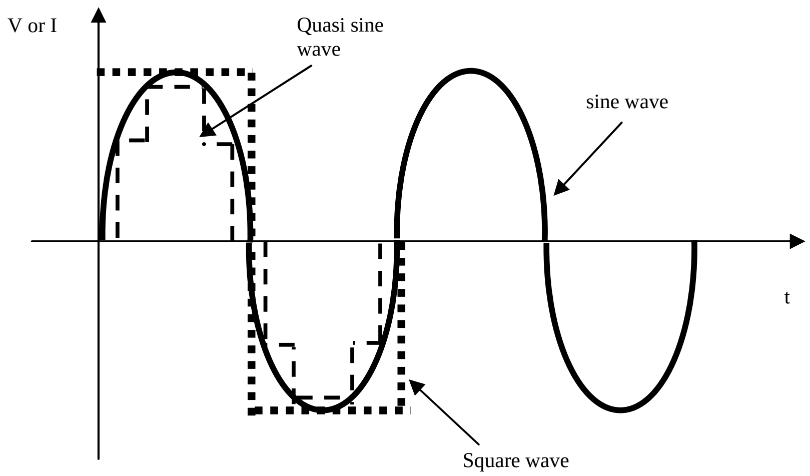


Fig. 6.4.3 Different types of waveforms

- **Single or three phase type**

As with the grid supply, which could be single phase (two wires labeled as phase or live and neutral) or three phase (three live wires and one neutral wire or three live wires), inverters are also designed to produce single phase or three phase supply. Inverters to be used with loads requiring three phase supply are classified as three phase inverters. Usually large power inverters are three phase type.

- **Continuous duty or back-up type**

The inverters designed for continuous operation are called continuous duty inverters. The inverters used to power loads like television, refrigerator, motors etc. are generally continuous duty type. The inverters used in computers as uninterruptible power supply are referred to back-up type because the inverters power the computers for a short period of time allowing users to save their work when the grid supply fails.

6.5 DC-DC Converters

DC-DC converters (DDC) are the devices used to derive DC voltage of higher or lower magnitude from the fixed input DC voltage. DDC are generally used to power electronic devices that operate from the voltage other than the system voltage of solar PV. For example, a radio/cassette player requiring 6V DC is to be operated from 12 V storage battery of the solar PV system. The radio will be damaged instantly if connected directly to the 12 V batteries. The only option would be first to down convert the 12 V DC to 6 V DC and then operate the radio. Similarly, a 24 V DC operated ink-jet printer can be operated from 12 V batteries by the use of appropriate DDC.

Basic Principles of DC-DC Conversion

There could be two versions of DC-DC conversion: from lower DC to higher DC (e.g. from 12 V to 24 V) or from higher DC to lower DC (e.g. from 12 V to 6 V). The first type of DDC is also called up-converter where as the second type is referred to as down-converter.

The simplest form down-converter type DDC can be implemented using a resistor in series between the source and load (fig. 6.5.1).

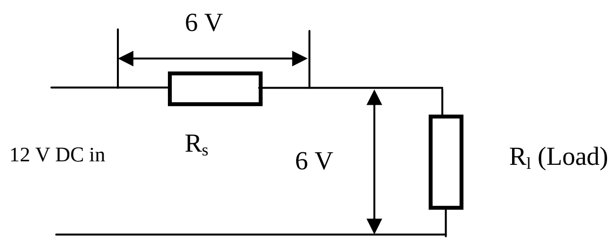


Fig. 6.5.1 Simple down converter type DDC

In the above figure, the 12 V DC input is converted into 6 V output by dropping extra 6 V in a series resistor R_s. This arrangement is simple but its efficiency is very low as the power is dissipated in series resistor as heat. Down-converter types DDC are easily available as integrated circuit (IC) package. The output voltage of these IC can be adjusted from fixed low voltage to voltage nearly equal to the input DC voltage by use of an external potentiometer.

The up-converter type DDC is more complex in design. The input DC is first converted into the AC by switching on and off in pre-determined interval and then this switched AC is up-converted by voltage booster. Finally, the higher magnitude AC is rectified to get required DC level (fig. 6.5.2). The feed-back from the output is provided to the switch control circuit to maintain the constant output DC level irrespective of the load (of course in the given limit of change in load resistance). The magnitude of the output voltage can be varied by varying the ratio between on and off times of the switch. The switch and output level control circuit is available as IC package.

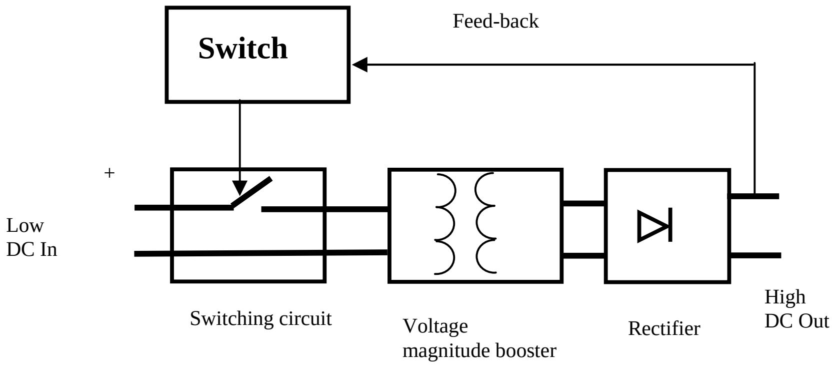


Fig. 6.5.2 Functional diagram of up-converter type DDC

Solid state DDC is also available in the market in the form of a slab. In this type of DDC, the input and output voltage levels are fixed.

Basic parameters of DDC

The basic parameters of a DDC are:

- Input voltage range- It is the range of input DC voltage within which the DDC produces steady output voltage
- Output voltage regulation – It is the range of swing of output voltage when the output load current changes from zero to maximum permissible value
- Efficiency – It is the ratio of output power delivered to the load and the input power drawn from the source
- Rated output current – It is maximum current that the DDC can deliver to the load.
- Radio Frequency Interference (RFI) level – This parameter indicates the level of interference made to other electronic devices from the operation of DDC.

Other parameters may include operating environmental conditions, safety measures, alarms etc.

6.6 Wiring and installation practices

Wire sizing (i.e. selection of the wires of appropriate size and type) is the critical aspect of solar PV system design. It is important to choose proper size wire in PV system to ensure safe operation and minimize voltage as well as power losses. National electric codes or standards specify how to choose wire type and size in great detail. Most of the national codes refer to the AC supply system only. For DC applications, in most cases, codes are simply not available. National PV standard, if available, must be used for sizing the cable.

Size and Types of Wires

Wires can be solid or stranded, bare or insulated, ordinary PVC insulated or with UV protection type insulation. Solid wire consists of a single wire of required cross-sectional area; where as stranded wires are made of multiple numbers of wires of smaller cross-sectional area. Often AC house wiring is done with solid wire or stranded wire with less number of wires. This is because, owing to the high system voltage (220 V in Nepal), the relative magnitude of the current flowing through the wires is low. But in PV applications, the DC voltage level is relatively lower than the AC, and therefore for same load the magnitude of the current will be relatively large. For higher currents, the cross-sectional area of the wire size must be larger. Solid wires with larger cross-sectional area become stiff and difficult to work with, and stranded wire is often used in PV installations.

Wire can be made of aluminum or copper. Aluminum wire can be considered for very long wire runs (e.g. national grid transmission lines), because it cost less than equivalent copper wire. But for most wiring applications in PV systems, copper wire should be used.

Type of insulation used in wire is also important in PV. Indoor wire, not exposed to the outdoor environment can have ordinary PVC insulation. But the outdoor wire must have special insulation (UV resistant insulation) so that the insulating material will not deteriorate over time due to exposure to Ultra-violet (UV) light. The wires need not to be directly exposed to the sunlight to deteriorate, as even light reflected on the back of the modules from the ground will eventually weather the wire insulation.

The standard unit of size of the wire is square millimeter (sq.mm. or mm^2). But in practice various other standards are in place: these are American Wire Gauge (AWG), Standard Wire Gauge (SWG), Brimingham Wire Gauge (BWG), US Steel Wire Gauge (US-SWG) and number based sizing system such as 7/22, 3/20 etc. However the wire size in the given standard can be converted in to mm^2 using appropriate conversion table or consulting the wire manufacturer's specification sheet. It is also the usual practice to specify the size of the wire in diameter (instead of cross-sectional area).

Review Questions

1. The specific gravity of a lead acid battery with 50% state of charge (SOC) is around

    a. 1.320
    b. 1.250
    c. 1.110
    d. 1.190

2. The condition of a flooded lead acid battery in which the specific gravity decreases from top to the bottom of the cell is called

    a. sulfation
    b. formation
    c. stratification
    d. corrosion

3. A 100 Ah capacity fully charged battery is discharged at 5 A rate for 8 hours. The depth of discharge of the battery after this period is

    a. 40%
    b. 5%
    c. 60%
    d. 8%

4. One of the followings is not the essential parameter of a charge regulator

    a. High Voltage Reconnect
    b. Total Harmonic Distortion
    c. Radio Frequency Interference
    d. Reverse Leakage Current

5. The minimum level illuminance required for comfortable reading is

    a. 50 Lux
    b. 10 Lux
    c. 200 Lux
    d. 2000 Lux

6. Typical efficiency of a good inverter should be over

    a. 50%
    b. 80%
    c. 60%
    d. 75%

7. An electronic device that converts DC voltage of one magnitude to the DC voltage of another magnitude is called

   a. Inverter
   b. Converter
   c. Charge Regulator
   d. Ballast

8. A 20 Watt Tube light operated from 12 V DC supply is turned on for 5 hours. Calculate the energy consumed (in Ah) by the light.

9. Select the appropriate inverter (i.e. the VA rating, input voltage, output voltage, output frequency) to operate a 29" color television and a laptop computer that requires 200V AC supply at 50 Hz.

10. The size of the cable increases with decrease in

   a. maximum allowable voltage drop
   b. length
   c. maximum permissible current
   d. cross sectional area

CHAPTER 7

Solar Home System Design and Installation

Duration: 490 minutes
180 minutes (Practical)

Physical Facilities required: Class room with white board and multi-media projection facility and open space for SHS installation.

Materials required:

a) Catalogues of various types of modules, batteries, charge regulators, lamps, DC-DC converters and DC-AC inverters, wire-size tables, PV standards, calculator and reference material.
b) Working components of SHS, multimeter, hydrometer, clamp meter, electronic tool kit, spare parts and other accessories.
c) A complete SHS unit and a wooden board for installation of SHS (one for each trainee)

Procedures: The Instructor/s

a) explains an overview of the practices and procedures of designing Solar Home System
b) provides an overview of the installation practices of Solar Home System
c) demonstrate the installation process of Solar Home System
d) The trainees install the SHS individually.

Instructor: The Trainer

Reference:

1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP
2. Solar Electricity Technical Training Manual (Level 1), AEPC/ESAP.
3. Solar Electricity Technical Training Manual (Level 2), AEPC/ESAP.

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
7.1	Design of Solar Home System (SHS)	Lecture and numerical examples and exercise	Class room	250 mins.	
7.2	Installation of Solar Module	Lecture and demonstration	Class room	30 mins	
7.3	Installation of Charge Controller	Lecture and demonstration	Class room	30 mins	
7.4	Installation of Battery	Lecture and demonstration	Class room	30 mins	
7.5	Wiring of the solar home system components	Lecture and demonstration	Class room	30 mins	
7.6	Lamp installation procedures	Lecture and demonstration	Class room	30 mins	
7.7	Switch installation procedures	Lecture and demonstration	Class room	30 mins	
7.8	Power socket installation procedures	Lecture and demonstration	Class room	30 mins	
7.9	Components assembly of Solar Home System	Lecture and demonstration	Class room	30 mins	
7.10	Installation of solar home system components systems	Lecture and demonstration	Class room	180 mins	

7.1 Design of Solar Home System (SHS) as per requirement of customer

Design of the solar home system should begin after the collection of detail information about electricity consuming loads or devices and their operation from the customer. The sample of the load profile from the SHS using customer is as given in the table 7.1.1

Table 7.1.1: Load profile of the SHS user

Particular	Quantity	Power (Watt)	Daily operation (Hours)	Remarks
Electric lamp	1	10	3	Living room
Electric lamp	1	7	3	Kitchen
Electric lamp	1	5	1	Bed room
Radio	1	3	3	Living room
Television (Black/White)	1	15	2	Living room
Total		48		

The daily-required electric energy for operating all the devices for the mentioned number of time in the table 7.1 should be calculated by following procedures.

Energy required for electric lamp

Energy consumption for operating each lamp is calculated by multiplying the power rating (Watt) of it by the time of operation in hour.

$$E_L = P_L H_L \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (7.1.1)$$

where,

E_L = Energy consumption by the lamp (Watt-hours)
P_L = Power rating of the lamp (Watt)
H_L = Daily operation time of the lamp (hours)

For example daily energy consumed by the 10 watt lamp in the table 7.1.1 for operating it for 3 hours per day is $E_L = 10 \times 3 = 30$ Watt hours.

Similarly, energy consumed by all the lamps is calculated and the total daily energy consumed by all the lamps is given by summation of all the energy consumption

$$E_{L\,Total} = E_{L1} + E_{L2} + E_{L3} + \ldots.. \qquad (7.1.2)$$

For the lamps given in the table 7.1.1, the total energy consumption for lighting lamps becomes,

$$\begin{aligned} E_{L\,Total} &= (10W \times 3 \text{ hours}) + (7W \times 3 \text{ hours}) + (5W \times 1 \text{ hour}) \\ &= 30 \text{ Wh} + 21 \text{ Wh} + 5 \text{ Wh} \\ &= 56 \text{ Wh.} \end{aligned}$$

Energy required for radio

Energy consumption for operating radio is also calculated by using the expressions similar to the energy consumption for operating lamp.

$$E_R = P_R H_R \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (7.1.3)$$

where,

E_R = Energy consumption by the radio (Watt-hours)
P_R = Power rating of the radio (Watt)
H_R = Daily operation time of the radio (hours)

Energy required for operating radio as per mentioned in the table 7.1.1 is given by using the equation 7.1.3 as following.

$$E_R = 3 \text{ Watt x } 3 \text{ hours} = 9 \text{ Watt-hour}$$

If more than one radio is used then the required energy is calculated by using following equation,

$$E_{R\ Total} = E_{R1} + E_{R2} + \ldots\ldots\ldots\ldots \qquad (7.1.4)$$

Generally, the power consumed by the small capacity radio and cassette players will not be mentioned. In this condition, power can be assumed to be between 3 to 5 Watts by considering size of the radio, battery type (small pen touch battery or large torch light battery) and number of battery. Power rating is generally mentioned in the large capacity radio and cassette players. If in case power rating is not mentioned but operating voltage and current are mentioned then we can obtain the power by multiplying rated current and voltage. For example if 9V DC,1A is written at the back side of the radio cassette player then energy consumed by it becomes 9V x 1A = 9 Watt.

Energy required for television

Energy required for operating television is also calculated by using the expressions similar to the energy consumption for operating lamp.

$$E_T = P_T H_T \qquad (7.1.5)$$

where,

E_T = Energy consumption by the television (Watt-hours)
P_T = Power rating of the television (Watt)
H_T = Daily operation time of the television (hours)

Energy required for operating television as per mentioned in the table 7.1.1 is given by using the equation 7.1.5 as following.

$$E_T = 15 \text{ Watt x } 2 \text{ hours} = 30 \text{ Watt-hour}$$

If more than one radio is used then the required energy can be calculated by summation of all the energy requirements as following,

$$E_{T\ Total} = E_{T1} + E_{T2} + \ldots\ldots\ldots\ldots \qquad (7.1.6)$$

Generally, power required for operating television is mentioned at the back cover of it. The power rating depends upon the television type (Black and White or Color), screen size and technology (glass tube or liquid crystal display -LCD). Color television of the same size will consume double the power as the Black/White television. Similarly, the regarding technology, LCD television consumes half the power compared to glass tube type.

Finally total daily energy requirement for operating all the devices of the solar home system users is calculated by using the equation 7.1.7.

$$E = E_{L\ Total} + E_{R\ Total} + E_T + \ldots\ldots \qquad (7.1.7)$$

For the devices mentioned in the table 7.1.1 the total daily energy requirement is given by,

$$E = 56 \text{ Wh} + 9 \text{ Wh} + 30 \text{ Wh} = 95 \text{ Wh}$$

<u>Selection of Solar PV module</u>

It is very important to know the information regarding the place where solar PV module is going to be installed before determining the size of the PV module. Information such as how many days in the year does sunshine occur in a year, which month have maximum sunshine hour and how much, which month has least sunshine hour and how much as well as in an average how much hour sun shine per day through out the year. If the customer cannot give the above information, then contact nearest meteorological station and obtain the required data. If this is not possible then consult the World Meteorological Map to determine the solar insolation at the place considered. Normally for Nepal, solar insolation is 4.5 kWh/m2/day (or Peak Sun of 4.5 hour). Insolation for different palces is given in the appendix 3.

After determining the Peak Sun, the current to be generated by the solar module is given by using the following equaltion.

$$I_M = \frac{E}{H_P \text{ x } B_V} \qquad (7.1.8)$$

where,

I_M	=	current generated by solar module (Ampere)
E	=	required total energy (Watt Hour)
H_P	=	peak sun (hours)
B_V	=	battery voltage (Volt)

Generally 12 V battery is used in the solar home system, so use B_V = 12V in the above equation.

using equation 7.1.8 for the table 7.1.1, we get,

$$I_M = \frac{\text{95 Watt-hours}}{\text{4.5 Hours x 12V}} = 1.75 \text{ Ampere}$$

After determining the value of I_M consult the solar module catalogue to select the module that rated current or current at Peak Power is equal to or greater than I_M calculated.

Selection of Battery

Selection of battery consists of determining the capacity of battery (Ampere-hour), voltage of battery (Volt) and type of battery (Ordinary battery or Deep Cycle battery).

Capacity of the battery is given by using the following expression,

$$C_B = \frac{E}{\eta_B \text{ x DOD x } B_V} x N_A \qquad (7.1.9)$$

where,

C_B	=	battery capacity (Ampere-hour or Ah)
E	=	daily energy consumption (Wh)
η_B	=	battery charging efficiency (normally 0.8 to 0.95)
B_V	=	battery voltage (Volt)
N_A	=	number of days to be operated without sunshine (Autonomy Days)
DOD	=	Depth of Discharge

Now considering N_A = 3 day, η_B = 0.8 and DOD = 50% (or 0.5) and using the equation 7.1.9 for conditions given in table 7.1.1 to determine the capacity of battery, we get

$$C = \frac{95Wh \text{ x } 3\, days}{0.8 \text{ x } 0.5 \text{ x } 12V} = 59.37 \text{ Ah}$$

The capacities of the battery available in the market are of standard sizes so during selection of the battery choose the available battery with the capacity that is just above the calculated capacity of the battery required. For example if calculated battery capacity is 59.37 Ah than select the standard 60 Ah battery. Since we have considered DOD = 50% and B_V = 12V the selected battery should be deep cycle battery.

If ordinary (swallow cycle) battery with DOD = 20% (or 0.2) is taken instead of deep cycle battery, then capacity of the required battery becomes,

$$C = \frac{95 \text{ Wh x } 3 \text{ days}}{0.8 \text{ x } 0.2 \text{ x } 12V} = 148.43 \text{ Ah}$$

That is we need to select battery with the capacity of 150 Ah.

Selection of Charge Controller

Charge controller should be able to with stand short circuit current (I_{SC}) of the module and maximum battery to load current ($I_{L\ max}$). Load current can be calculated by using following equation,

$$I_{L\ max} = \frac{P_T}{B_V} \qquad (7.1.10)$$

where,

$I_{L\ max}$	=	maximum battery to load current (Ampere)
B_V	=	solar energy storing battery voltage (Volt)
P_T	=	Total power (Watt)

To determine total power (P_T) the power consumed by all the appliances like lamps, radio, TV has to be added. For the example in the table 7.1 the total power is calculated as

$$P_T = 10 \text{ watt} + 7 \text{ watt} + 5 \text{ watt} + 3 \text{ watt} + 15 \text{ watt} = 40 \text{ watt}$$

and maximum load current is given by

$$I_{L\max} = \frac{P_T}{B_V} = \frac{40 \text{ watt}}{12 \text{ V}} = 3.33 \text{ A}$$

Generally the charge controller should be selected whose current bearing capacity should be two times that of $I_{L\ max}$ and I_{SC}. The voltage rating of the charge controller should be same as the operating voltage of the solar home system.

Selection of DC/AC Inverter

Inverter are generally use in the solar home system to operate color television. Hence the input DC voltage of the inverter should be 12 V and output AC voltage should be 220 V. the frequency of inverter should be that of the national grid frequency (50 Hz). Waveform of the inverter should be pure sine wave but the cost of this type of inverter is little higher than the inverter with square wave. The power rating of the required inverter is calculated by using the following equation,

$$P_{\text{inverter}} = \frac{P_{load}}{PF \ \ x \ Efficiency} \qquad (7.1.11)$$

where,

P_{inverter}	=	Power rating of inverter (VA)
P_{load}	=	Load power (Watt)
PF	=	Load Power factor
Efficiency	=	Inverter Efficiency

Usually during selection of the inverter power factor PF is taken as 0.8 and efficiency is taken as 0.8.

Example: If 21" color television whose rated power is 50 Watt is to be operated with 220V AC supply then capacity of the inverter to be selected is determined by using the equation 7.1.11 as following,

$$P_{\text{inverter}} = \frac{50Watt}{0.8 \text{ x } 0.8} = 78 \text{ VA}$$

It is to be noted that during turning ON of the switch of the television the initial power consumed by the television will be higher than the rated power. The inverter should be capable of supplying this surge power. Therefore, the power rating of the inverter selected should be 2 to 3 times of this calculated power. For the above example, the inverter with the capacity of 200 VA should be selected.

Selection of DC/DC converter

Some small electrical appliances like radio, cassette player will operate at the voltage lower than 12V DC. For example small radio can operate in 3V DC with 500 mA current and some cassette player have 25 Watt capacity which can operate in 9V DC with 3A current. During selection of the inverter, attention should be given to determine if the selected inverter could supply the required voltage and current. The size and cost of the inverter for 12V DC supply with 3V DC, 500mA output is quite different from the inverter for 12V DC supply with 9V DC, 3A output. Therefore, during the selection of the inverter for solar home system detail information on the required voltage and current of the appliances to be operated by the system should be known before selection process.

.

The output voltage of the selected DC-DC converter should match the required input voltage of the appliance.

Selection of switch

During selection of switch, we should consider the current flowing through the switch and voltage applied. The voltage applied in the solar home system is 12V DC, so DC rated switch selection must be done. Switches are used for operating the electric lamps or television. Generally, electric lamp consumes less than 1A current so switch should be selected with DC rating of 2A. If the DC rated switch is not available in the market then 5A AC switch can be used. For television operation, the selection of 15A rated AC switch is appropriate.

Selection of the wire size for solar home system

In solar home system five different types of wire size are used as shown in the figure 7.1.1.

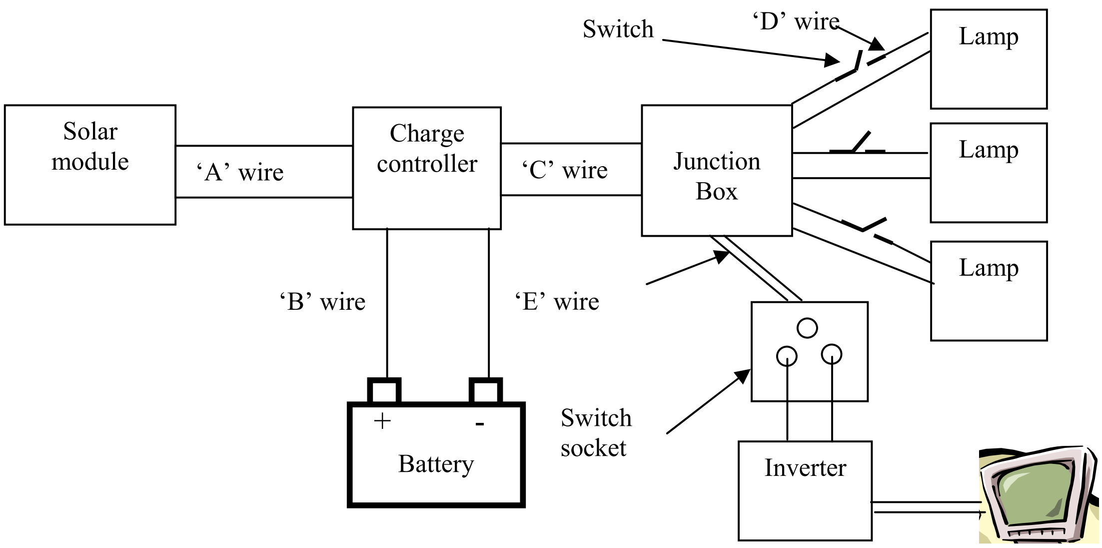


Figure 7.1.1 Wire sizing of solar home system

Wire joining the solar module and charge controller 'A'

The selection of wire joining solar module with the charge controller called 'A' wire should be as short as possible and should be resistant to sun light and water as well as ultra violet ray in sun light. The outer cover of this wire should be UV protected type.

The inner diameter of the conductor of the wire depends upon the voltage drop between the solar module and charge controller. The thickness of the conductor indicates how much energy can be dropped between the solar module and charge controller. The size of the wire required is calculated by using the Standard Wire Gauge (SWG) formula as following.

$$S = \frac{0.3 \times L \times I_M}{\Delta V} \qquad (7.1.12)$$

where,

S = Cross Sectional Area of wire (mm^2)

L = Length of wire joining solar module and charge controller (meter)

I_M = current flowing from solar module to charge controller (Ampere)

ΔV = maximum allowed voltage drop percentage (5%)

ΔV indicates the voltage drop or voltage loss across the wire.

For example, if L = 3 m, I_M= 4A and ΔV= 3% then using equation 7.1.12, we get

$$S = \frac{0.3 \times 3 \times 4}{3} mm^2 = 1.2\, mm^2$$

Use the table in appendix 4 to select the wire with cross sectional area of 1.2 mm^2. Here the size of the wire (diameter) is given in Standard Wire Gauge (SWG), American Wire Gauge (AWG) and British Wire Gauge (BWG).

The S cross sectional area of the wire is calculated by using following expression

$$S = \frac{\pi d^2}{4}$$

or,

$$d = \sqrt{\frac{4S}{\pi}}$$

where,

S = Cross sectional area of wire (mm^2)

d= Diameter of wire (mm)

π= 3.14 (Constant)

For above wire having calculated wire diameter of 1.23 mm, SWG wire number 18 should be selected. Instead of selecting single strands containing wire, multiple strands containing wire can also be selected which has more bending strength, less voltage loss and hence help to store more energy in the battery. Hence instead of SWG 18, SWG 7/22

(7 strands of SWG 22 wire) can be used which cross-sectional area becomes 3.57 mm2 (nearly 3 times more than SWG 18).

Wire joining charge controller and battery 'B'

The size of the wire joining the charge controller and battery is also calculated by using the equation 7.1.12 as above but the value of ΔV should be taken as 1%. Besides, for this purpose there is no need to use UV protected wire, as it is located inside the house. While sizing 'B' wire the value of current (I) should be the largest value of current flowing through the wire. During the charging process, the current flowing through this wire is similar to the current received from module I_M and during discharging process the current in this wire is equal to the total load current connected to it. The value of current taken for calculating the cross sectional area should be the higher value of both current.

In the above example if the maximum load current is 4A or less and distance between the charge controller and battery is 1 m then required wire size is given by,

$$S = \frac{0.3 \text{ x } 1m \text{ x } 4A}{1} = 1.2 \text{ mm}^2$$

Here also the distance between the charge controller and battery should be least as possible for decreasing the loss across the wire.

Wire joining charge controller and junction box 'C'

For calculating the size of the wire joining the charge controller and junction box use equation 7.1.12 with the value of ΔV taken as 1%. The current is taken as the maximum total load current flowing through it.

Wire joining junction box and lamp 'D'

Take ΔV up to 5% in the equation 7.1.12 for calculating the size of the wire joining the junction box and lamp.

Wire joining junction box to DC switch socket or inverter or TV (Black/White)'E'

Take ΔV less than 5% in the equation 7.1.12 for calculating the size of the wire joining the junction box to DC switch socket or inverter or TV (Black/White).

7.2 Installation of Solar Module

Before the installation of solar module the physical inspection and electrical test of the module should be done.

The physical inspection consist of the following observations
(a) Check whether glass of module is broken/scratch or not.
(b) Observe whether solar cells of a module are connected to one another inside the module.
(c) Check whether Aluminum frame housing the module is damaged or not.
(d) Condition of the junction box cover OK or not.
(e) Condition of the wire connecting screw inside junction box OK or not.

If the condition (a), (b) and/or (c) is not fulfilled then change the module. If condition (d) and (e) is not fulfilled then we can still use the module by replacing the faulty parts of the module.

For the electrical testing of the module, expose the module to the good intensity sun light and measure the DC voltage. For this, the selector knob of the multimeter should be adjusted to the position indicating more than 20V DC range. Orient the module to the clear sky sun light and connect the positive (+) terminal of the module to the positive terminal of the multimeter and negative (-) terminal to the respective negative terminal. If the module is to be used for 12V system then the multimeter should reads around 18 to 22 V. For the 6V module, the multimeter reading should be between 9 to 11V. If solar module is damaged, it will not indicate above-mentioned voltage and in such case the module needs to be changed.

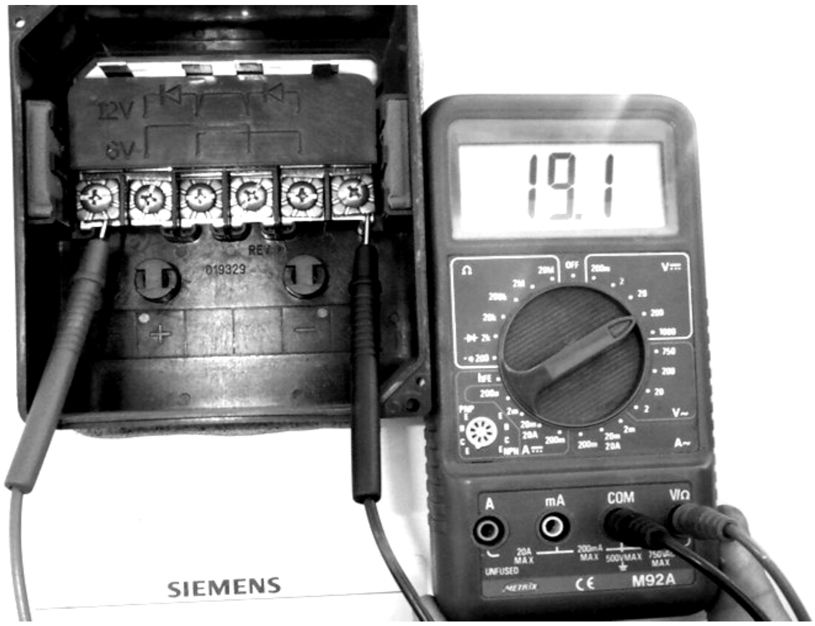


Figure 7.2.1 Measurement of solar module voltage

If the physical and electrical test of the solar module is satisfactory then only proceed for the installation of the module. For this, select the place where the pole used to hold the module can be erected stably. This place should be free from shadow casting obstructions from sunrise to sun set. It should also be inaccessible to the children. As efficiency of the module decreases when dust or bird excreta get accumulated on the solar module there should be provision for cleaning the module from time to time. Erect the pole with stable and strong foundation after determining the appropriate location.

After that, assemble the support structure to the solar module for fixing it to the pole. Different types support structures are shown in the figure 7.2.2 below.

Figure 7.2.2. Solar modules with support structure

Open the junction box cover of the module and connect one end of the wire joining module with the charge controller. Measure the distance required to extend the wire from the module junction box up to the charge controller terminal and cut the wire. Figure 7.2.3. shows the junction box of the module with wire connected to it.

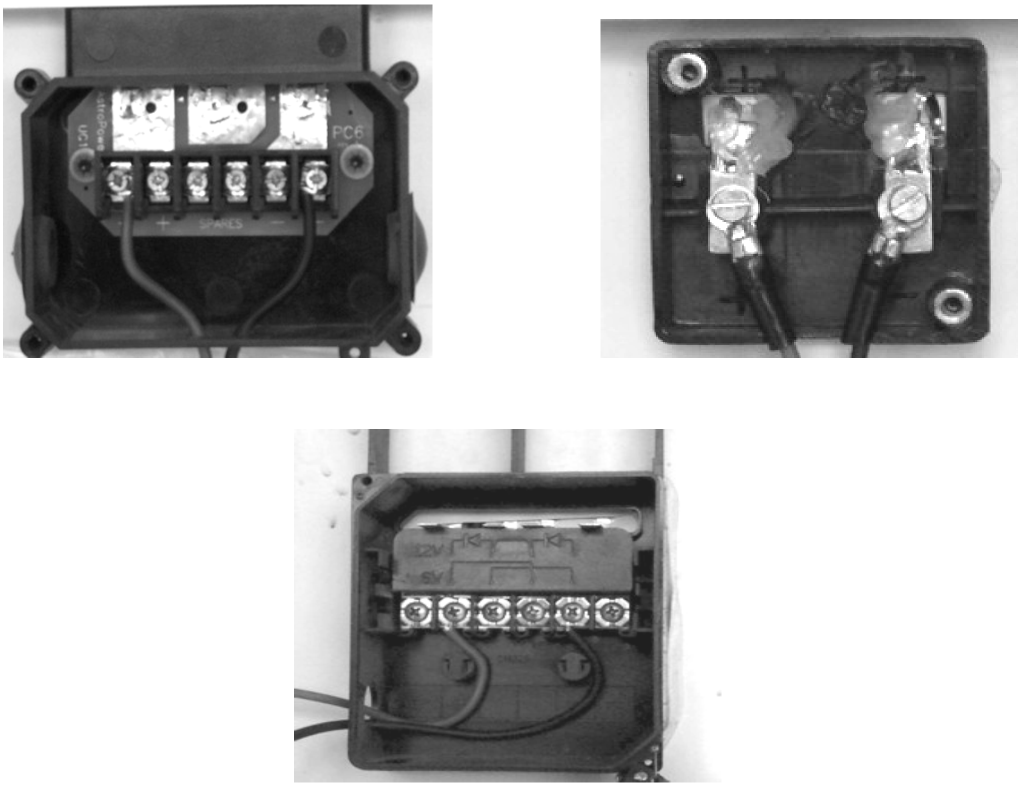


Figure 7.2.3. Wire connections at the junction box of the modules

After that, assemble the solar module to the supporting pole. During tightening of the nut and bolts, left them little bit loose for adjusting the position of the module towards the south direction. Use the compass to determine the south direction and turn the solar module towards the south direction. Then tighten the nut and bolts to fix the module to the supporting pole rigidly.

Figure 7.2.4. Use of compass to determine south direction

Finally loosen the nut bolts joining the module frame with support structure to tilt the module 30° toward north.

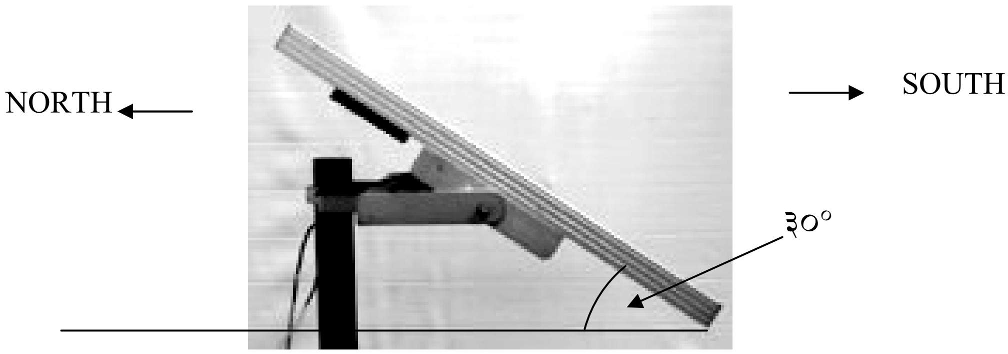


Figure 7.2.5. Tilting of the solar module to 30° North

After tilting the module at 30° tighten the nut and bolts joining the solar module frame and support structure. For titling the module to 30° use the set square containing 30°, 60° and 90° angles. If the solar module is located at the dust prone places then solar module must be cleaned at least once a week.

7.3 Installation of Charge Controller

Before installing the charge controller, determine the proper place for its location. The place for the installation of the charge controller should be free from the sunlight and rain, easily accessible, far from fire and smoke sources and not accessible to the children (on the wall above wooden board). Beside this, the distance between solar module and charger controller should be shortest as possible. As well as distance between battery and charge controller should also be shortest as possible. Considering above points and consulting with the customer the appropriate place for the installation of the charge controller should be determined.

Charge controller generally contains two holes to hang it over the wall. For installing it first, mark the position of the hole using pencil by putting the charge controller in straight position over the predetermined place. Remove the charge controller and drill the hole by using the hand drill and insert the nylon grip inside the hole by using hammer until the surface smoothen. Then position the charge controller in the place and use the screw to fix it on to the wall. Tighten the screw exactly on the nylon grip hole. To test the rigidity, hold the charge controller by two hands and pull little bit forward. If the charge controller totally loosen and come out then select other more rigid place for installation. Some suppliers provide the cabinet for housing charge controller and battery, in such case there is no need for fixing charge controller on the wall.

During connecting the wire coming out of the solar module to the charge controller care should be taken to cover the module by cloth during sunshine period. After connecting the wire to the charge controller, the cloth should be removed. By doing this it will protect the charge controller.

7.4 Installation of Battery

Battery should be installed at air circulating open space with no sun light falling over it and leveled surface. Its location should not be easily accessible to the children. There is no need to cover the battery. As battery produces hydrogen during charging and discharging process, there should not be any activity near the battery that result danger of catching fire like cigarette smoking, lighting kerosene lamp etc. The location of the battery should be isolated from any source of the fire.

During installation of the battery the short circuit connection between positive (+) and negative (-) terminal of the battery should be prevented as it produce large amount of current flow which might result undesirable accident. Do not touch positive and negative terminals of the battery with bare hand at any cost.

During operation of the battery, rusting might occur around the terminal of the battery and wire connecting screw might get loosen due to the ambient condition. To prevent this nut bolts should be tighten properly and Vaseline or petroleum jelly should be applied over the connecting terminals.

Connect the positive (red) wire of the battery to the corresponding positive battery terminal of the charge controller and connect the negative (black) wire of the battery to the corresponding negative battery terminal of the charge controller. After that, connect the corresponding black and red wire coming out of the charge controller to the respective negative and positive terminals of the battery. After that, screws located at the battery terminals should be tighten properly and vaseline or petroleum jelly should be applied over the connecting terminal surface to prevent rusting.

During the initial operation, the battery should be fully charged during daytime and only nominal load should be connected during night time for few days so that its voltage will comes around 12.5V and specific gravity between 1.240 to 1.250 range.

7.5 Wiring of the solar home system components

Wiring the solar home system should be done by following the systematic procedures for effective and efficient result.

7.5.1 Locating the path of wiring and marking it

Wiring is done firstly by determining the location of the lamps after consultation with the costumer. Most of the costumer may not know where to install the lamp, as they have not used the electrical lamps before. The installer should guide them to finalize the location of the lamps keeping in view that lamps position should illuminate in all direction, provide light to the nearby rooms, corridor and lobby so that people may feel easier to move around and children cannot reach the lamps. Mark the position of the lamps locations by using the marker.

After that locate the place for installing the junction box that should be situated at the maximum distance of 15 feet from the charge controller and should be at same distance from all the lamps as much as possible. After locating the position of the junction box and lamps, determine the shortest path between junction box and lamps followed by marking the path with chalk. During determining the path for the wiring of the lamp locate the position of the switch (preferably near the side of the door) and provide the provision for wiring the switch with red wire as well.

7.5.2 Types of junction box and their installation procedures

In solar home system only one pair of wire exist at the outlet of the charge controller but there will be multiple pairs of wires connecting several lamps. In this condition, junction box is used to connect the charge controller to multiple numbers of loads simultaneously.

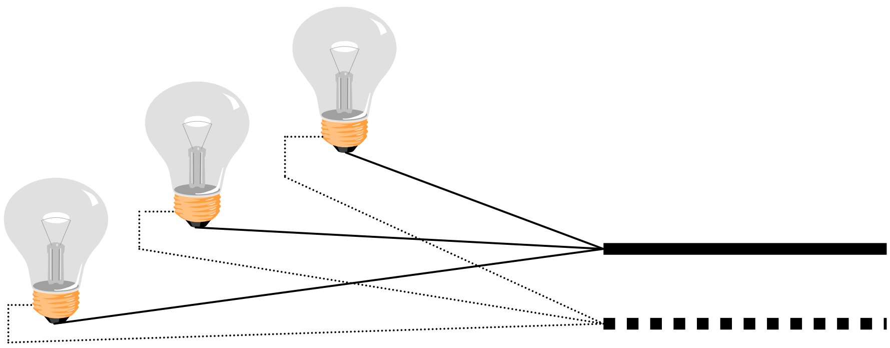


Figure 7.5.1. Method of joining one pair of wire simultaneously with three pairs of wire

Generally, two connector blocks of conducting materials are placed inside the junction box. The connector block possesses the provision of connecting many wires at a time. In one connector block red wire (+) from the controller and all the red wire from the lamps are connected and in another connector block black wire (-) from the controller and all the black wire from the lamps are connected.

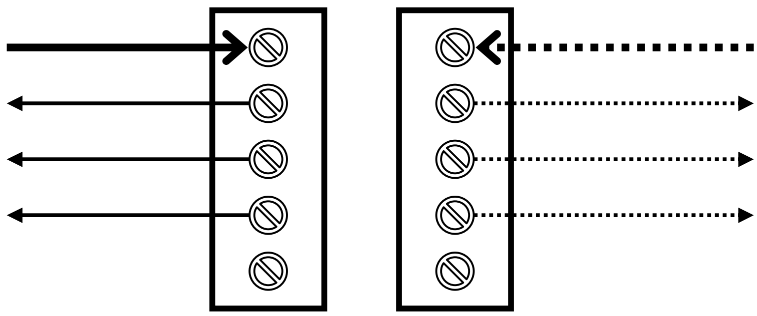


Figure 7.5.2. Method of joining the wires in junction box

The picture below shows the sample of junction box used in Nepal for SHS

Figure 7.5.3. Sample of junction box used in Nepal

Junction box should be installed at the wall as charge controller. There are two holes in the junction box for fixing it at the wall. The procedure for the installation is similar to that of installing charge controller.

During connection of wire inside the junction box, first connect all the red (+) wires to the (+) connector block of the junction box and all the black (-) wires to the (-)connector block of the junction box. After that connect the red wire coming from the (+) terminal of the charge controller to the (+) connector block of the junction box and connect the black wire coming from the (-) terminal of the charge controller to the (-) connector block of the junction box. Connection of the wire to the connector blocks of the junction box is shown in the figure 7.5.4.

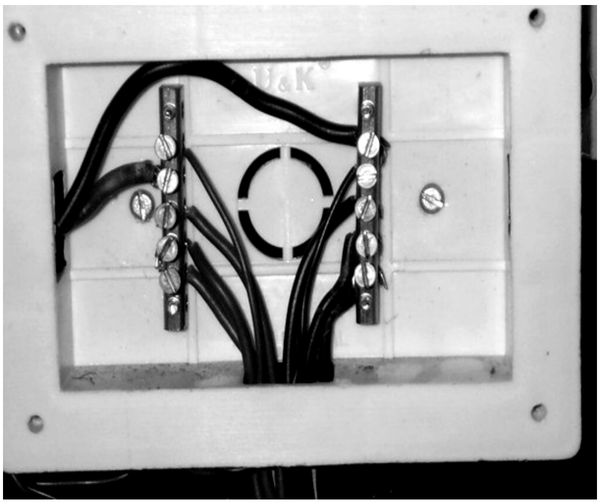


Figure 7.5.4. Connection of the wire to the connector blocks of the junction box

7.5.3 Wiring procedures

Wiring should be started after the identification of the location to install lamps and switches as well as installation of junction box. Following tools and materials are needed for the wiring purpose,

Tools

1. Wire Cutter	– used for cutting wire
2. Wire Stripper	– used for taking out the insulator of the wire
3. Flat Screw Driver	– used for tightening screws
4. + or Philips Screw Driver	– used for tightening screws of charge controller
5. Hammer Medium	– used for fixing wiring clips in the wood
6. Hand Drill	– used for making hole (smaller than screw) in the wood
7. Combination Plier	– used for cutting wire, taking out nails and holding things
8. Crimping Tool	– used for attaching the cable shoe on the wire
9. Multimeter	– used for checking wiring connection, functioning of switch, measuring voltage of the battery and solar module.

During wiring process, all these tools should be kept in one bag or in the half jacket containing multiple pockets. By doing this tools will not get lost and can be obtained instantly when required.

Materials

1. Wiring clip for holding two wires joining solar module to charge controller, charge controller to battery, and battery to junction box
2. wiring clips for holding the wire joining junction box to lamps
3. small nails for fixing clips
4. screws of different sizes
5. red and black insulation tapes
6. torch light

While wiring it is necessary to use wooden batten or plastic batten along the path through which the wire passes for holding it upon the batten by using clips. Start the wiring from the junction box to switch and from the corresponding switch to lamp as shown in the figure 7.5.5. If the mud plaster is used in the rural house then wooden peg/grip (1 inch long) should be used in the drilled holes and after that batten fixing nail or screw be applied over the wooden peg. If the wall is made from the baked brick then use the nylon grip for proper holding of the batten. The batten should be locked at two ends (by nail or screw) for small length and should be locked at four ends for longer one.

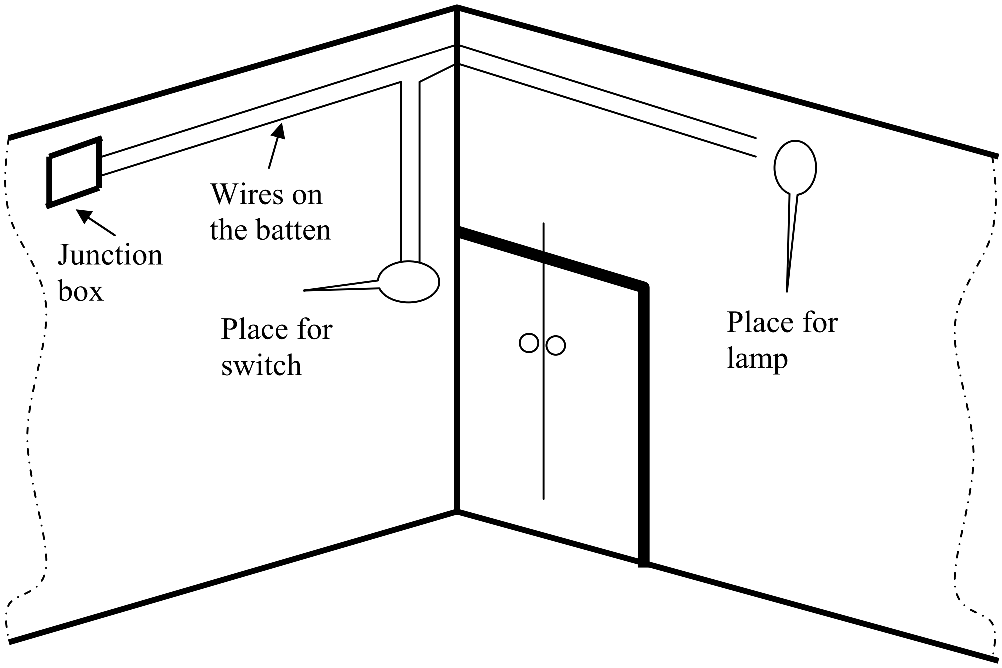


Figure 7.5.5. Use of batten for wiring

After fixing the batten on the wall start the process of holding wires on the batten. Care should be taken not to cut the wire too long and too short. Clips should be used at the distance of 1 inch on the batten for holding the wire. Extra length of 3” – 4” should be left at the end of the wire near junction box for the joining purpose. A loop of 4” should be provided in the red wire for using the switch as shown in figure 7.5.6.

If the switch is already provided in the supplied lamps of SHS then there is no need of making loop. Provide around 3” – 4” of extra length to the wire at the end near lamp holder for connection to the lamp. If power socket is to be installed then follow the procedure as mentioned above.

If the wooden or plastic batten is not available then use clips on the wooden frames, beam, and column as much as possible for holding the wire.

As per mentioned above perform the wiring process for joining solar module to charge controller, from charge controller to battery and junction box.

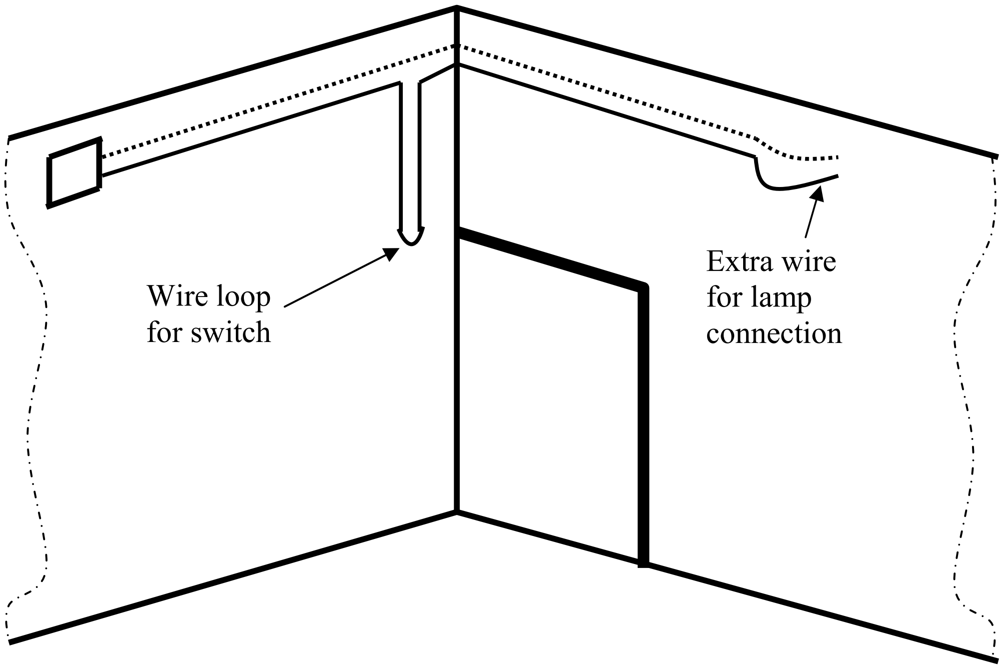


Figure 7.5.6. Wiring from junction box to lamp

7.6 Lamp installation procedures

Solar lamps possess two ⇨ shaped holes for holding it on the wall and over the beam as shown in the figure 7.6.1. In some lamps, these holes can be seen from outside where as in some lamps the cover at the housing end needs to be removed for viewing them.

For installation of the lamp, first mark the position of the lamp frame holes on the location specified for its installation by using pencil. If the location consists of wooden wall or beam simply use the screw at the marked point for fixing the lamp. If the base frame for installation is made from other material use wooden grip or nylon grip for screwing purpose as used for installing charge controller. While tightening the screw left about ¼ " of screw free for inserting the lamp frame holes and after that pull it as shown in the figure 7.6.2 for the locking purpose. Tighten the screw fully. During the process, make sure that wires of the lamp should be facing towards the end of wire extending from the junction box.

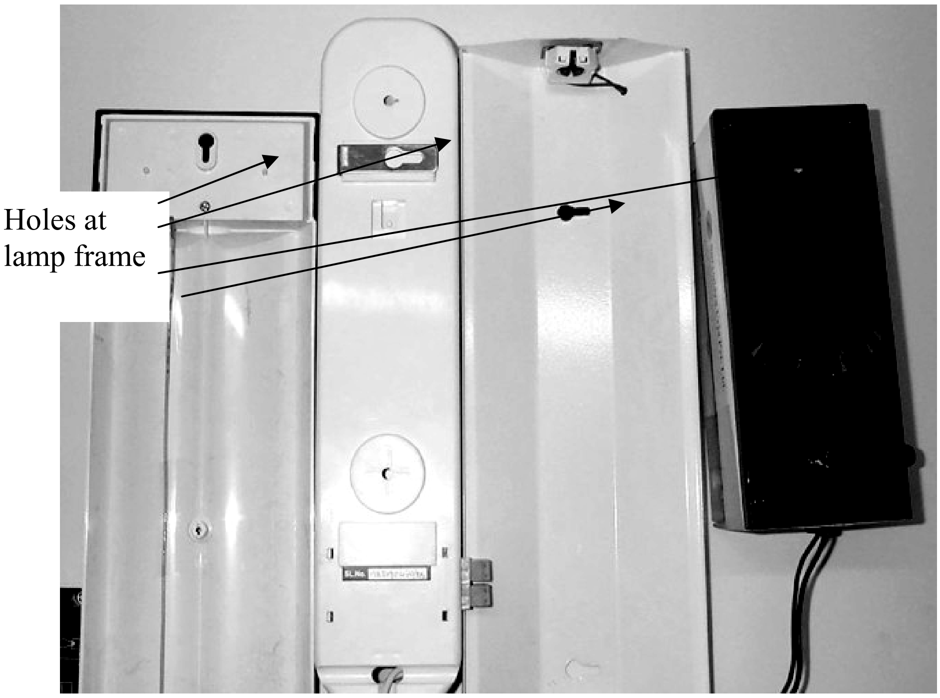


Figure 7.6.1. Holes made at the frame of the lamp for installation purpose

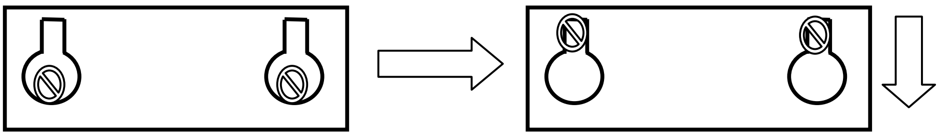


Figure 7.6.2. Method of using screw over the holes of lamp frame

The wire connection of the lamp is done by joining red (+) wire coming from the junction box (color of wire joined at (+) positive terminal of battery) to the (+) mentioned positive terminal of the lamp and joining black (-) wire coming from the junction box (color of wire joined at (-) negative terminal of battery) to the (-) mentioned negative terminal of the lamp.

For connecting the wire to the terminal, remove the ½" insulation from the end of the wires and twist 1-2 turn to the bare end of the conductor. Loosen the screw of the terminals and insert red wire inside the (+) terminal of the lamp and insert black wire inside the (-) terminal of the lamp. Tighten the screw of the terminal to secure the connection of the wire to the respective terminals. Check the connection of the wire to the terminal by slightly pulling it. If the wire pull out then tighten the screw for fixed securing. The wire connection to the terminal of the lamp is shown in the figure 7.6.3.

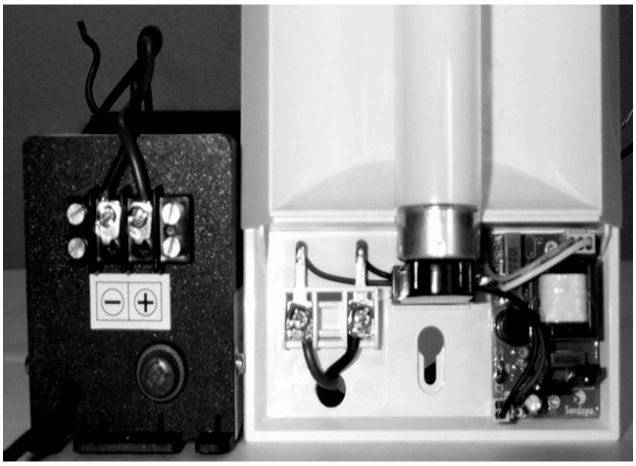


Figure 7.6.3 Wire connection to the solar lamps

7.7 Switch installation procedures

Two types of switches are generally used in the solar home system. First type is wall mount switch, which is fixed permanently on to the wall of the house by using the mounting screws. Second type is bed switch or hanging switch, which is not fixed on to the wall but instead hanged with the help of wires. The quality of latter one should be of better one other wise there is possibility of frequent failure.

Figure 7.7.1. Types of switch

Switch should be installed on the predetermined location marked initially during wire layout design. Use screw to fix the switch on the wooden wall. If the wall is made from mud or brick use wooden or nylon grip for holding screw.

The wiring of the switch starts with the cutting of the red wire in the middle of the loop provided by using the wire cutter. Use the wire stripper to remove the ½ inch of the wire insulation from the cut ends of the wire. During removing insulation make sure that no piece of wire get broken or no stain from the stripper be made o the wire. If the insulation removed wire is very flexible, twist 1-2 turns. Then remove the screw from the wire holding holes inside the switch by using screwdriver and insert the insulation removed wire ends into two different holes. Do not insert the insulation containing part of the wire inside the wire gripping holes of the switch. Tighten the screw to grip the wire end inside the holes and test the gripping of wire by pulling the wire slightly.

In some lamps switch is already included in the lamp itself as shown the figure 7.4.2. For these type of lamps there is no need for the installation of the switch on the wire passing through the lamp but care should be taken to determine the position of lamp so that switch is easily accessible.

Figure 7.7.2. Solar lamps with inbuilt switch

7.8 Power socket installation procedures

For the operation of television and cassette player, the power needs to be given through the battery. For supplying the power to these appliance three-pin socket will be used. The location of the socket should be in that place where usually family gathering take place such as living room. For the installation of the socket mark the position in the wooden pillar or wall for the housing the socket. Extend the 3/22 grade wire from the junction box to the socket. Remove the insulation from the end of the extended red and black wires and insert it into the holes in the terminal of the socket. Screw the holes containing the inserted wires inside the terminals of the socket. For the uniformity in the wiring connection use (+) red wire on the left side of the socket and (-) black wire on the right side when viewed from front side as shown in the figure 7.8.1.

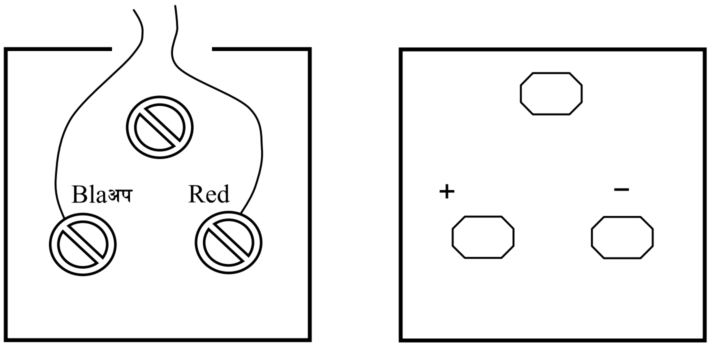
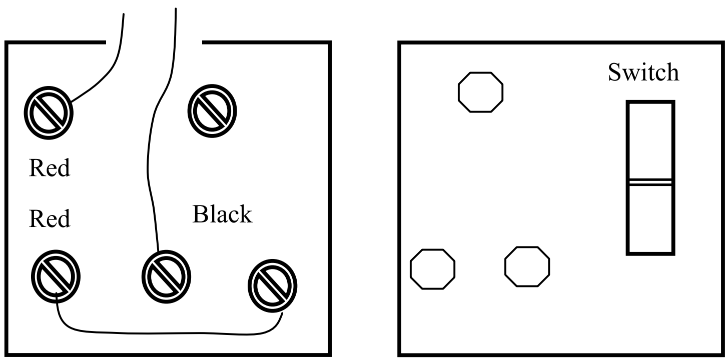


Figure 7.8.1. Wiring connection for socket

If there is switch also in the socket then use the wiring method as shown in the figure 7.8.2.



Back side view Front side view

Figure 7.8.2. Wiring connection for socket with switch

7.9 Components assembly of Solar Home System

During the installation of the solar home system each components of the system must be tested and installed separately followed by joining each other as following,

a) Connection of the wire going towards the battery to charge controller
b) Connection of the wire coming from charge controller to the battery
c) Check the functioning of the indicator in the charge controller showing condition of the battery
d) Connection of the wire coming from the solar module to the charge controller

e) Check the functioning of the indicator in the charge controller showing the charging of the battery from the module

f) Connection of the wire coming from junction box to the charge controller

7.9.1 Connection of the wire going towards the battery to charge controller

Wire for connecting charge controller with the battery is generally supplied separately by the SHS manufacturer. This wire is generally thicker than the one used for connecting the lamps and it contains cable shoe at one end for connecting it to the battery as shown in the figure 7.9.1.

Figure 7.9.1 Wire for connecting charge controller with battery

The other side of this wire does not contain cable shoes. The insulation of about ½” should be removed from this free end and its red wire should be connected to the terminal of the controller printed with battery (+). During connection of the wire to the terminal , the wire should be inserted into the hole of the terminal and screw should be tightly used to fix it properly. The length of the bare wire inserted into the terminal should be equal to the thickness of the terminal only and cut the wire if extend beyond that to prevent short circuit. Follow the same procedure for the black wire by connecting its free end with the battery (-) printed terminal of the charge controller.

7.9.2 Connection of the wire coming from charge controller to the battery

This connection should be done very carefully. If mistake occurs this might damage the charge controller. For connecting it, first identify the positive (+) terminal of the battery. Connect the red wire with cable shoe coming from battery (+) printed terminal of the charge controller to the (+) terminal of the battery. Then connect the black wire with cable shoe coming from battery (-) printed terminal of the charge controller to the (-) terminal of the battery carefully.

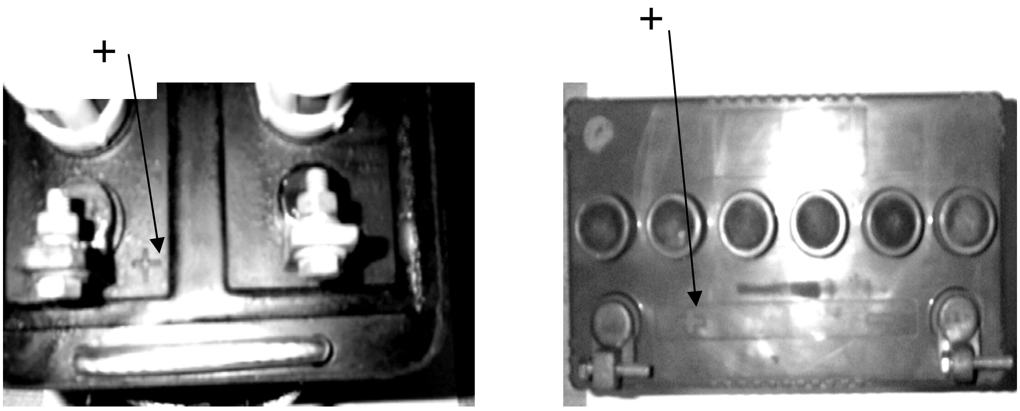


Figure 7.9.2 Positive (+) and negative (-) sign printed in the battery

After connecting the wire to the battery observe whether the battery condition-indicating indicator of the charge control light. If the indicator light properly then connection is considered as correct. If the indicator does not light properly, examine the connections made at the battery and charge controller once again. If the connections are found perfect, apply petroleum jelly, grease, or Vaseline at both terminals of the battery. If the connections done to the battery and charge controller are OK but battery condition indicating indicator is not functioning correctly then there is the possibility faulty in of either charge controller or battery. In this case first replace charge controller if this does not work then replace battery.

7.9.3 Connection of the wire coming from the solar module to the charge controller

Before joining the wire coming from solar module to the charge controller check the wire if there is proper voltage generated from the solar module. For this adjust the selector switch of the multimeter to DC 50V range and connect the red probe of the multimeter to the (+) terminal and black probe to the (-) terminal of the solar module. Remove ½" long insulation from the red and black wire coming from the solar module. Connect the red probe of the multimeter to the red wire coming from (+) terminal of the solar module and black probe of the multimeter to the black wire coming from (-) terminal of the solar module. The voltage should read between 12 – 22 V if the voltage coming from the module if functioning well. If the meter shows negative value then check the wire connected to the junction box of solar module (connection of red and black wire may be interchanged). If every things goes well connect the red wire coming from the (+) terminal of the module to the terminal of the charge controller printed (+) below the solar module sign. Follow the same procedure for the black wire coming from the (-) terminal of the module by connecting (-) terminal of the module to the terminal of the charge controller printed (-) below the solar module sign. Cover the solar module with cloth during connecting it to the charge controller to prevent electric shock. If the connection goes well then indicator in the charge controller showing the charging of the battery by solar module will light.

7.9.4 Connection of the wire coming from the junction box to the charge controller

Before connecting the wire coming from junction box to the charge controller, switch off all the light and loads connected to junction box. Then connect the red wire coming from (+) terminal of the junction box to the respective positive connector of the charge controller with (+) printed below sigh of lamp. Now carefully connect black wire coming from (-) terminal of the junction box to the respective negative terminal of the charge controller with (-) printed below sigh of lamp. If there is short circuit inside the connections of the junction box with red and black wire coming from load touching each other then the fuse of the charge controller might goes off or the spark might occur burning wire. If this happens, disconnect the wire joining the junction box with charge controller and check the connections at the junction box. Check the short circuit along the length of the wire joining the junction box with charge controller by using multimeter. If every thing goes well then connect red wire first and just touch the bare end of the black wire coming from the junction box to the respective terminal of charge controller. If it connections and wire condition are OK then it should not give spark. Connect the black wire to the controller if every thing goes well.

7.9.5 Connection of the DC/DC Converter

To connect the input of the DC/DC converter to the power socket join the wire coming from (+) and (-) terminal of the converter to the respective connector of the three pin plug. Then connect the plug to the socket and switch ON the converter. If there is power indicator in the converter then it should light. Then measure the output voltage of the converter. If multimeter shows proper voltage reading then installation of the converter is considered as done correctly.

7.9.6 Connection of the DC/AC Inverter

For connecting the DC/AC inviter to the system, first of all connect the required length of wire to the three pin plug taking into consideration of the polarity of the three pin socket i.e. (+) and (-) terminals. Then connect the other end of the wire to the respective (+) and (-) DC input terminals of the inverter. The inverter main switch and socket switch must be switched OFF before these connections. After finishing the connection, switch ON the socket switch followed by inverter main switch. Measure the AC volt output from the inverter. If the reading shows around 220 V then installation of the inverter is considered as done correctly.

7.10 Installation of solar home system components

The trainees are required to install Solar Home System consisting of

1. Solar module
2. Battery
3. Lamp
4. Charge Controller
5. DC/DC Converter
6. DC/AC Inverter

Review Questions

1. Before connecting wire (joining charge controller to the battery) to the charge controller

    a. Wire should be connected to the battery
    b. Wire should not be connected to the battery
    c. Wire should be connected to the lamp
    d. Wire should be connected to the module

2. While connecting terminal of charge controller with that of the battery

    a. (+) terminal of the charge controller should be connected to the (+) terminal of the battery
    b. (+) terminal of the charge controller should be connected to the (-) terminal of the battery
    c. (-) terminal of the charge controller should be connected to the (+) terminal of the battery
    d. (-) terminal of the charge controller should be connected to the (-) terminal of the battery

3. Petroleum jelly is applied to the terminals of the charge controller

    a. Right
    b. Wrong

4. Switch need to be connected to all types of lamp

    a. Right
    b. Wrong

5. Before joining the junction box to the charge controller following inspection should be done

a. Disconnect wire coming from solar module
b. Disconnect wire coming from lamp
c. Disconnect wire coming from battery
d. Check the wire going to junction box for short

6. If short circuit happens, analog multimeter shows

a. α Ω
b. 100 Ω
c. 0 Ω
d. 300 Ω

7. In Nepal generally solar module is tilted at

a. 10° North
b. 15° North
c. 30° North
d. 60° North

8. Resistance of fuse will have a value of

a. 220 Ohm
b. 50 Ohm
c. 0 Ohm
d. 1000 Ohm

9. Inverter efficiency depends upon

a. Load power (Watt) but not Inverter Efficiency
b. Load Power factor but not Inverter Efficiency
c. Inverter Efficiency but not Load Power factor
d. Both Load power (Watt) and Inverter Efficiency

10. Current flowing through the wire is

a. Increase as cross sectional area of the wire increases
b. Decreases as cross sectional area of the wire increases
c. Increase as length of the wire increases
d. Decreases as maximum allowed voltage drop percentage increases

CHAPTER 8

Repair and Maintenance of Components of Solar Photovoltaic System

Duration: 220 minutes
140 minutes (Practical)

Physical Facilities required: Class room with white board, multi-media projection facility and table with open space.

Materials required:
a) Catalogues of various types of modules, batteries, charge regulators, lamps, DC-DC converters and DC-AC inverters, wire-size tables, PV standards, calculator and reference material.
b) Working and damaged components of SHS, multimeter, hydrometer, clamp meter, electronic tool kit, spare parts and other accessories.

Procedures: The Instructor/s
a) Provides an overview of the repair and maintenance of different components of Solar Home System
b) The trainees test, repair and maintain components of Solar Home System indivually.

Instructor: The Trainer

Reference:
1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP
2. Solar Electricity Technical Training Manual (Level 2), AEPC/ESAP.

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
8.1	Solar Module	Lecture and demonstration	Class room	30 mins.	
8.2	Battery	Lecture and demonstration	Class room	40 mins	
8.3	Charge Controller	Lecture and demonstration	Class room	40 mins	
8.4	Solar Lamp	Lecture and demonstration	Class room	35 mins	
8.5	DC-AC Inverter	Lecture and demonstration	Class room	35 mins	
8.6	DC-DC Converter	Lecture and demonstration	Class room	40 mins	
8.7	Demonstration of various components, their testing and repairing procedures	Lecture and demonstration	Class room	140 mins	

8.1 Solar Module

Solar PV module is considered as damaged if the value of short circuit current (I_{SC}) and open circuit voltage (V_{OC}) deviates too much from the value given in the specification. If this happens, the new module should replace it. During installation of the new module, the above-mentioned parameter should be checked again.

If bypass diode is being used in the module and the terminals of the module shows zero or negligible value of I_{SC} and V_{OC} then bypass diode must have been short-circuited. This can be checked by using simple multimeter. If the bypass diaode is found damaged then replace it with new one and again check I_{SC} and V_{OC} of the new diode for conformity.

If the module is seen broken or cracked then there is no option but to replace it with the new module.

8.2 Battery

Physical Inspection and General maintenance of Battery

During the physical inspection of the battery, clean the dust accumulated over it by clean and dry cloth. Observe if there is any cracked developed around the container of the battery. If there is any crack and the leakage of electrolyte replace the battery.

Battery should be kept in open-air circulated, sun light prevented and children unaccessible smooth level place. It should not be kept covered. As hydrogen gas is generated during charging and discharging process prevent any source of fire near battery such as cigarette smoking, lighting kerosene lamps etc.

Care should be taken while working with battery as it contains sulphuric acid inside it. If acid get spill over the hand wash the hand with water immediately and contact the nearest health post or medical facilty. The acid containing hand should not touch eye. If that happens it might damage the eye and even result blindness. Prevent the children from staying near the battery when adding distilled water to the battery.

The top surface of the battery should be clean and dry. The vent plug of the battery should be left open all the time. The contacting surface of the terminal should be clean by "0" number abrasive paper. Screw connection should be kept coverd by petroleum jelly and vacelline to prevent rusting.

The water level in the battery should be checked every 3 month and distilled water should be added to maintain water level above lower limit level by topping up distilled water up to the upper limit level of all six compartments (cells) of the battery. All the caps of the compartments of the battery should be closed tightly after filling it with distilled water.

The battery should be maintained above 6° C as its electrolyte consisting of solution of sulphuric acid does not work well below that temperature. For the cold places, it is better to keep battery inside the room and wrapt it with warm cloth or rolls of cotton around the battery except top portion of it to maintain the required temperature.

The battery should not be left unused after adding sulphuric acid solution into it. If it is left unused for long time there will be self discharge process going on inside it which will damage the battery permanently. The battery should be charged to full level at least once a month if it is to be left unused for long time.

During operation of the battery, the terminals of the battery may result rusting due to the ambient condition and screw may get loosen. To prevent this vaseline or petroleum jelly should be applied around the terminal connections. If the rusting occur in the terminal connections with the appearance of the white or green amorphous powder, remove the rusting layer with the use of washing soda or warm water to clean them. While cleaning make sure that it doesnot get inside the battery. Apply vaseline or petroleum jelly over the connections.

There will be large current flowned between (+) and (-) termninals of the battery if they are connected or short-circuited. Hence, the two terminals of the battery should not be touched at the same time with bare hands.

Every battery has certain operating life. If its operating life finishes, the battery will charge quickly and discharge very quickly once the load is connected to it. In this condition, the new one should replace the old battery.

Old battery can be sold to the scrapt buyer for recycling. Therefore, the disposable old battery should be kept safe without spilling its inside acid until it is being sold for recycling.

Battery Water and Electrolyte Level observation

The performance of the battery depends also on the purity of the battery water used in the electrolyte of the battery. For the battery water purpose only distilled water, demineralised water or de-ionised water should be used. Tap water or underground water should not be used for the battery water purpse. Technically battery water should consists of Ph value between the range of 6.5 and 7 and conductivity between the range of 2 to 6 micro simen (μS). The battery water storing bottle or container should not contain any dust or contamination.

Funnel should be used over the vent plug while adding battery water to the battery. Lines showing lower level and upper level of the electrolyte are marked ouside the battery container. If the electrolyte level goes below lower level mark, battery water should be added up to the upper level by opening six vent plugs on the top surface of the battery and adding battery water on each of the cell of the battery.

Battery Acid and Specific Gravity Measurement

In Lead acid battery dilute, pure sulphuriuc acid is used as the electrolyte. The purity of the battery acid used inside the battery determines the perfromane and life of the battery. Only battery grade sulphuric acid should be used and use of commercial and technical grade sulphuric acid should be strictly avoided.

The specific gravity of the electrolyte of fully charged battery is 1.250 (at 25° C) or more depending upon the design of the manufacturers. The specific gravity of electrolyte of the new battery lies between 1.240 to 1.260. The state of charge will be about 50% if the specific gravity of the electrolyte is 1.190. If the specific gravity goes below 1.100 the battery might be in damaged condition.

The battery are generally supplied by manufactuere in dry discharged condition. For the operation of the battery, battery grade sulphuric acid having specific gravity of 1.240 to 1.260 should be used.

The specific gravity also depends upon the temperature of the electrolyte. Generally, the value of specific gravity is given for the electrolyte at 25° C. For every rise in 10° C of electrolyte, the specific gravity value should be increased by 0.007 for the monitoring purpose.

The specific gravity is measured by using hydrometer. It consists of upper rubber ball, middle glass tube with measuring facility and lower small plastic pipe as shown in the figure 8.2.1.

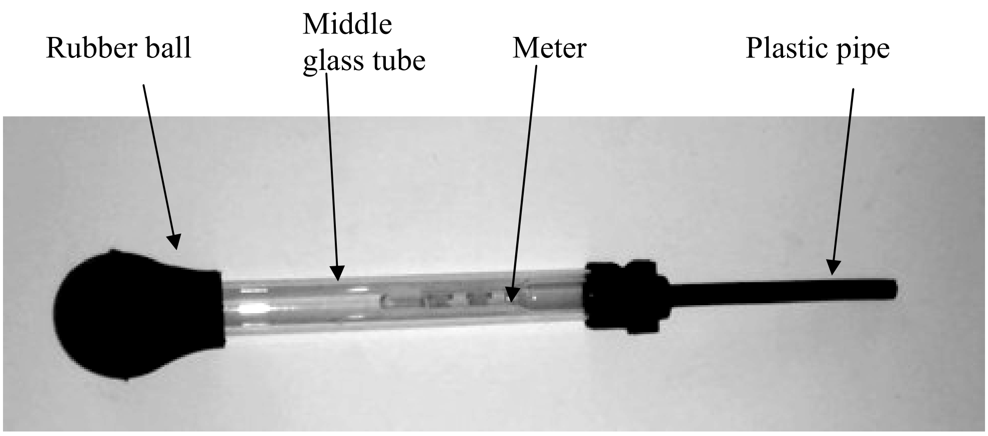


Figure 8.2.1 Hydrometer

For measuring specific gravity of electrolyte first press the rubber ball of the hydrometer and dip its plastic pipe into one of the battery cell through vent plug hole. Slowly release the pressure on the ball so that the electrolyte of the cell is sucked upward until the middle glass tube of the hydrometer get filled with it. Release the pressure totally upon the rubber ball and take the reading of the specific gravity by observing the value of the marking level in the meter that is coincident with the upper level of the liquid filled inside the tube. The figure showing the measurement from hydrometer is shown in the figure 8.2.2.

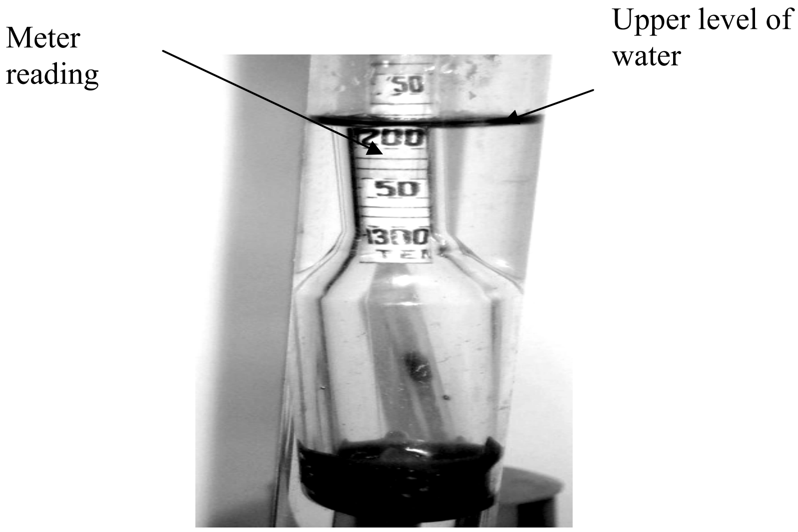


Figure 8.2.2 Measurement of specific gravity by Hydrometer

After taking the reading of the specific gravity, the entire electrolyte sucked upward during measurement should be sent back to the respective cell compartment of the battery. Single measurement of specific gravity might contain error so several measurements should be taken and the value that repeats the most should be considered.

Battery Voltage and its Measurement

a) Open Circuit Voltage

Voltage between two terminals of the battery when it is not receving any energy from the module and when it is not supplying any energy to the load is called open circuit voltage (O.C.V.). Approximately one cell of battery produces O.C.V. = Specific Gravity + 0.84. Battery cell having sopecific gravity of 1.250 would produce O.V.C. of 1.250 + 0.84 = 2.09 volt. A 12V battery contains 6 such cells and the O.C.V. for the fully charged battery becomes 2.09 X 6 = 12.54V.

b) Terminal or Load Voltage

Voltage observed between (+) and (-) terminals of battery during charging and discharging process is called terminal voltage, the value of which is always less than O.C.V.

c) End Point Voltage

The minimum allowable voltage during discharging process of battery is called end voltage (E.P.V.). For 12V standard Lead acid battery, E.P.V. is taken as between 10V to 10.5V.

Generally, in the ordinary battery when there is no charging process and no load connected to it, if O.C.V. is 12.6 there will be 90% energy stored inside the battery. If the battery O.C.V. is 11.5V, the stored energy will be less than 50% and there will be chance of being damaged for swallow cycle battery. The battery will be considered dead if the O.C.V. reaches below 11V.

The voltage is measured by using analog or digital multimeter. For measuring voltage of the battery multimeter should be set at 50V range. Then the red (+) probe of the meter should be conneted to the (+) terminal of the battery and black (-) probe of the meter should be conneted to the (-) terminal of the battery. Load should not be connected during measurement of O.C.V. but load should be connected and operated during the measurement of terminal voltage.

Hard Sulphation

When battery gets discharged fine grain of crystalline $PbSO_4$ get deposited over the positive and negative plates of the battery cells. But during charging process these crystalline grain get dissolved and convert into the active material of the plates. But if the battery is left for long time in the discharged or partily charged condition, the $PbSO_4$ form will convert into the permanent hard crystal covering the active material of the plates. These hard sulphate deposites act as the insulator for electrfical charg and thus increases the battery internal resistance. This will prohibit the battery from charging process and during discharging process no energy will be released. This state of the battery is called dead state.

If the battery is going through hard sulplation following indications will be observed,

a) Lower specific gravity of the electrolyte
b) Lower voltage of the battey cell
c) Higher temperature of the electrolyte during charging and discharging process
d) White grain are seen over the battery plates

Hard sulphation also result when over charging is done to the battery. If the regular operation of the battery is interrupted due to the formation of hard sulphation then battery should be replaced by the new one.

8.3 Charge Controller

Charge controller is considered as damaged or in not in normal condition if the following conditions are observed,

a) Unability of solar module to charge battery
b) Battery do not reach over-charge protection state

c) No voltage in the load connector of the charge controller
d) Lighting of the bulb even when battery is in under charge state

a) Unability of solar module to charge battery

- Check the voltage of the solar module at the charge controller connector.
- If the there is no voltage check for the loose connection at the connector or check by-pass diode of the solar module.
- Examine RFC Choke
- Check the reverse protection diode if it is open
- Examine the short circuit of the source and drain terminal of the charging circuit MOSFET
- Check the voltage (as per manufacture specification or not) of the control circuit used in the charging circuit
- Examine whether the track from the charging circuit to the PCB is open or not
- Check MOSFET

Replace the components if it is found not functioning properly and check the operation of charge controller.

b) Battery do not reach over-charge protection state

- Check the voltage of the drain and source gate of the MOSFET used in the overcharge protection circuit using multimeter. If found not functional replace it with new MOSFET.
- Examine the voltage of the ocercharge circuit as per given in the circuit
- If the battery is old or dead, then also charge controller would not go to the over charge protection mode during the charging of the battery from the solar module.

c) No voltage in the load connector of the charge controller

- No load voltage occurs if the fuse went off
- If track is open in PCB load voltage may not occur
- If Load MOSFET is open then also load voltage may not occur. Check it by using multimeter
- Examine voltage as per given in the load circuit. If not found as per given check for the components of the circuit
- Check load ON/OFF switch

The circuit diagrams for Series PWM, Shunt PWM, Series ON/OFF, Shunt ON/OFF type charge controllers are given in the figure 8.3.1. to 8.3.4. The possible problems and remedies for them are given in the table 8.3.1.

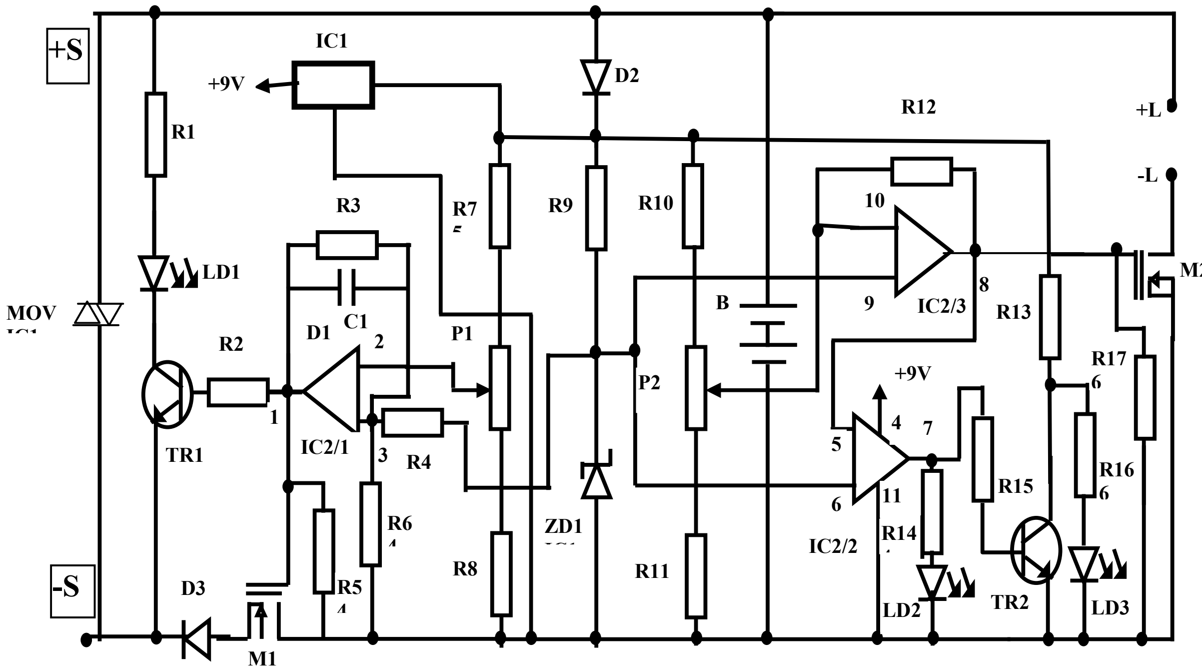


Figure 8.3.1. Circuit diagram for Series PWM type charge controller

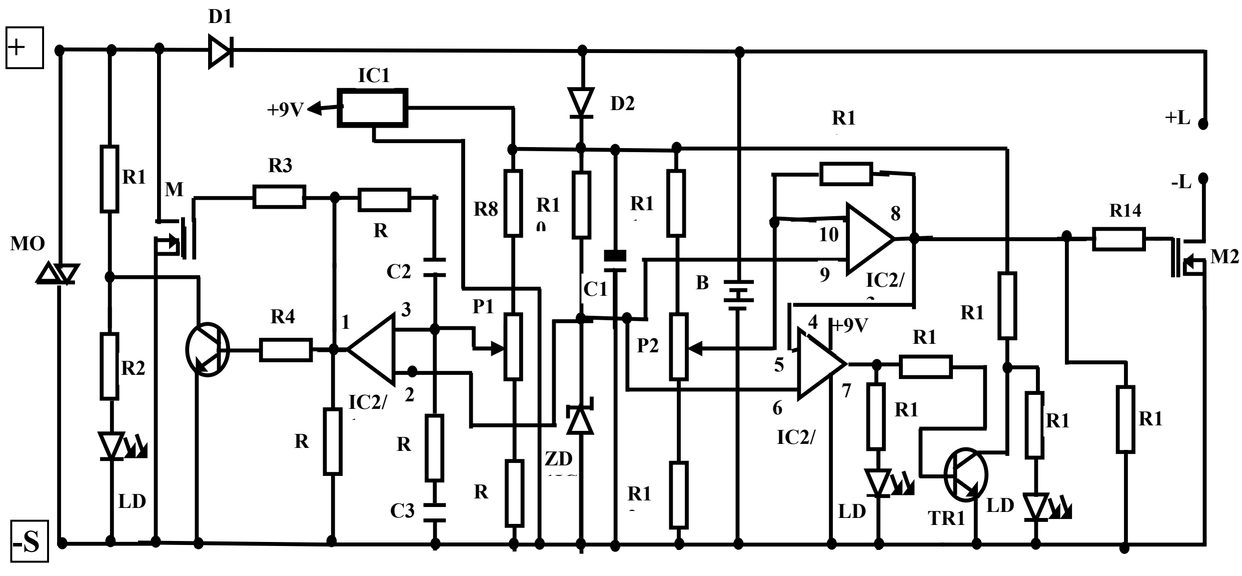


Figure 8.3.2. Circuit diagram for Shunt PWM type charge controller

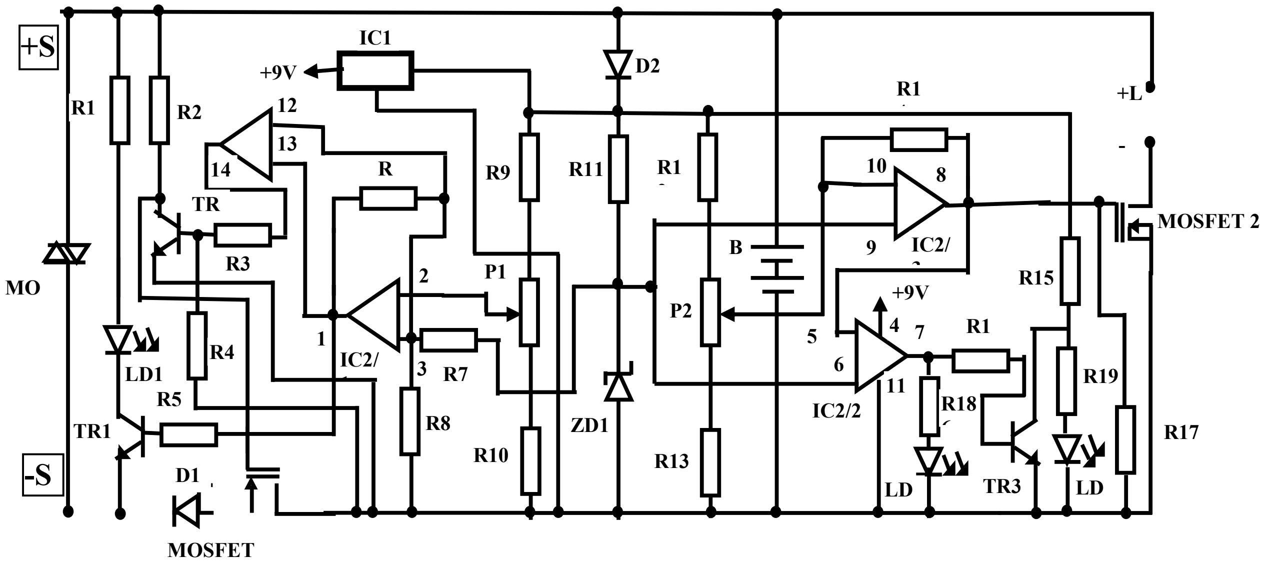


Figure 8.3.3. Circuit diagram for Series ON/OFF type charge controller

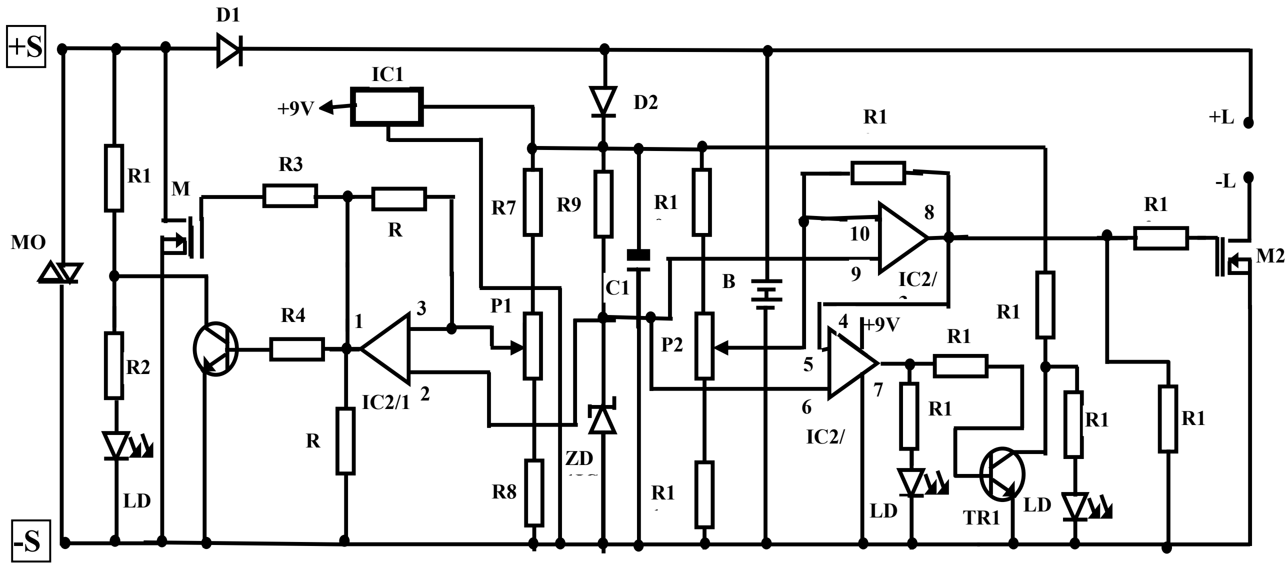


Figure 8.3.4. Circuit diagram for Shunt ON/OFF type charge controller

Table 8.3.1. Possible problems and remedies for the Series PWM, Shunt PWM, Series ON/OFF, Shunt ON/OFF type charge controllers

A. Series PWM Controller

S/N	Problems	Causes	Remedies
1	Solar module does not charge battery	1. Damage of MOSFET Q1 2. Short circuit of MOV 3. Track open 4. Loose Connector 5. Damage of solar module bypass diode 6. Damage of the blocking diode 7. Hard sulphation in the battery 8. Damage of solar module	1. Check MOSFET Q1 2. Check MOV 3. Examine if track is open or not 4. Check connector if loose or not 5. Examine solar module bypass diode 6. Check blocking diode 7. Measure battery voltage and specific gravity of electrolyte 8. Check solar module
2	No voltage in the load terminal of charge controller	1. Burnt down of fuse 2. Damage of MOSFET Q2 3. Track open 4. Open circuit of any component 5. Damaged/Burnt down of IC 6. Damage of switch used in charge controller 7. damage of diode	1. Check fuse 2. Check MOSFET Q2 3. Examine if track is open or not 4. Check for open circuit of MOSFET Q2 components (LVD section circuit) 5. Check IC 6. Examine switch used in charge controller 7. Check diode
3	Low Voltage Disconnection not activated or light lamps even if battery voltage drop below 10.8V	1. Damage of MOSFET Q2 2. Incorrect setting of potentiometer set point 3. Damage of DB diode	1. Check MOSFET Q2 2. Adjust the setting knob of potentiometer. If it does not work change charge controller 3. Check DB diode
4	Red indicator lights even at Low Voltage Disconnection	1. Resistor connected to LED3 being open 2. Track open 3. Damage of DB diode 4. Damege of LED3	1. Check if Resistor connected LED3 is open 2. Examine if Track is open or not 3. Check DB diode 4. Check LED3 and replace if not functioning

S/N	Problems	Causes	Remedies
5	High Voltage Disconnection not activated even if battery voltage rises up to 14 - 14.8V or solar module charging battery even above set point	1. Damage of MOSFET Q1 2. Incorrect setting of potentiometer set point 3. Any component of High Voltage Disconnection (HVD) being open 4. Track open 5. Damaged/Burnt down IC	1. Check MOSFET Q1 2. Adjust the setting knob of potentiometer. If it does not work change the charge controller 3. Check if component of High Voltage Disconnection (HVD) is open 4. Examine if track is open 5. Check IC
6	Yellow or green indicator not lights even if Battery is charging	1. Resistor connected to LED may be open 2. Track open 3. Damaged/Burnt down Transistor Q3 4. Damaged LED	1. Check if Resistor connected to LED is open 2. Examine if track is open or not 3. Check Transistor Q3 4. Check LED and replace if found damaged

B. Shunt PWM Controller

S/N	Problems	Causes	Remedies
1	Solar module does not charge battery	1. Damage of MOSFET T1 2. Short circuit of MOV 3. Track open 4. Loose Connector 5. Damage of solar module bypass diode 6. Damage of the blocking diode 7. Hard sulphation in the battery 8. Damage of solar module	1. Check MOSFET T1 2. Check MOV 3. Examine if track is open or not 4. Check connector if loose or not 5. Examine solar module bypass diode 6. Check blocking diode 7. Measure battery voltage and specific gravity of electrolyte 8. Check solar module
2	No voltage in the load terminal of charge controller	1. Burnt down of fuse 2. Damage of MOSFET Q2 3. Track open 4. Open circuit of any component 5. Damaged/Burnt down of IC 6. Damage of switch used in	1. Check fuse 2. Check MOSFET Q2 3. Examine if track is open or not 4. Check for open circuit of MOSFET Q2 components (LVD section circuit) 5. Check IC

S/N	Problems	Causes	Remedies
		charge controller 7. damage of diode	6. Examine switch used in charge controller 7. Check diode
3	Low Voltage Disconnection not activated or light lamps even if battery voltage drop below 10.8V	1. Damage of MOSFET Q2 2. Incorrect setting of potentiometer set point 3. Damage of DB diode	1. Check MOSFET Q2 2. Adjust the setting knob of potentiometer. If it does not work change charge controller 3. Check DB diode
4	Red indicator lights even at Low Voltage Disconnection	1. Resistor connected to LED3 being open 2. Track open 3. Damege of LED3	1. Check if Resistor connected LED3 is open 2. Examine if track is open or not 3. Check LED3 and replace if not functioning
5	High Voltage Disconnection not activated even if battery voltage rises up to 14 - 14.8V or solar module charging battery even above set point	1. Damage of MOSFET Q1 2. Incorrect setting of potentiometer set point 3. Any component of High Voltage Disconnection (HVD) being open 4. Track open 5. Damaged/Burnt down IC	1. Check MOSFET Q1 2. Adjust the setting knob of potentiometer. If it does not work change the charge controller 3. Check if component of High Voltage Disconnection (HVD) is open 4. Examine if track is open 5. Check IC
6	Yellow or green indicator not lights even if Battery is charging	1. Resistor connected to LED may be open 2. Track open 3. Damaged/Burnt down Transistor Q3 4. Damaged LED	1. Check if Resistor connected to LED is open 2. Examine if Track is open or not 3. Check Transistor Q3 4. Check LED and replace if found damaged

C. Series ON/OFF Controller

S/N	Problems	Causes	Remedies
1	Solar module does	1. Burnt down of fuse	1. Check fuse

S/N	Problems	Causes	Remedies
	not charge battery	2. Damage of MOSFET T1 3. Short circuit of MOV 4. Track open 5. Loose Connector 6. Damage of solar module bypass diode 7. Damage of the blocking diode 8. Hard sulphation in the battery 9. Damage of solar module	2. Check MOSFET T1 3. Check MOV 4. Examine if track is open or not 5. Check connector if loose or not 6. Examine solar module bypass diode 7. Check blocking diode 8. Measure battery voltage and specific gravity of electrolyte 9. Check solar module
2	No voltage in the load terminal of charge controller	1. Burnt down of fuse 2. Damage of MOSFET T2 3. Track open 4. Open circuit of any component 5. Damaged/Burnt down of IC 6. Damage of switch used in charge controller	1. Check fuse 2. Check MOSFET T2 3. Examine if track is open or not 4. Check for open circuit of MOSFET Q2 components (LVD section circuit) 5. Check IC 6. Examine switch used in charge controller
3	Low Voltage Disconnection not activated or light lamps even if battery voltage drop below 10.8V	1. Damage of MOSFET T2 2. Incorrect setting of potentiometer set point	1. Check MOSFET T2 2. Adjust the setting knob of potentiometer. If it does not work change charge controller
4	Red indicator lighting even at Low Voltage Disconnection	1. Resistor connected to LED2 being open 2. Track open 3. Damege of LED2	1. Check if Resistor connected LED2 is open 2. Examine if track is open or not 3. Check LED2 and replace if not functioning
5	High Voltage Disconnection not activated even if battery voltage rises up to 14 -14.8V or solar module charging battery even above set point	1. Damage of MOSFET T1 2. Incorrect setting of potentiometer set point	1. Check MOSFET T1 2. Adjust the setting knob of potentiometer. If it does not work change the charge controller
6	Yellow or green	1. Resistor connected to	1. Check if Resistor connected to

S/N	Problems	Causes	Remedies
	indicator not lights even if Battery is charging	LED1 may be open 2. Track open 3. Damaged LED1	LED1 is open 2. Examine if track is open or not 3. Check LED1 and replace if found damaged

D. Shunt ON/OFF Controller

S/N	Problems	Causes	Remedies
1	Solar module does not charge battery	1. Burnt down of fuse 2. Damage of MOSFET T1 3. Short circuit of MOV 4. Track open 5. Loose Connector 6. Damage of solar module bypass diode 7. Damage of the blocking diode 8. Hard sulphation in the battery 9. Damage of solar module	1. Check fuse 2. Check MOSFET T1 3. Check MOV 4. Examine if track is open or not 5. Check connector if loose or not 6. Examine solar module bypass diode 7. Check blocking diode 8. Measure battery voltage and specific gravity of electrolyte 9. Check solar module
2	No voltage in the load terminal of charge controller	1. Burnt down of fuse 2. Damage of MOSFET T3 3. Track open 4. Open circuit of any component 5. Damaged/Burnt down of IC 6. Damage of switch used in charge controller	1. Check fuse 2. Check MOSFET T3 3. Examine if track is open or not 4. Check for open circuit of MOSFET Q2 components (LVD section circuit) 5. Check IC 6. Examine switch used in charge controller
3	Low Voltage Disconnection not activated or lights lamp even if battery voltage drop below 10.8V	1. Damage of MOSFET T3 2. Incorrect setting of potentiometer set point 3. Damage of transistor T2	1. Check MOSFET T3 2. Adjust the setting knob of potentiometer. If it does not work change charge controller 3. Ckeck transistor T2
4	Red indicator lights	1. Resistor connected to LED2	1. Check if Resistor

S/N	Problems	Causes	Remedies
	even at Low Voltage Disconnection	being open 2. Track open 3. Damege of LED2	connected LED2 is open 2. Examine if track is open or not 3. Check LED2 and replace if not functioning
5	High Voltage Disconnection not activated even if battery voltage rises up to 14 -14.8V or solar module charging battery even above set point	1. Damage of MOSFET T1 2. Incorrect setting of potentiometer set point 3. Any component of High Voltage Disconnection (HVD) being open 4. Track open 5. Damaged/Burnt down IC	1. Check MOSFET T1 2. Adjust the setting knob of potentiometer. If it does not work change the charge controller 3. Check if component of High Voltage Disconnection (HVD) is open 4. Examine if Track is open 5. Check IC
6	Yellow or green indicator not light even if Battery is charging	1. Resistor connected to LED1 may be open 2. Track open 3. Damaged LED1	1. Check if Resistor connected to LED1 is open 2. Examine if Track is open or not 3. Check LED1 and replace if found damaged

8.4 Solar Lamp

The fault of the lamp may be due to the following reasons.

a) Damage of the switch
b) Unavailability of DC volt to the lamp from the junction box
c) Burnt down of fuse
d) Burnt down of lamp
e) Damage of the ballast

There fore before checking the ballast, checking for all possible reasons from (a) to (d) should be followed. If these checking show positive result then only ballast should be checked.

Any component of the ballast should be removed from PCB before replacing it with new one. Multimeter should be used to check the taken out component of the ballast and if found damaged it should be replaced by new one.

i. Checking of Choke or Fuse

Set the multimeter to Ohm-meter range. Continuity in connection should be shown when connectiong probes of the multimeter with two terminals/wires of the choke or fuse. If there is continuity in connection then meter shows 0 Ohm or buzzer will ring.

ii. Checking of Diode

While measuring diode resistance from Ohm-meter the value of resistance should be 500 Ohm to 600 Ohm from one side and very high resistance when connection is reversed.

iii. Checking of Resistor

The value of the resistance measured by Ohm-meter should be as per the color coding of resistance.

iv. Checking of Transformer

The measured resistance of the coils of the transformer by Ohm-meter should be as per the windings of the coil.

v. Checking of Transistor

Forward and reverse resistance of base-collector, base-emmiter and collector-emitter of transistor should be measured for checking transistor. The value shown by multimeter during checking transistor should be as following.

Example: for NPN Transistor

Forward resistance (base-collector) -	low Ohm
Forward resistance (base-emitter) -	low Ohm
Collector – emitter resistance -	high Ohm
Reverse resistance (base – collector)-	high Ohm
Reverse resistance (base – emitter)-	high Ohm
Reverse collector – emitter resistance-	high Ohm

The circuit diagram for the ballast with pre-heating and ballast without pre-heating is given in the figure 8.4.1. to 8.4.2.

The possible problems and its solutions for ballast of the lamp is given in the Table 8.4.1.

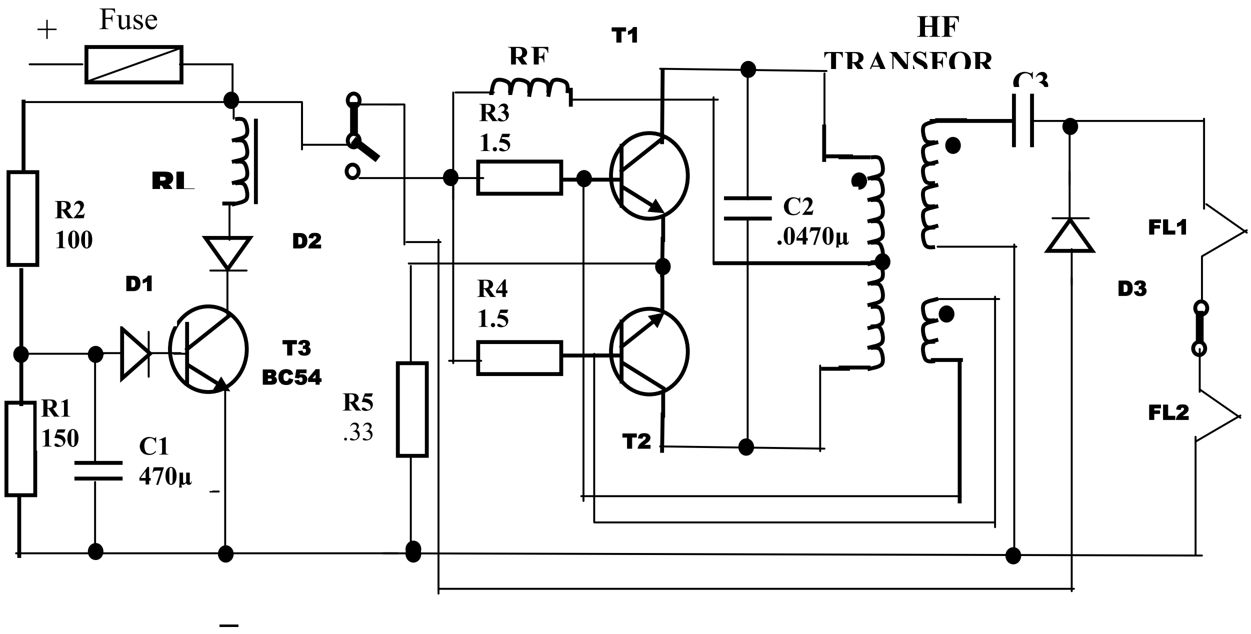


Figure 8.4.1 Circuit diagram for the ballast with pre-heating

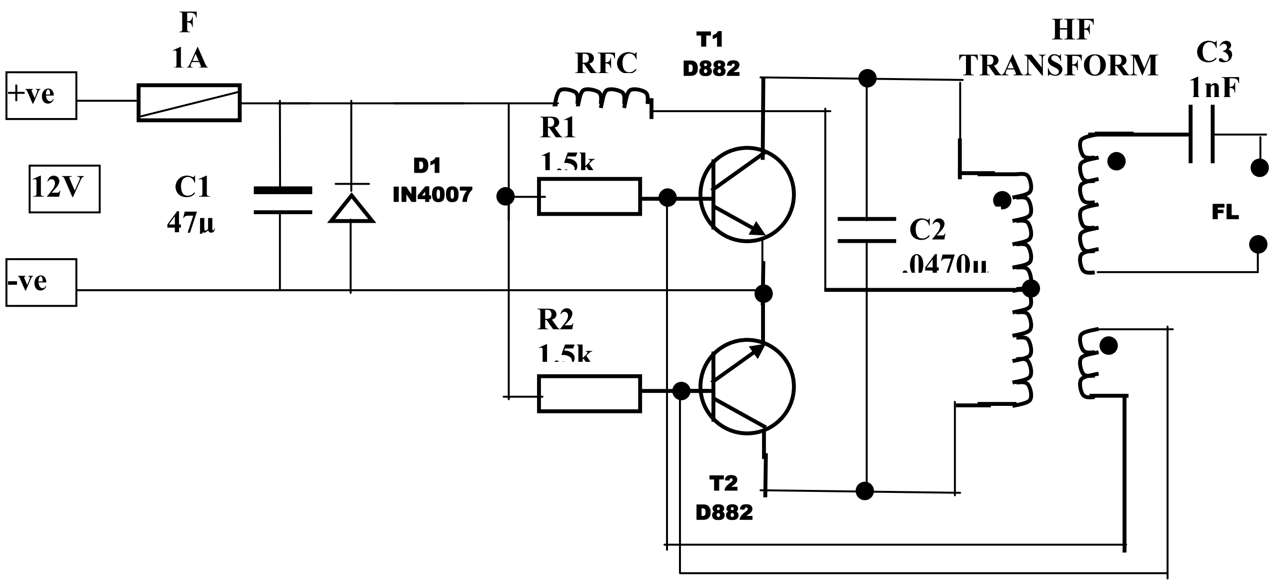


Figure 8.4.2 Circuit diagram for the ballast without pre-heating

Table 8.4.1 Possible problems and its solutions for ballast of the lamp

A. Ballast with pre-heating

S/N	Faults	Causes	Remedies
1	Lamp not lights / illuminate	Battery may be deep discharge	Measure battery voltage
		No input voltage in lamp	Check input voltage. Input voltage valushould be 10.8 to 12V.
		Damage of charge controller	Check charge controller
		Pins of the lamp may not be touching holder properly	Rotate the position of the lamp
		Damage/Burnt down of transistor of ballast	Check transistor and if found damaged replace it
		Fuse may be burnt down/ damaged	Check fuse and if found burnt down/ damaged replace it
		Damage of transformer of ballast	Check transformer for continuity and if found damaged replace it
2	Continuous fuse burnt down	Short circuit of diode D1	Check diode D1 and if found short replace it
		Short circuit of transitors	Check transistors and if found short replace them
		Primary Winding of transformer may be burnt down/ damaged	Check Primary Winding of transformer
3	No Pre-heat occurs	Damage of Relay	Check Relay and measure voltage of the positive pin. It should be about 12V. If pin voltage is OK then check resistor R5 and C4. Replace them if found burnt down/ damaged

B. Ballast without pre-heating

S/N	Faults	Causes	Remedies
1	Lamp not light/illuminate	Battery may be deep discharge	Measure battery voltage
		No input voltage in lamp	Check input voltage. Input voltage valushould be 10.8 to 12V.
		Damage of charge controller	Check charge controller
		Pins of the lamp may not be touching holder properly	Rotate the position of the lamp
		Damage/Burnt down of transistor of ballast	Check transistor and if found damaged replace it
		Fuse may be burnt down/ damaged	Check fuse and if found burnt down/ damaged replace it
		Damage of transformer of ballast	Check transformer for continuity and if found damaged replace it
2	Continuous fuse burnt down	Short circuit of diode D1	Check diode D1 and if found short replace it
		Short circuit of transitors	Check transistors and if found short replace them
		Primary Winding of transformer may be burnt down/ damaged	Check Primary Winding of transformer

8.5 DC/AC Inverter

DC/AC inverter should be examined as per procedures mentioned below,

- Measure at output for 220V AC
- Measure at input for 12V DC
- Check Fuse
- If input shows 12V DC and fuse seems OK but output doesnot give 220V AC , then inverter is considered as damaged and should be send to suppliers for further repairing.

8.6 DC/DC Converter

Following are the possible problems in DC/DC Converter

a) No DC output from Converter

Check the ON/OFF switch. If found OK check the voltage at different points of the components as per circuit diagram given by manufacturer. If measurement shows deviation from the standard value, replace the damaged component by the same number/rating component.

b) No matching output voltage with respect to the selector switch

Check the switch by using multimeter. If found faulty replace it with new one.

The circuit diagram for the DC/DC Converter is given in the figure 8.6.1. The possible problems and its solutions for DC/DC Converter is given in the Table 8.6.1.

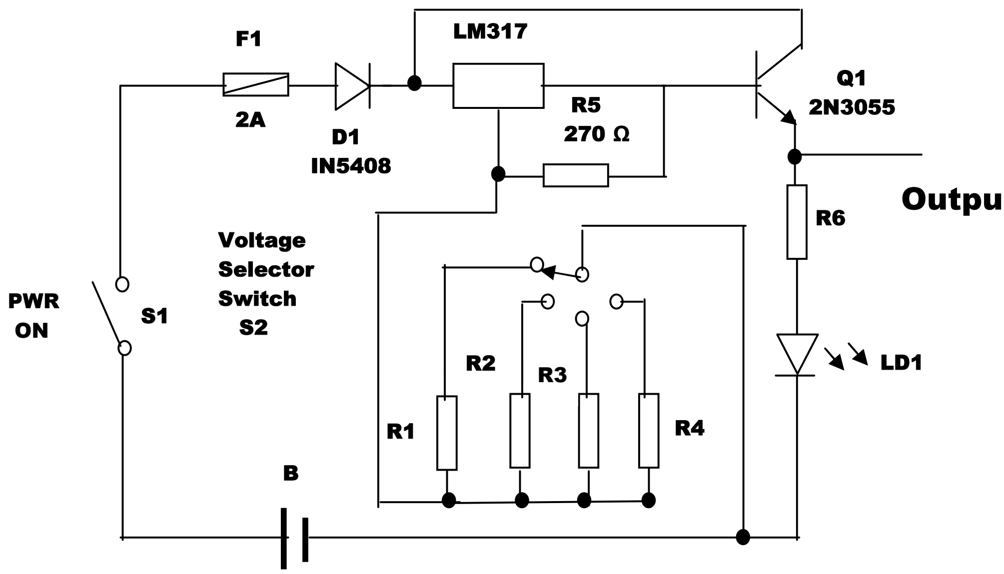


Figure 8.6.1 Circuit diagram for the DC/DC Converter

Table 8.6.1 The possible problems and its solutions for DC/DC Converter

S/N	Faults	Remedies
1	No output voltage in any position of selector swtich	Check input voltage and it should be around 12V. If input voltage is OK check IC LM317
2	No voltage observed in all positions of selector swtich	If all position of selector switch shows zero output voltage and selector switch connection seems OK then IC should be replaced
3	Some positions of the selector switch shows voltage and some positions does not shows voltage	Check resistance of the positions of the selector switch that does not shows voltage. If resistance shows open circuit then change the resistance. If resistance is OK then check selector switch.

8.7 Demonstration of various components, their testing and repairing procedures

The demonstration class shall be conducted involving demonstration of testing and repairing procedures for

1. Solar module
2. Battery
3. Lamp
4. Charge Controller
5. DC/AC Inverter
6. DC/DC Converter

Review Questions

1. The voltage of the discharged battery is about

   a. 14 V
   b. 18 – 21 V
   c. 11 V
   d. 12.6 V

2. In Lead Acid battery the reason for hard sulphation is due to

   a. Over charging
   b. Over Discharging
   c. Charging up to 12.6V
   d. Discharging up to 11V

3. If all the lamps does not illuminate, the reason can be due to

   a. Burnt down of bulb
   b. Damaged charge controller
   c. Damaged DC/DC converter
   d. Damaged DC/AC Inverter

4. If blocking diode inside the charge controller becomes open circuit

   a. No lamp will illuminate
   b. Battery will not be charged
   c. Will not charge battery at night
   d. Over charge of battery will occur

5. If one of the lamp of SHS doesnot light, first of all

   a. Replace the lamp and check
   b. Repair charge controller
   c. Repair the ballast
   d. Add distilled water to the battery

6. In the damaged transistor

   a. Both side resistance of base-collector will be high
   b. Both side resistance of base-collector will be low
   c. Both side resistance of emitter- collector will be high
   d. Both side resistance of emitter-collector will be low

7. Resistance of fuse will have a value of

   a. 220 Ohm
   b. 50 Ohm
   c. 0 Ohm
   d. 1000 Ohm

8. If IC inside charge controller damaged then

   a. Replace with any IC
   b. Replace IC with transistor
   c. Repair IC and connect it
   d. Replace IC of same number only

9. Output voltage of the DC/AC inveter is

   a. 150 V
   b. 200 V
   c. 220 V
   d. 12 V

10. If module is cracked

   a. Repair the module and use it
   b. Use the same module
   c. Replace the module with new one
   d. Replace module base frame

CHAPTER 9

Design Aspects of large Solar Photovoltaic Systems (non-pumping application)

Duration: 360 minutes
120 minutes (Field Visit)

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required: Catalogues of various types of modules, batteries, charge regulators, lamps, DC-DC converters and DC-AC inverters, wire-size tables, PV standards, calculator and reference material.

Procedures:

a) The instructor provides an overview of the practices and procedures of designing a complete solar PV system for non-pumping applications.
b) At the end of the Chapter, visit to large non-pumping solar PV installation site is arranged.

Instructor: The Trainer

Reference:

1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP

Lesson Plan

Sub-chapter	**Lesson details**	**Teaching Methodology**	**Facilities required**	**Duration**	**Remarks**
6.1	Load calculations	Lecture and numerical examples and exercise	Class room	30 mins.	
6.2	Sizing of Module /Array	Lecture and numerical examples and exercise	Class room	30 mins	
6.3	Sizing of Storage Battery	Lecture and numerical examples and exercise	Class room	30 mins	
6.4	Sizing of Charge Controller	Lecture and numerical examples and exercise	Class room	30 mins	
6.5	Sizing of Wire/ Cable	Lecture and numerical examples and exercise	Class room	60 mins	
6.6	Sizing of Inverter	Lecture and numerical examples and exercise	Class room	30 mins	
6.7	Sizing of DC-DC Converter	Lecture and numerical examples and exercise	Class room	30 mins	
6.8	Installation Procedures, Safety and Protection	Lecture and numerical examples and exercise	Class room	120 mins	

9.1 Load Calculation

The design of a solar PV system begins with the calculation of energy consumed by the installed load in one day. Inaccurate calculation of the load may lead to system failure or high loss of load probability. Generally, people want more electricity, but there is always a tradeoff between what people want and what they actually are willing to pay for. There could be two approaches in calculating load:

- The fund available is fixed, and the load size is determined based on available fund;
- The fund is not a problem, and the load is determined based on user's requirement.

The first step in load calculation is to prepare a table of daily consumption of electrical energy by various appliances to be powered by the solar PV. By load we will refer to the energy consumed by particular appliances per day. There are few concerns that the designers need to check before preparing the load table.

A. Accurate load knowledge – The entire solar PV system design will be based on the size of the load. If the information is inaccurate, the initial cost will be too high or the battery and array/module could be too small and the system will eventually fail. It is therefore essential that time be taken to look carefully at the load requirements and the expected usage pattern. Using literature values for load consumption is common, but it is more accurate to have the load demand measured to be sure. Often nominal numbers are presented in literature, and a particular piece of equipment may require more or less power than stated. If an existing application is being retrofitted with a PV power system, it is very important to not just look at the old generator capacity and try to recreate it with PV. Very often an oversized diesel generator was installed, perhaps because that size was used elsewhere or to allow for future growth. A PV power system can be designed to accurately match the current load requirement without limiting the ability to expand in the future to meet grater demand. The load profile throughout the year must be accurately determined. Any seasonal variation might influence the choice of tilt angle or battery size for autonomy. The "duty cycle" or hours of operation for intermittent loads must be estimated carefully. In the case of telecommunications equipment, not only the hours of transmitting but also the hours of standby or quiescent operation need to be included in the load calculations.

B. Load efficiency – Improving load efficiency is the quickest way to reduce PV power system cost. A more efficient load device may even be slightly more expensive than an existing or conventional load device (for example CFL against incandescent lamps).

C. Load profile throughout the year – An average value (daily, weekly, monthly or yearly average) for the load is useful for rough system sizing, but seasonal variation of the load throughout the year will influence the choice of tilt angle for the array and the final array and battery size. The insolation on a flat surface varies greatly, with the least during the winter and the greatest during the summer. Now if the load demand is small in winter and large in summer, as with air cooling loads or refrigerators or water pumping for irrigation as well as drinking purpose, then tilting the array in optimum angle for summer days will give an insolation profile that best matches the load profile. If the load is relatively constant every month of the year then a different tilt angle is better. Tilting the array up increases the insolation intercepted during the winter months and sacrifices some during the summer months, with a resulting profile that is more constant throughout the year to better match the requirements of a constant load.

D. AC or DC – As far as possible DC loads should be preferred over AC loads to minimize the cost and avoid use of inverters. Use of inverters add the cost, reduces system reliability and introduce power loss.

E. Apparent and real power consideration – For sizing purpose, the real power in watts consumed in the load is the value needed. For wiring design and inverter choice, the apparent power will be important because the current that will be flowing in the wires into a heavily inductive load will be greater than what would be calculated by just dividing watts by volts. Also the inverter must be chosen so that it can handle the expected apparent power (or the power factor) of the loads.

The load (or the energy consumed) is generally expressed in Watt-hours (Wh). But for more accurate sizing of the array and battery, sometimes the load is expressed in Amepre-hours (Ah). If Wh is known, Ah can be calculated as (formula 9.1.1):

$$Ah = Wh / \text{system voltage} \qquad (9.1.1)$$

For example if a 12V DC operated 10 Watt lamp is turned on for 5 hours, then the total load is:

Wh = 10 W x 5 hours = 50 Wh.
This value expressed in Ah would be 50/12 = 4.17 Ah.

Now if a color television with 60 W power consumption is operated from 220 V AC for 5 hours, then the Wh value would be 60 W x 5 hours = 300 Wh and in Ah it would be 300/220 = 1.36 Ah. It seems that Ah value of 10 W lamp is much more higher than that of a 60 W color television. It is so because of the system voltage. Therefore whenever the load is expressed in Ah, the system voltage has to be spelled out e.g. 4.17 Ah @12 V or 1.36 Ah @220 V. To avoid confusion, it is better to express Ah of the all loads in a single voltage of the PV system (12, 24, 48 or 96 etc.). In the above example of color television, if we calculate the Ah @ 12 V, it would be 300 Wh/12V= 25 Ah. This value now is far greater than the Ah value of 10 W lamps.

The Load Table

The next step of load calculation is to prepare load tables for AC and DC loads. The suggested load tables (tables 9.1.1 and 9.1.2) are shown below.

Table 9.1.1 Load table for AC loads

A	B	C	D	E
AC device or appliance (i)	Device Watts	Hours of daily use	Days of use per week	Average Wh per day
i =1 to N, where N is the total number of devices				
(1) Total average AC Wh per day				

Mathematically the results of the above table can be expressed as:

$$\text{Total average AC Wh per day } (W_1) = \{\sum (B \times C \times D)\}/7 \qquad (9.1.2)$$

The Wh calculated using (9.1.2) has to be supplied from the DC source via inverter. Therefore the DC equivalent Wh required to generate total average AC Wh would be:

$$\text{DC equivalent Wh per day } (W_2) = W_1 / \text{efficiency of the inverter}$$
$$\text{(in decimal expression i.e. 0.9 for 90\%)} \qquad (9.1.3)$$

The load table for DC device and appliance can be calculated in similar way as done with AC load.

Table 9.1.2 Load table for DC loads

A	B	C	D	E
DC device or appliance (i)	Device Watts	Hours of daily use	Days of use per week	Average Wh per day
i =1 to N, where N is the total number of devices				
(2) Total average DC Wh per day				

The same mathematical expression (9.1.2) will be used to calculate total average DC Wh per day (W_3).

Finally the total Wh required to operate all the AC and DC loads (W_4) will be equal to:

$$W_4 = W_2 + W_3 \qquad (9.1.4)$$

The total daily average load in Ah (A) can be calculated by dividing W_4 by the system voltage:

$$A = W4/\text{ system voltage} \qquad (9.1.5)$$

The above procedure of preparing the load table is best suited if the load is uniform throughout the year. If there are loads that are seasonal in nature, then the load table has to be prepared for each month of the year.

Example 9.1.1

Followings are the details of the load to be used in a remote small Hospital powered by solar PV. Calculate the total average load for summer and winter.

s/n	Description of load	Power consump-tion (W)	Opera-ting voltage (V)	Nos.	Daily operating hours (H)	Opera-ting season	Remarks
1	Lamps	10	24	10	12	all	
2	Halogen lamp	200	24	3	3	all	
3	Vaccine refrigerator	480* (Wh)	24	1	24	all	*- total energy consumpti on in 24 hours
4	Fan	20 W	24	5	10	During six summer months only	
5	Color television	40	220 V AC	1	3	all	

In the above load profile items 1-4 are operated from 24 V DC and item 5 requires an inverter to produce 220 V AC. Moreover the fans are used only for six summer months.

Using formula 6.1.2 we can calculate total average AC Wh (W_1) per day:

W_1 = (40 x 3 x 7)/7 = 120 Wh @ 200 V AC

DC equivalent Wh for this AC load (formula 6.1.3) is:

W_2 = 120 / 0.9 (inverter efficiency) = 133.3 Wh, say 140 Wh.

Now let us calculate the total average DC Wh load (except the fan load) using the formula 6.1.2 again (here we assume that all the loads are used 7 days a week):

W_3 = (10 x 10 x 12) + (200 x 3 x 3) + (480) = 1200 + 1800 + 480 = 3480 Wh

The fan load is:

W_3 (fan) = 20 x 5 x 10 = 1000 Wh

Therefore the total average daily loads of the hospital for winter months (when fans are not in use) and summer months (when fans are in use) are:

W_4 (winter) = W_2 + W_3 = 140 + 3480 = 3620 Wh

W_4 (summer) = W_2 + W_3 + W_3 (fan) = 140 + 3480 + 1000 = 4620 Wh.

Since all the DC loads are operated from 24 V DC, we can take this value as the system voltage for DC side. An inverter with 24 V DC as an input need to be selected for the operation of the television set.

Finally the total average daily load in Ah would be (formula 6.1.5):

A (winter) = 3620/24 = 150.8 Ah

A (summer) = 4620/24 = 192.5 Ah.

Maximum Load Current

The knowledge of the maximum current ($I_{max\ load}$) drawn by all loads when operated simultaneously is important while selecting the charge regulators. The $I_{max\ load}$ is the sum of currents drawn by all the loads. While calculating $I_{max\ load}$, care should be taken in determining the current drawn by the loads like telecommunication equipment, fax machines, printers, photocopiers etc. These equipment draw significantly high current in one mode (operation) and very low current in other mode (stand-by). While calculating $I_{max\ load}$ the current drawn by these equipment in operation mode should be considered.

Critical and Non-critical Loads

Critical loads like vaccine refrigerators, telecommunications equipment, emergency room lighting, and operation theater lighting etc. need to be operated without interruption. If these are connected through the charge regulator, the LVD of CR may get activated at some point of time and interrupt the supply. To avoid such situation, all the loads considered to be critical are to be connected directly from the battery bypassing the CR.

Nominal System and Array Voltage

While calculating load in Ah, it is very critical to define which voltage was used to convert Wh into Ah. The nominal voltage of a power module (modules that are used for charging 12 V batteries) is taken as 12 V, though it may operate in any voltage range from 0 to Voc. The solar PV system voltage may be different than the nominal module voltage. For example if large AC loads are to be used, the large capacity inverter is required. The nominal DC input voltage for large capacity inverters are no more 12 V, they are rather 48 V or higher. Higher system voltage is selected in order to reduce the size of cable. With higher voltage, the same power can be delivered at lower current. And since the required size of the cable depends upon the magnitude of the current, usually high voltage-low current configuration is used. In this case the module/array voltage should match the system nominal voltage. And all the DC loads are to be selected to operate from the nominal system voltage.

For a small home system 12 V could be selected as the system voltage. The DC input of a low capacity inverter is also 12 V. Therefore there should be no problem in using 12 V DC loads and smaller AC loads operated through the inverter. But if the AC load is large (in the range of few kVA), the input DC voltage required may be even 120 or 240 V DC. In this case the array is wired to produce 120 or 240 V as system voltage. Now there should be no question of using 12 V DC operated appliances in the system under consideration, unless separate module/array is wired to produce a system voltage of 12 V.

9.2 Sizing of Module /Array

The goal of array sizing is to balance the usually opposing goals of maximum reliability and minimum cost. The mechanics of the calculations are quite simple, but the judgment on the part of designer and the user about the efficiency and appropriateness of the loads that make a system cost effective.

The basic information required for array sizing is:

A. Environmental Information: The environmental information required for proper array sizing is Insolation in the given location, ambient temperature extremes, latitude, longitude, module mounting techniques and autonomy days. Usually the insolation is recorded on a horizontal surface. A mathematical model of the movement of the sun must be used to translate the data to what would be incident on a tilted surface. The average daily maximum and minimum temperatures for each month must be known. The maximum temperatures will be needed to predict the loss of voltage by the array and can impact the choice of modules. The minimum temperatures are needed to calculate battery size to prevent freezing. Latitudes and longitudes are needed to identify optimum tilt angle of the array. Finally module-mounting technique (fixed at one angle, adjustable during the year or with a sun tracker) is to be known as it can have a large impact in overall array output and sizing.

B. Load information: Total Wh and Ah consumed per day, any seasonal distribution of load pattern.

C. Other information likes ground cover, permissible voltage loss in cables, load surge etc.

The first step in sizing the array is to determine the estimated design insolation or the peak sun for given locality. For Nepal, the solar radiation data sheet for various parts of the country can be used (see appendix 3). To be in safer side, the minimum insolation (monthly average) should be considered as estimated design insolation. For most part of Nepal a value between 4.5 to 5.5 could be consider safe. The required total array output current can be calculated using the following formula:

$$I_{array} = \text{Total average daily load in Ah @ system voltage} / (\text{peak sun x derating factor x Columbic efficiency}) \quad (9.2.1)$$

Here, the derating factor is generally taken equal to 0.9 and the Columbic efficiency equal to 0.95.

If a single module cannot deliver the current (here we refer to I_{mp} of the module) calculated using formula (6.2.1) above, then number of modules have to be connected in parallel to produce the required level of current. The number of modules to be connected in parallel can be found by using the following formula:

$$N_p = \frac{I_{array}}{I_{mp}} \quad (9.2.2)$$

It is to be noted that Np may not be the whole number. The actual value of Np should always be rounded up to the next highest integer value.

Example 9.2.1

Suppose the daily load requirement is 575 Ah and the peak sun (minimum monthly average) for the locality is 5. The total array current required, as per formula (6.2.1) would be:

I array = 575 / 5 x 0.9 x 0.95 = 134.51 A

Now a module with Imp = 3.1 A is selected to form an array, then the number of modules to be connected in parallel would be:

Np = 134.51 /3.1 = 43.39 rounded to 44.

Now if we consider the peak sun to be 5.5, the number of modules will drop down to 40 only. And if we take the value of peak sun to be 4.5, the number of modules will increase to 49.

As we see from the above example, slight increase or decrease in design insolation value significantly affects the number of modules required to meet the daily load demand. Therefore it will be the responsibility of the designer to consider most optimum and safe value of insolation and the tilt angle to arrive at optimum number of modules required.

The required number of modules is also a function of I_{mp}. Higher the value of I_{mp}, lower will be the number of modules required. But modules with higher I_{mp} cost more. And again, the judgment and market knowledge of the designer will play critical role in optimizing the cost of the array.

The next step is to determine the number of strings of parallel-connected modules to obtain desired system voltage. This number is found by using the following formula:

$$N_s = \text{nominal system voltage / nominal module voltage} \qquad (9.2.3)$$

The total number of modules required to deliver the daily average energy (in Ah) at the system voltage is:

$$N_t = N_p \times N_s \qquad (9.2.4)$$

It is to be noted here again that if sun-tracking system is used, the insolation level could be greatly increased (by 30% in average). By increasing the insolation level, the number of modules required is decreased. Moreover, the ground reflectivity also plays not less significant role in the availability of solar radiation in the inclined surface. However the effect of reflection from the ground (called 'Albedo effect') usually been considered while calculating insolation in inclined surface.

9.3 Sizing of Storage Battery

Battery system sizing and selection criteria involve many decisions and trade-offs. Choosing the right battery for a particular PV application depends upon many factors. While no specific battery is appropriate for all PV applications some common sense and a careful review of the battery literature with respect to the particular application requirements will help the system designer to greatly narrow down his choice. The following parameters summarize some of the considerations in battery selection and design.

- Type of system and mode of operation
- Size and weight
- Battery autonomy
- Max. allowable DOD
- Daily DOD requirements
- Temperature and environmental conditions
- Cycle life and calendar life
- Reputation of the manufacturer
- Sealed or unsealed
- Self-discharge rate
- Disposal regulations
- Maximum cell capacity
- Charging characteristics
- Gassing characteristics
- Susceptibility to freezing
- Susceptibility to sulfation
- Electrolyte concentration
- Terminal configuration
- Maintenance requirements
- Cost factor
- Warranty period
- After-sales-services

However as a rule of thumb the required capacity of a battery bank may be roughly calculated as follows (formula 9.3.1):

$$C = \frac{D_{Ah} \times DOA}{DOD \times EFF} \qquad (9.3.1)$$

Where C = required capacity of the battery bank in Ampere-hour
DAh = daily load in Ampere-hour.
DOA = Days of autonomy
DOD = Max. allowable depth of discharge (say 0.8 for deep cycle batteries)
EFF = Efficiency of the battery system (generally 0.7 to 0.9)

Battery Subsystem Design

Once a particular type /make of battery has been selected, the designer should consider the battery subsystem, i.e., the number of batteries in series and parallel, selection of proper type and size of wires, over-current and disconnect requirements.

- *Series Connection of Battery*

Batteries connected in series have only one path for the current to flow and the total voltage is the sum of the individual battery voltages.

- *Parallel Connection of Batteries*

Batteries connected in parallel have more than one path for the current to flow and the voltage across the entire circuit is the same voltage as across the individual parallel branch.

Battery Bank Voltage Selection

Battery bank voltage selection is often dictated by the load voltage requirements, most often 12 or 24 Volts for small remote stand-alone PV systems. For bigger loads requiring a larger PV array it is sometimes wiser to go to the higher voltages, if possible, in order to reduce the system load current. Lower system currents minimize the size and cost of conductors, fuses and other current handling components of the PV system.

Example 9.3.1

Problem:
Appropriate battery bank is to be designed and selected for the following case:

Total daily energy consumption-	20 Ah @ 24 V
System voltage-	24 V
Load type-	Telecommunication equipment at remote location
Maximum allowable DOD-	60%
Efficiency of battery system-	0.8

Solution:
Since the load is Telecommunication equipment installed in remote location, the autonomy days has to be selected at higher limits, say 5 days. The total required battery capacity is calculated using formula 6.3.1:

$$C = (20 \text{ Ah x } 5)/(0.6 \text{ x } 0.8) = 208.33 \text{ Ah at } 24 \text{ V.}$$

To achieve this capacity we can use one deep cycle battery rated at 200 Ah or use two 100 Ah batteries connected in parallel. Since the battery voltage is generally 12 V, we may use two 200Ah batteries in series to meet the system voltage requirement or use 4 nos. of 100 Ah batteries configured to 200 Ah at 24 V.

9.4 Sizing of Charge Regulator

While selecting the charge regulator, the following parameters of the CR need to be checked and matched with the PV system parameters:

Operating Voltage

The sizing or selection of CR starts with selecting the operating voltage. It is evident that the operating voltage of CR and the system voltage of solar PV must be the same.

Maximum Load Current Capacity

Next step is to calculate the maximum load current capacity of CR. The maximum load current handling capacity of CR should be greater than the maximum possible load current resulting from the simultaneous operation of all the appliances powered by the PV. The maximum possible load current can be calculated by using the following formula (9.4.1):

$$I_{lmax} = \{\Sigma \text{ power consumed by appliances}\} / \text{system voltage} \qquad (9.4.1)$$

While using the above formula, the critical loads directly supplied from the battery bypassing the CR are to be excluded. Similarly by system voltage we mean the DC side voltage. The above formula is applicable to the AC load operated through the inverter.

Maximum Charge Current Capacity

The maximum charge current capacity of the selected CR should always be greater than the maximum current supplied by the PV array under STC. The maximum possible current from the array is the short circuit current. It is therefore advisable that the charge current capacity of the CR be selected greater or equal to the total short circuit current produced by the array.

Self-consumption

Self- consumption (or quiescent current) of the CR should be as low as possible. Generally, the PV standard of the given country specifies the maximum allowable level of self-consumption.

Level of Protection

The CR must have provision of protection from over current or short circuit on the load side. This protection could be appropriately rated fast blow type wire fuse or electronic fuse. Another essential level of protection is the reverse polarity protection on the array and the battery side. The CR should also incorporate appropriate measure for protection against surge induced from the array side.

Reverse Leakage Current

The selected CR must have negligible or almost zero reverse leakage current from battery to array.

Voltage Drop Across the CR

The level of voltage drop in the CR (from array to battery and from battery to load terminals) shall be less or equal to the specified percent of the system voltage.

Level of Radio Frequency Interference

The level of radio frequency interference (RFI) induced by the CR at specified distance from the CR should be negligible or less than specified value.

Low Voltage Disconnect Set Point

The LVD set point of the selected CR should be field adjustable. The selected value of LVD depends upon the type of the battery used, the surrounding temperature and the permissible daily depth of discharge (DOD). The LVD set point should be adjusted as per specifications spelled in the standards or as per the specification of the battery.

High Voltage Disconnect Set Point

The HVD set point again depends upon the type of the battery selected. Some CRs have built in function of detecting the state of the charge of the battery and adjusting HVD accordingly. If this auto-adjustment facility is not available in the CR, then reference has to be made to the standards or specification of the battery to determine the HVD set point.

Charging Algorithm

Simple ON-OFF type CR should be avoided as far as possible. The minimum algorithm shall be PWM. If the cost permits, the three stage intelligent charger would be the best option. The selected CR should be fully solid-state type.

Operating Ambient Conditions

The selected CR must operate without failure in the extreme environmental conditions of the locality. Therefore the maximum permissible ambient temperature and humidity of the selected CR should match with the environmental conditions of the locality.

Workmanship

The CR enclosure should display good workmanship and should provide protection against dust, water, oil, smoke and insects.

- *Regulators for large AC systems*

The large PV system using AC only in conjunction with the inverter may not need separate charge regulator. The large inverters usually have built in charge regulators as the array output is directly fed to the input of the inverter. In such cases, the designer should verify that the inverter meets all the requirements pertaining to the function of the charge regulator.

9.5 Sizing of Wire/ Cable

There are two factors that dictate the selection of wire size. Properly selected wire size must satisfy both the factors equally.

- ***Ampacity Based Sizing***

The sizing of the wire based on the current handling capacity (the capacity that does not produce overheating of the wire) is the first approach in wire sizing. The household AC wiring is based on this principle only as the voltage drop in the wire does not play major role in AC applications. The current handling capacity (or Ampere- Capacity or Ampacity) of the wire is chosen to be slightly greater (usually 25%) than the maximum load current that will flow the wire. The wire specification chart usually specifies the Ampacity for given wire size in the form of a table.

While calculating the DC load current, the total real power required to operate the load is to be divided by the system voltage. But for AC load currents, the apparent power needs to be divided by the system voltage. Since for reactive AC loads apparent power is higher than the real power, Amapcity of the wire need to be higher.

- ***Voltage Drop Based Sizing***

For the wire to be used in low voltage, high current applications voltage drop across the wire is another important factor to consider. All conductors have some small resistance, which causes a loss of voltage in a circuit depending on the size and length of the wire. The specific value of voltage drop (voltage factor) for given wire size is expressed in terms of volt/amp/meter. The voltage drop in wires causes less voltage applied to the load from battery or from array to the battery. Less charging voltage means less energy stored and less voltage at load means unstable operation of the load. Therefore the national standards specify the maximum allowable voltage drop in each segment of the wire. The selected wire may meet the Ampacity requirements but may not be suitable with regards to the allowable voltage drop. The Nepal Interim PV quality assurance (NIPQA) has specified the following level of voltage drop (ΔV) in each wire segment:

- Less than 5% between CR and loads
- Less than 3% between array and CR and CR to inverter
- Less than 1% between CR and the battery

The voltage drop in each wire segment can be calculated using the following formula:

ΔV = Maximum current flowing through the wire x
Wire length (both way) x Voltage factor (9.5.1)

NIPQA has specified the formula for determining the wire size (in sq.mm) based on both Ampacity and voltage drop requirements:

$$S = \frac{0.3LI_m}{\Delta V} \qquad (9.5.2)$$

Where is,

S	–	Required wire size (cross-sectional area of the copper wire in sq.mm),
L	–	Length of the wire in meters,
Im	–	The maximum current in Ampere, and
ΔV	–	Maximum allowable voltage drop in percent.

It is to be noted here that the above formula takes care of voltage factor as well as the Ampacity level of the copper wire and is included in the multiplier coefficient equaling to 0.3. The size of the wire for each segment is to be calculated using the above formula.

The wire sizing between array and the battery requires great deal of attention compared to other wire segments. The effect of voltage loss in the wires between the array and the battery is slightly different than the effect between the battery and the loads. The main effect for the load case is the reduced voltage level to the loads, impairing performance of some of the voltage critical loads. However, the main effect of small size wire between the array and the battery bank is to reduce the amount of current that flows into the battery. The voltage potential of the array applied to the battery terminals is reduced at all currents, thereby "dragging in" the entire IV curve. Because the batteries operate in a narrow range of voltage close to the "knee" of the array IV curve, the net effect is to operate the array (as seen by the battery) at a lower current level (fig. 9.5.1).

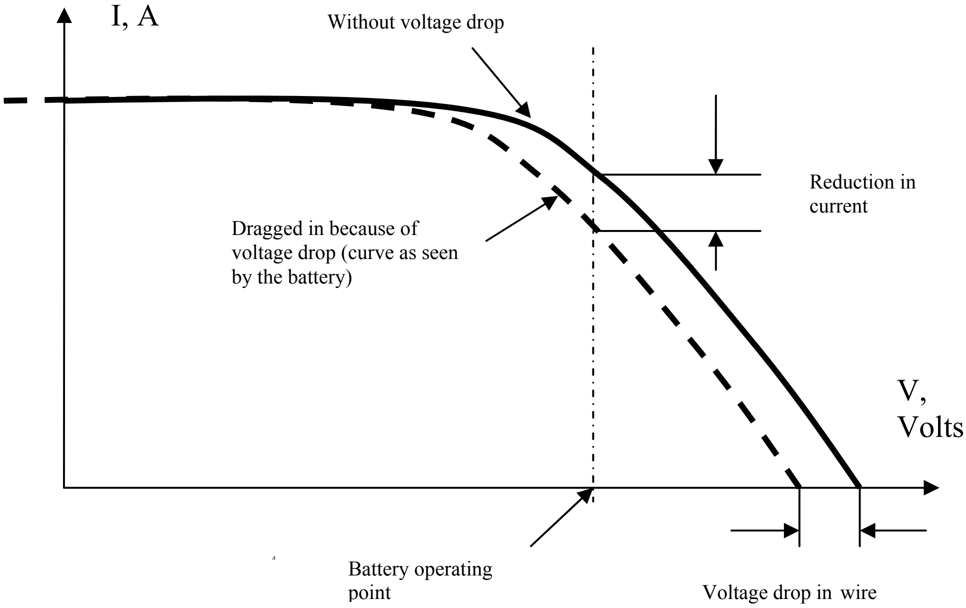


Fig. 9.5.1 Effect of voltage drop in array-battery wire

The consequence of improperly sized wire is that the actual charging current would not be what the designer expects, and over the time the battery would never be fully recharged and the system would fail.

Besides being large enough to minimize voltage drop, the wire from the array to battery (it includes both the wires from array to CR and CR to battery) should have an ampacity rating of at least 1.4 times the array operating current Imp. This is for safety reasons. It is possible for an array to operate in a short circuit condition. The array could in fact operate for prolonged periods at up to 20% above its Isc, due to reflection of light white clouds, or reflectance of light from white sand, snow, light-colored buildings or structures.

9.6 Sizing of Inverter

Inverter sizing is based on the following criteria:

- ***Surge Capability***

Most of the reactive loads (usually inductive loads like motors, compressors and color televisions in degaussing mode) require a surge of power 4-6 times their nominal running power to start. The selected inverter must be able to deliver the surge power requirement of the load.

- ***Continuous power output***

The inverter must be able to deliver its rated output power continuously for at least 30 minutes without overheating and thermal runaway.

- ***Efficiency***

Efficiency is the measure of the power wasted by inverter while performing DC to AC conversion. This adds to the total load that the PV must operate and increases array size and initial cost. The selected inverter must have above 90% efficiency almost over the entire power range (i.e. from 10% of the rated load to over 100% of the rated load). Care must be taken to ensure that the rated efficiency is applicable to both purely resistive as well as highly reactive loads.

- ***Voltage regulation***

The selected inverter must produce stable output over permissible variation in the input voltage.

- ***Total Harmonic Distortion***

The inverter must produce very low harmonic distortion. High level of distortion caused by the harmonics may severely affect the performance of inductive loads like motors.

- ***Waveform***

The waveform of the inverter output can be an important factor in matching inverter to load. The square wave inverters cannot surge sufficiently, perhaps only 10-20% above the maximum continuous power. The efficiency (with respect to the fundamental frequency) can be as low as 50-60% and the voltage regulation capability is low. However owing to the lower cost, these inverters are useful for small inductive loads or resistive loads.

The modified square wave or so-called quasi- sine wave inverters have better surge handling capabilities (up to 300-400%) and have good voltage regulation. Efficiency of these inverters could be more than 90%, because the waveform contains fewer harmonic components compared to square wave.

Pure sine wave inverters have efficiency and surge capability slightly below modified sine wave inverters. But the quality of output is very high, as required by the delicate electronic loads. However high cost of these inverters prohibit extensive use in common applications.

- ***Serviceability***

The inverter design should allow easy servicing in the field by allowing cards (printed circuit boards) to be swapped and exchanged to minimize down time.

Apart from the criteria discussed above, the designer should also check the standards applicable and select the inverters meeting the local standards.

9.7 Sizing of DC-DC Converter

The DC-DC converter must be selected based on the following parameters:

- ***Output voltage***

The output voltage of the DDC should match the input supply voltage requirement of the load. The DDC output may not exactly match the load supply requirement, but it should be within the acceptable limits.

- ***Maximum output current***

The DDC must be able to supply the load current drawn by the device under continuous operation mode. Therefore the maximum current delivered by the selected DDC must be greater than the load current.

- ***Efficiency***

For low power applications, the efficiency may not be a parameter of great concern, as the total losses in the DDC may contribute only few percent of the total system load. But for loads with continuous operation, like telecommunication equipment, the efficiency of the DDC should be relatively high.

- ***Interference level***

The radio frequency interference (RFI) induced by switch mode DDC would be of the concern when it is used to power the radio receivers or sensitive electronic test / measuring instrument. The induced RFI may cause the reception of the stations impossible or cause error in measurement. The RFI level should be as per applicable standards.

- ***Overload and reverse polarity protection***

The selected DDC must have adequate protection against overload or short circuit. This could be wire or electronic fuse of appropriate rating. Similarly, the DDC should have the protection against connecting the load in wrong polarity.

9.8 Installation Procedures, Safety and Protection

The actual installation procedure begins with the design of installation diagram, site selection for installation of array and battery bank, preparation of bill of quantities of the required items, installation materials and list of safety measures. In this chapter, overview will be given to the various steps of installations pertaining to non-pumping applications. However many of these could also be applied to pumping applications as well.

The installation process for smaller systems consisting of one module, a CR, a battery and few DC loads may be very simple. But the larger systems require special attention to minimize probability of system failure and also to minimize overall cost of the system.

9.8.1 Line Diagram for Installation

The entire PV system should be diagramed before final costing and installation. The diagram should include wiring of modules in the array or sub-arrays, regulators; AC and DC load centers, battery bank, inverter, grounding and circuit protection.

For a very simple system such as solar home systems, a simple wiring plan can be sketched as shown in figure 9.8.1.1.

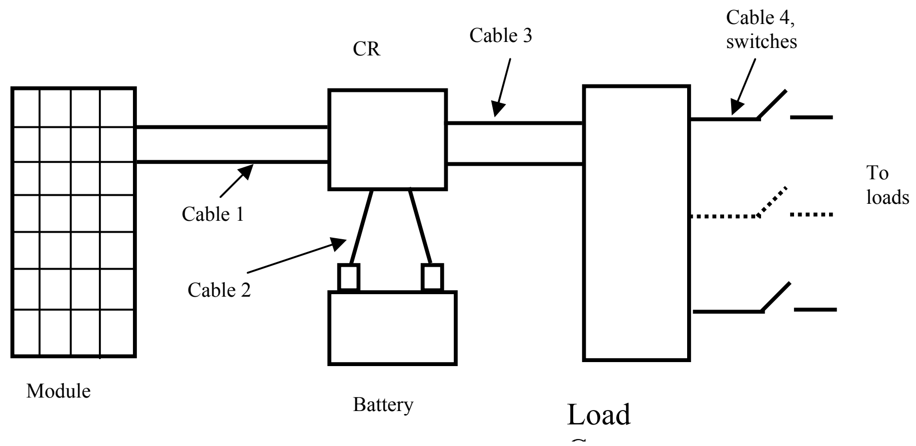


Fig. 9.8.1.1 Installation diagram for simple PV system

The module capacity; length and size of wires; type and model of CR; type, capacity and voltage of the battery; load center details etc. are to be indicated in the diagram for easy installation process. However, actual location of the components of the system will depend upon the plan of the building where the system is to be installed. Selecting the best locations for mounting the module and installing the CR, battery and load center can minimize the required length of the cables.

The larger system requires more attention as simple errors can result in system malfunction or complete collapse of the system. Therefore for larger systems complete system diagram should be made. But rather than drawing all the components of the complete system at once, it will be helpful to sketch a simple system block diagram (fig. 9.8.1.2) and then add components and complexity.

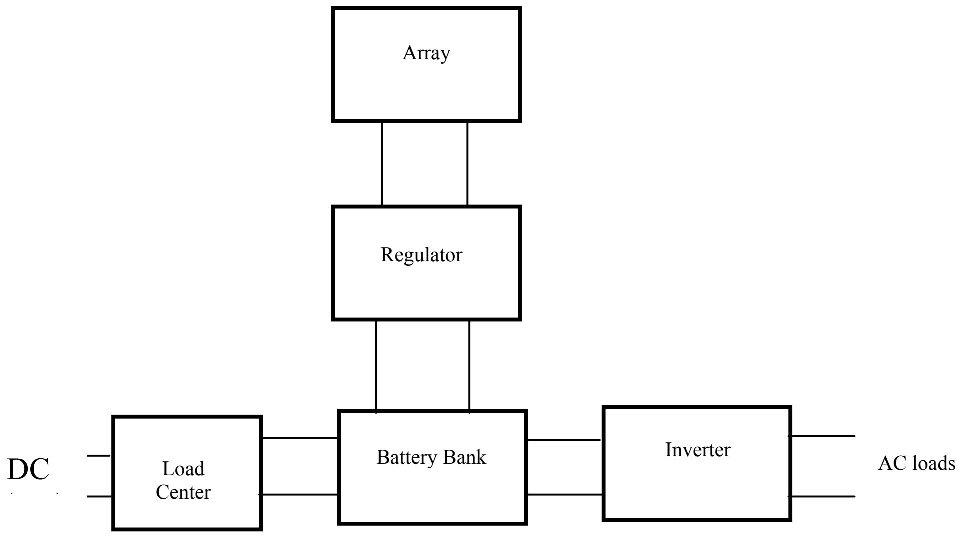


Fig. 9.8.1.2 Simple block diagram of larger system

The next step would be detailing each blocks of the simplified block diagram. The steps could be:

- Decided if a single regulator is available to handle the full array current. If not split the array into sub-arrays.
- If both AC and DC loads are to be used, decide the ratio of the respective powers. For example if majority of the load is AC and DC load is just few DC lamps, then most probably separate module may be wired for DC load and array configured for AC loads.
- Decide the input voltage of the inverter and arrange modules in the sub-arrays to produce required DC system voltage.
- Wire the battery bank.
- Create AC/DC load centers.
- Decide on adding isolation/blocking diodes.
- Add disconnect switches, circuit breakers or fuses.
- Re-calculate required wire size and length for each sector.
- Ensure that the electrical system, the structures, junction boxes and load centers are grounded and protected from lightning.

- ***Number of CR and Sub-array***

It is often easier and wise to divide a large array into smaller sub-arrays of required system voltage. These sub-arrays are then combined in parallel to produce full array current at system voltage. The first reason to break a large array into sub-arrays is that the charging current from the entire array may be too large for the charge regulators desired (selected CR with required facilities and options may not be suitable to handle full array current). Secondly, the wire size may be too high to carry the full array current; may be very expensive; stiff and difficult to work with. Finally, maintenance or repairs can be done on some modules or controllers without the entire system being shutdown.

Number of sub-arrays is primarily the function of current handling capacity of the selected CR. The number of sub-arrays and CR can be calculated using the simple formula:

$$N_{CR} \text{ or } N_{sub\text{-}array} = (Np \times Imp \times 1.25) / \text{CR charge current rating} \qquad (9.8.1.1)$$

Where is:

N_{CR} – Number of CR required;
$N_{sub\text{-}array}$ – Number of sub-arrays required;
N_p – Total Number of modules connected in parallel in the array;
I_{mp} – Nominal current of the module.

In the above formula the factor 1.25 represents over-rating of CR current capacity for

safety reasons.

As an example lets consider an array of 40 modules with 3.4 A nominal current connected in series (two modules in each string to produce 24 V system voltage) and 20 strings in parallel (fig. 9.8.1.3).

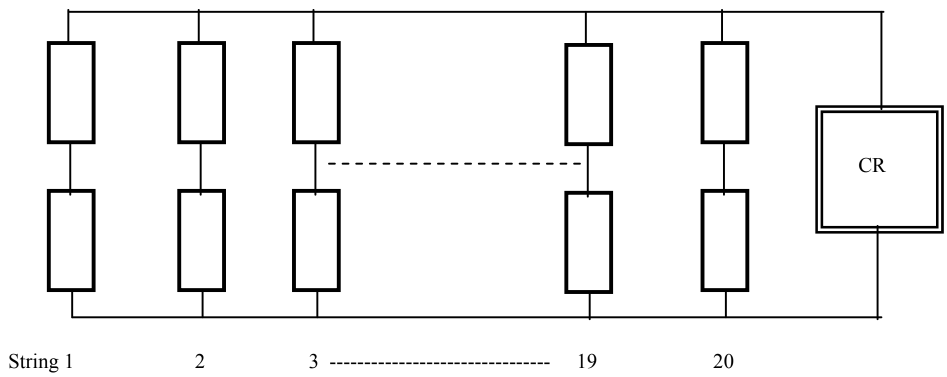


Fig. 9.8.1.3 Example of an array with 40 modules at 24 V system voltage

Suppose the selected CR has the current rating of 30 A and the system voltage of 24 V. Then according to (6.8.1.1), the required number of CR or sub-arrays is:

N_{CR} = (20 x 4.1 x 1.25)/30 = 3.42 rounds up to 4.

Thus each sub-array will now consist of strings of 5 parallel-connected modules. And a CR with 30A current rating controls each sub-array (fig. 9.8.1.4).

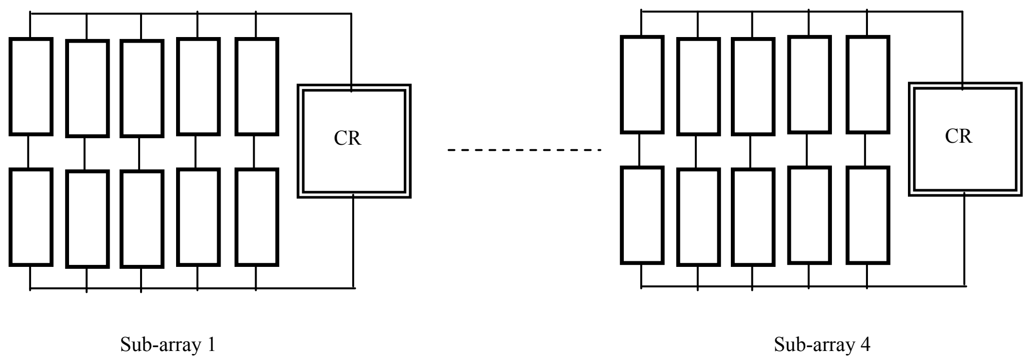


Fig. 9.8.1.4 Dividing an array into sub-arrays

The number of sub-arrays calculated using above formula needs to be rounded up to next highest integer. As far as possible, each sub-array should contain equal number of strings. In case if it is not possible, one sub-array may be slightly smaller than others.

- ***Module wiring on structures***

Once the number of sub-arrays and controllers have been calculated, it would be wise to make a sketch of how the modules in the sub-array would be interconnect. In above example each sub-array consists of a total of 10 modules; two modules (one string) connected in series to produce 24 V system voltage and 5 strings connected in parallel to increase the current level at system voltage. Assuming that a single support structure can accommodate 10 modules (5 rows and two columns), the wiring diagram, with isolation diodes for each string, would look as shown in fig. 9.8.1.5.

In the figure it is assumed that the modules have two separate junction boxes each for positive and negative terminals. Some modules may have single junction box with separate terminals for positive and negative outputs. The weatherproof field diode box is used to house the isolation diodes and combining terminals (bus bars) to produce single outlet for each sub-array.

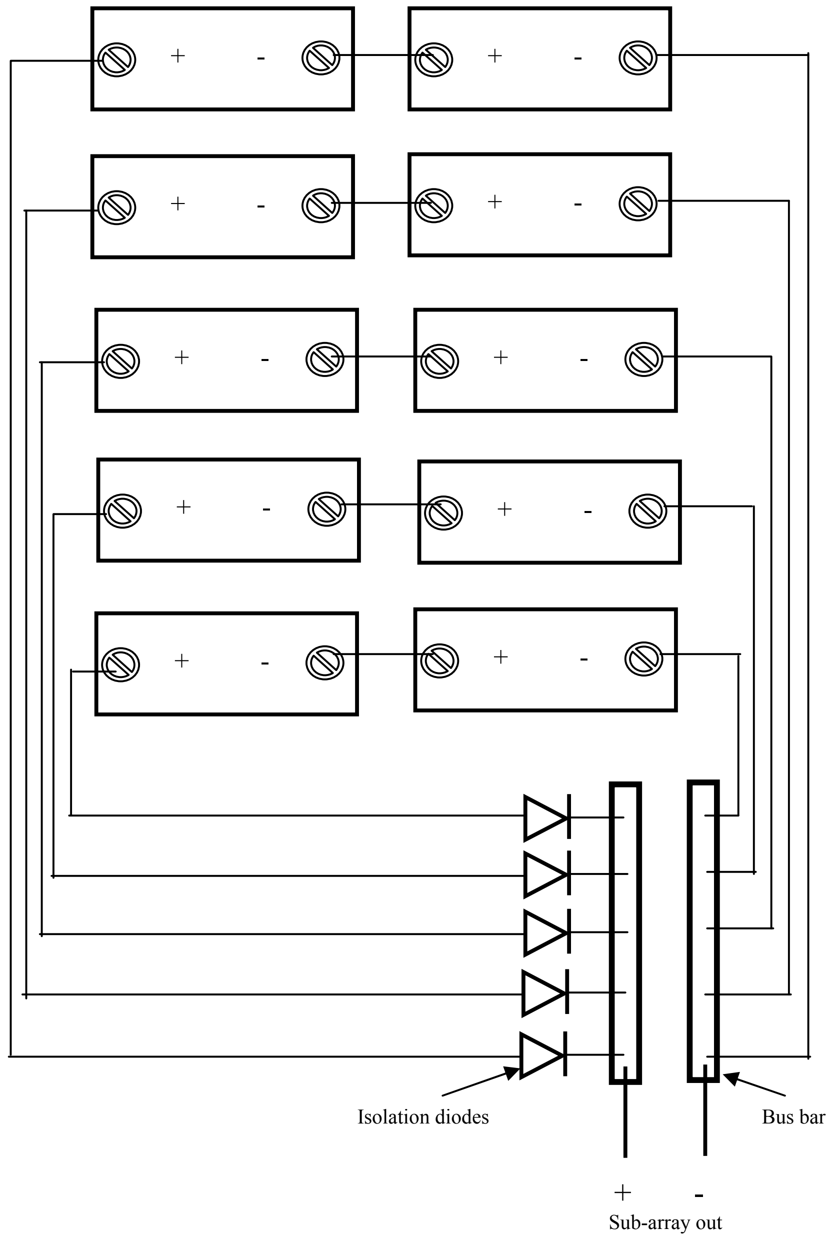


Fig. 9.8.1.5 Schematic sketch of module wiring for a sub-array

As the last stage of array installation design, complete diagram with individual sub-arrays as the input to the system may be sketched as follows (fig. 9.8.1.6a). This is the case when the number of CR is equal to number of sub-arrays.

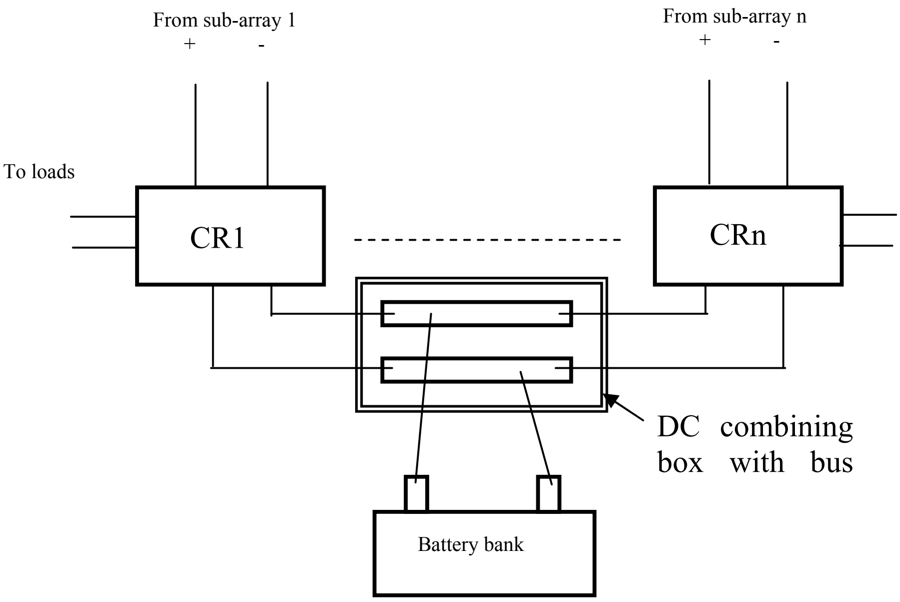


Fig. 9.8.1.6a Sketch of final interconnection of sub-arrays with separate CR

In the case when a single CR is used but the array is grouped into sub-arrays, the final installation sketch would look like (fig. 9.8.1.6b):

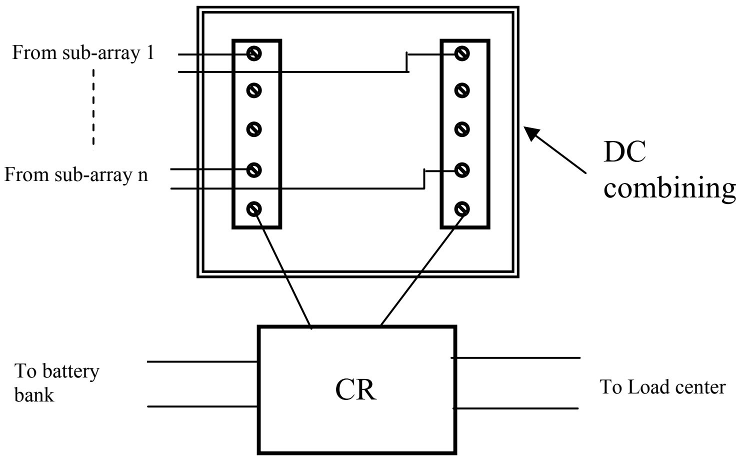


Fig. 9.8.1.6b Sketch of final interconnection of sub-arrays with single CR

- ***Fuse and Protection Design***

Once the array wiring design is sketched and the wire size of each sector calculated, the next logical step would be to decide the number and rating of the fuses, circuit breakers and disconnects. It is usual practice to add fuses or circuit breakers of rated capacity at the output of each sub-array. Similarly PV disconnect circuit breaker is installed at the array input of CR. A separate battery disconnect circuit breaker of rated capacity is also required to isolate battery bank during installation and for maintenance purpose. Fused outlets from battery bank is also has to be designed for DC as well as AC loads. A suggestive sketch of complete PV layout with fuses and circuit breakers is shown in fig. 9.8.1.7 below.

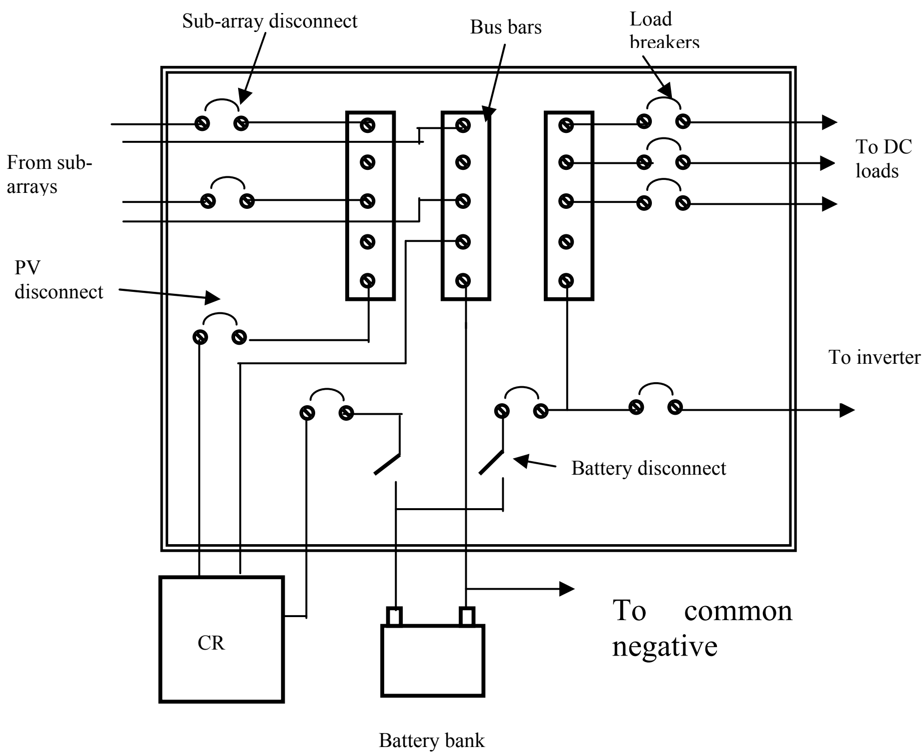


Fig. 9.8.1.7 Fuses and disconnect arrangement

The ratings of the fuses or the circuit breakers should be at least 1.5 times the maximum current flowing through the sector.

9.8.2 Installation Steps

The major safety considerations for installation of array and battery bank are to be outlined first. These considerations are as follows (but not limited to):

- ***Array***
  - Establish and enforce safety procedures
  - Follow national electric code for installations
  - Fence array and control access

- Keep instruments, controls in locked areas
- Cover high voltage (greater than 50V) modules/array with black plastic during installation and maintenance

- ***Battery***
  - Vent battery enclosures and control access
  - Provide battery disconnect at battery bank
  - Follow and post all battery handling safety procedures
  - Keep open flames and sparks away from batteries
  - Never break battery circuit during charge or discharge
  - Wear protective clothing while working on batteries
  - Have fresh water on hand in case of electrolyte splashes on skin or eyes
  - Do not lift batteries by the terminal post.

There is no hard and fast rule for installation of PV system if all the safety precautions are taken and national codes are followed. However the following discussions will provide guidelines for successful installation.

Wiring

It is a good practice first to complete load wiring (i.e. wiring of light points and other power outlets) and test for flawless wiring. It is advisable to use colored cables for DC wiring: red for positive, black for negative and green for grounding. Then the fixing of load centers, junction boxes, charge regulators etc. can be accomplished and tested.

Array

The number of modules to be connected in series and parallel is determined when the system is sized. Wiring of the modules is accomplished using properly sized cables. Before installation, it is recommended that the wiring schematic be made to show proper connections. Each module can be considered as a battery, which develops voltage and amperage when light falls on it. The wiring diagram should show each module having plus and minus terminals, arranged in blocks and interconnected.

Batteries

The type, number and series-parallel connection diagram of the batteries is determined when the system is sized. As most of the batteries come initially charged precautions shall be taken to avoid short-circuits between the two terminals of the battery.

Interconnections between System Components

As discussed earlier, it is good practice to install the components of the system (array, battery bank, load centers with protection devices and disconnects), junction boxes and load wiring independently. After the installation of system components, the interconnection between the components can be accomplished. The suggested steps of interconnection are:

- Connect the output of battery bank to battery input of charge regulator through the load center with battery disconnect open circuited. Do not connect loads at this point. Then turn ON the battery disconnect and ensure proper indications in CR. Measure the load output of CR and confirm that it is in line with the battery bank voltage.
- Now disconnect the battery bank from the CR and connect loads (with load disconnects turned OFF) to the CR output. Turn ON the battery disconnect and turn ON the loads one by one and verify the normal operation of the loads.
- Turn off the battery disconnect, load disconnects. Connect sub-arrays to the load center initially turning off each sub-array disconnects and PV disconnect.
- Turn ON the battery disconnect, PV disconnect and one sub-array disconnect. The battery banks should start charging by only one sub-array configured at system voltage. If no abnormalities detected, turn ON other the second sub-array disconnect and monitor proper operation of CR. Gradually turn ON all the sub-array disconnects.
- Take measurements of the system parameters like irradiance, array output voltage, battery bank voltage, charging current and load current and note them in the log book.

9.8.3 Safety and Lightening Protection

Danger of High Voltage and Current

The current due to the high voltage is extremely dangerous and could be fatal to the human. The human body acts as the conductor of electricity and when the amount of electricity flowing through the human body exceeds 9-12 mA range, fatal consequences can be observed. The amount of current through body depends upon the resistance of the body and the applied voltage. The body resistance of a healthy and cheerful fellow may be above 3 kilo Ohms under normal condition. In this case the single battery or module voltage may not be fatal when touched. But if the body is moist and the mental condition is worse, the resistance may drop significantly and even the low voltage as that of single 12 V battery may be fatal when touched. The effect of current flow in the body also depends upon the path of current. For example, touching one of the wires by only one hand may not be that critical as there is no complete path for the current to flow. But if positive terminal of the battery is touched by one hand and the negative by another, the circuit for the current is complete through the chest and the effect would be highest. The effect of electric shock would be fatal independent of the body conditions, if the system voltage were relatively high.

The users of this manual are advised to consult other literatures on electrical safety for detail understanding of the effect of electric shock and ways to minimize it.

Common Risk Associated with Battery Bank

Battery storage in PV systems poses several safety hazards:

- Hydrogen gas generation from charging batteries
- High short-circuit currents
- Acid or caustic electrolyte
- Electric shock potential

- *Hydrogen Gas*

When flooded, non-sealed, lead-acid batteries are charged at high rates or when the terminal voltage reaches 2.3-2.4 volts per cell, the batteries produce hydrogen gas. Even sealed batteries may vent hydrogen gas under certain conditions. This gas, if confined and properly not vented, poses an explosive hazard. The amount of gas generated is a function of battery temperature, the voltage, the charging current, and the battery bank size. The large numbers of batteries in smaller or tightly enclosed areas require venting. A catalytic recombiner cap (Hydrocap) may be attached to each cell to recombine some of hydrogen with oxygen in the air to produce water. If these combiner caps are used, they will require occasional maintenance.

In no case should charge regulators, switches, relays, or other devices capable of producing an electric spark be mounted in a battery enclosure or directly over a battery bank. Care must be exercised when routing conduit from a sealed battery box to a disconnect. Hydrogen gas may travel in the conduit to arcing contacts of the switch. As a safety measure smoking and use of matches, cigarette lighters or any other flaming lamps in the battery room must be avoided completely.

- *High Short-circuit Current*

Batteries are capable of generating tens of thousands of Amperes of current when short-circuited. A short-circuit in a conductor or in the load side not protected by over current devices can melt wires, wrenches or other tools, battery terminals, and spray molten metal around the room. The short-circuit may also ignite fire in the battery room. Therefore the exposed battery terminals and cable connections must be protected. This generally means that the batteries should be accessible only to a qualified person. The danger may be reduced if insulated caps or tape are placed on each terminal and insulated tool is used for servicing and installation. The battery voltages must be less than 50V in dwellings. Moreover, batteries should not be installed in living areas.

- *Acid or Caustic Electrolyte*

A thin film of electrolyte can accumulate on the tops of the battery and on nearby surfaces. This material can cause flesh burns. It is also a conductor and in high-voltage battery banks poses shock hazard.

Battery servicing hazards can be minimized by using protective clothing including face masks, gloves, and rubber aprons. Self-contained eyewash stations and neutralizing solution would be beneficial additions to any battery room. Water should be used to wash acid or alkaline electrolyte from the skin and eyes.

Grounding and Lightning Protection

Grounding in electrical circuits is primarily for safety. A short-circuit, also known as a fault condition, occurs when an electrical conductor makes contact to any structural component (junction box, load center, appliance, metallic conduit etc.), or to another conductor. Current can flow through this new path, which might include a person's heart if they are touching the faulty component.

Dangerous currents can be made to bypass the body by having a highly conductive path back to the energy source in the form of a grounding wire. A large current can flow through the wire, large enough to cause the overcurrent devices (fuses or circuit breakers) to open the circuit and stop the flow. The ground wire is not a part of the power circuit. It is normally a non-current carrying wire and is on "stand-by" in case the normal circuit becomes unsafe.

All exposed metal surfaces. Including the module frames, array mounting structures, any metal housing of regulators or load centers, and all loads should be grounded. It is the general practice (unless otherwise agreed) to connect negative terminals of all the sources of electrical energy to the ground terminals. Therefore the negative legs of battery bank and array should also be grounded. This is often called "system ground". All grounds, structural and electrical, should come together and be connected to one ground rod. More detailed discussion on selection of grounding conductor, grounding rod and grounding process can be found on the respective literature.

The basic concerns of lightning protection are to attract lightning strikes away from the installation structures and to an air terminal of adequate size and conductance to carry away the current of the strike without harm to installation or people. The basic elements of a protective system are an air terminal (arrestor), a down conductor to carry the current to earth, and a grounding system that adequately and safely dissipates the sudden current into earth.

Experiments have indicated that a glass front module with a rigid metal frame is able to withstand almost any lightning strike if the frame is grounded to the earth. The metal frame acts as a grounding rod (lightning arrestor) attracting all the current to it. However, a strike, which breaches the integrity of encapsulation, might, under some conditions, eventually destroy the module. But even if the module survives a lightning storm, additional protection may be required for the cabling, regulators and load. A grounding rod (or the frame connected to the grounding system) will protect the array from direct strikes but further protection is required for induced voltages and the side flashes they can create. The terminals of balance of system components can be protected by the use of varistors (MOV) or glass discharge tubes (GDT).

The degree of protection needed for any particular installation will be determined by factors such as site location (frequency and intensity of lightning strikes), size of the array, safety considerations, and cost.

9.8.4 Site Selection for PV Array, Battery Bank and Other System Components

Array

It is very important to properly select the site for installation of array/modules. If the system is relatively small, consisting of few modules only, then these can be easily installed on the roof-top. Large array requires large field or roof-top area for installation. The site for array installation should not be shaded by nearby trees, buildings, etc. from approximately 09:00 to 15:00 on the shortest day of the year, which in the northern hemisphere is December 21.

It is necessary to orient the array south or north depending on where in the world the installation site is. Array located in northern hemisphere need to orient towards south and that in southern hemisphere towards the north. The array should be oriented within 15^0 of true south or north. The best way to find the true south (for northern hemisphere) is to locate the magnetic south by using magnetic compass and then calculate the true south by using the magnetic declination data of the location.

The array field must be as close as possible to the battery bank and control room. Keeping this distance minimum will lower the cost in cables.

Battery Bank

The battery bank must be installed in well ventilated shed or room protected from temperature extremes. It is advisable to keep the banks within 3-5 meters from the CR if possible. While arranging the batteries in the bank, it is a good idea to have air gap between them to cool and equalize temperature.

Control Units

It is a good practice to assemble CR, sub-array circuit breakers, PV disconnects, Battery disconnects and load breakers in a single housing (load center) made of corrosion resistant enclosures with clear marking of each of the breakers and disconnects. The sub-array combining boxes could be located near the modules. The load center must be positioned, within the permissible distance from the battery bank.

The exact locations of system components must be designed after inspecting the installation site and consulting with the owner of the system.

Example 9.8.1

Let us consider the load requirements as worked out in example 9.1.1. The total load in winter and summer are 3620 Wh and 4620 Wh respectively. The system voltage is 24 V DC for all loads except the color television. This unit is to be powered from an inverter of appropriate rating.

<u>*Array Sizing*</u>

For the purpose of array sizing, let us assume that the location of the site is 28^0 N (Latitude), the minimum yearly average insolation at the site is 4500 $Wh/m^2/day$, and the temperature variation is 40C minimum to 36^0C maximum.

The total required array current can be calculated using formula 9.2.1 assuming derating factor and columbic efficiencies to be 0.9 and 0.95:

$$I_{array}\,(winter) = 150.8 / (4.5 \times 0.9 \times 0.95) = 39.27\ A$$

$$I_{array}\,(summer) = 192.5 / (4.5 \times 0.9 \times 0.95) = 50.13\ A$$

It is evident from the above figures that a single module cannot generate required current; therefore number of modules has to be connected in parallel. Suppose a 65 Wp module with I_{mp} = 4 A is selected. Then the number of modules to be connected in parallel, N_p, would be (formula 9.2.2):

$$N_p\,(winter) = 39.27/4 = 9.81, \text{ say } 10$$

$$N_p\,(summer) = 50.13/4 = 12.53, \text{ say } 13$$

Now since the system voltage is other than the module voltage, number of parallel-connected module strings is to be connected in series. The required number of strings in series, N_s is (formula 9.2.3):

N_s = 24 V/12V = 2

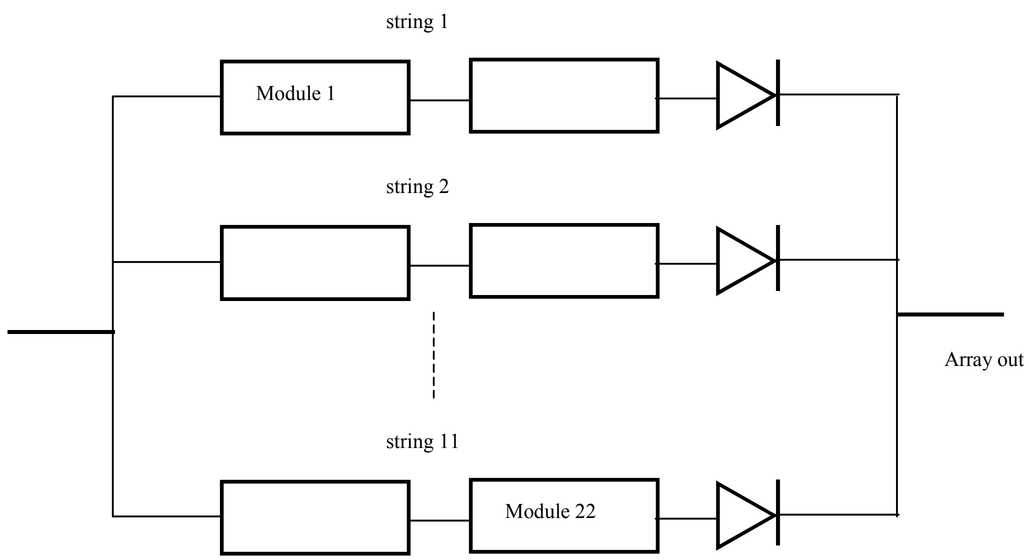
Finally the total number of modules, N_t, in the array would be (formula 9.2.4):

N_t (winter) = 10 x 2 = 20

N_t (summer) = 13 x 2 = 26

Here we can decide to use all 26 modules so that the energy demand is met for entire year. This option would mean that we would be spending more money for 6 additional modules that may not be required for 6 winter months. While calculating the array current, it was assumed that the value of peak-sun (4.5) was at average tilt angle equal to the latitude of the site, i.e. 28^0. Instead of aligning the array in fixed angle, we can make seasonal adjustment of the tilt angle (39^0 for 6 winter months and 17^0 for six summer months) to intercept more radiation and subsequently more array output power. Assuming that seasonal adjustments of the tilt angle results in an average of 20% increase in output power, we may come-up with 20% less modules for six summer months. With this assumption we conclude that 22 modules (instead of 26) would meet the load demand of summer months.

Finally the array configuration would be:



Battery Sizing

For battery sizing it is better to consider the peak load throughout the year. In our case it is the summer load and is equal to 192.5 Ah@24 V. Moreover as the supply is used for hospital we may consider the load to be critical and therefore assume days of autonomy (DOA) to be at least 5. It is evident that the battery bank should again come to the full state of charge some days after continuous discharge for 5 autonomy days. For this to happen, the daily energy supplied by the array should exceed the daily energy consumed. In other words, the array to load ratio (ALR) of the system should always be greater than 1.
The ALR for summer and winter months can be calculated using the following:

ALR (summer) =
= (11 modules strings x 4 A x 5.5 peak-sun x 0.9 derating factor x 0.95 columbic efficiency)/energy consumed
= 206.9/192.5 = 1.07

In above calculations the peak-sun is considered to be 5.5 instead of design value of 4.5. It is done to take care of the 20% gain in array output power resulting from the seasonal adjustment of the tilt angle to optimum level.

Repeating the same calculations we get
ALR (winter) = 206.9/150.8 = 1.37

The relatively low value of ALR (1.07) for summer months is an indication of the fact that loss of load may occur for some time if next session of no-sunshine days follows immediately after the first session of 5 autonomy days. In such case we may advise the client to turn of some of the non-critical loads like TV and fans. Alternately we may decide to increase the number of modules in the array if the client is not comfortable with first option.

The capacity of the battery bank can be calculated using formula 9.3.1. Assuming the allowable DOD to be 80% (deep cycle batteries are considered) and the charging efficiency to be 0.8, the required battery capacity would be:

C = (192.5 x 5)/(0.8 x 0.8) = 1503.9 Ah, say 1500 Ah.

In the above calculation we have considered the summer load of 192.5 Ah because it is the highest amount of energy drawn from the battery.

Now we may decide to use 12 V block batteries of appropriate capacity (say 100 Ah) or use 2 V cells of higher capacity (say 500 Ah). In the first case the total number of 100Ah, 12 V batteries required is 30. In the second case 36 numbers of 500 Ah, 2V cells are required. It is now up to the designer to select the type of the battery based on the cost issues.

Charge Regulator Sizing

The CR to be used must handle the full short circuit current from the array. Assuming the short circuit current of the selected module to be 4.6 AP 30, the total maximum charge current would be:

I_{array} = 11 strings x 4.6 A = 50.6 A

The charge current handling capacity of the selected CR should be greater or equal to 50.6 A. A CR with 60 A charge current handling capacity would meet our requirement.

The maximum possible load current is calculated using formula 9.4.1:

I_{lmax} = {10 W lamps x 10 nos. + 200 W lamps x 3 nos. + (480 Wh refrigerator/24 hours) + 20 W fans x 10 nos. + 40 W TV x 1 no.} / 24 V system voltage

= 860 W / 24 V = 35.8 A

The load current handling capacity of the selected CR must exceed 35.8 A. A CR with 40 A load current handling capacity would meet our requirement.

Since the system voltage is 24 V, the operating voltage of the selected CR should also be 24V.

Other parameters (e.g. regulation type, regulation algorithm, LVD and HVD set-points, RFI, protections etc.) of the selected CR must be verified using the technical specification of the CR.

Wire Sizing

For wire sizing the NIPQA standard may be followed as detailed in formula 9.5.2. For the purpose of wire sizing let us assume the following length of wire required for installation:

- Array to load center (allowable voltage drop 3%) - 20 m (cable S1)
- Load center to Battery bank (allowable voltage drop 1%) - 5 m (cable S2)

Then according to formula 9.5.2:

S1 = (0.3 x 20 m x Iarray)/3 = (0.3 x 20 x 50.13)/3 = 100 sq. mm.

S2 = {0.3 x 3 m x Imax (load or array current whichever is the highest)}/1 =
= (0.3 x 3 x 50.13)/1 = 45.11 sq.mm.

Since the size of the cable available in the market may not be exactly equal to the size calculated, the cables with cross-sectional area just exceeding the calculated value may be selected.
Wire size of other segments of installation can be calculated in the similar manner.

Inverter Sizing

In the example the only load powered from AC is the 40 W color television. Assuming that the TV draws three times its nominal current during power ON, the capacity of the selected inverter should be:

P = 40 W x 3 time (surge) / 0.8 power factor = 150 VA.

The input DC supply voltage of the selected inverter should be 24 V DC. Since the load of the inverter is not very sensitive to the wave shape of AC, we may decide to choose high efficient square-wave inverter.

Example 9.8.2

A solar PV power system is to be designed for the operation of VHF telecommunication equipment. Followings are the available data:

- Site location: 28^0 N (Latitude)
- Minimum yearly average insolation: 4 kWh/m^2/day
- Temperature variations: 300C (max.) to 40C (min.)
- Power consumption by VHF set in talk/receive mode: 50 W
- Power consumption by VHF set in stand-by mode: 10 W
- Average talk/receive time (24 hours average): 4 Hours
- System Voltage: -48V DC

Load Calculation

The total energy consumed by the VHF set in 24 hours (a day) is:

W = 50 W x 4 hrs. (Talk/receive duration) + 10 W x 20 hrs. (Stand-by mode) = 400 Wh

The total energy consumed in Ah is:

A = 400 Wh / 48 V system voltage = 8.33 Ah

Since the VHF is in operation 24 hours a day and 365 days a year continuously, there is no seasonal variation in load profile.

Array Sizing

Total array current required is:

I_{array} = A, Ah / (4 peak-sun x 0.9 derating factor x 0.95 efficiency) = 2.43 A

A single module with I_{mp} >= 2.43 A can supply required current. Therefore the number of modules to be connected in parallel is one. Let us select a 50 Wp module with I_{mp} = 2.9 A.

The number modules to be connected in series is:

N_s = system voltage/12 = 48/12 = 4

Therefore the array configuration would be just four 50Wp modules connected in series. The array may be tilted to the angle equal to the latitude of the site to intercept optimum radiation throughout the year.

Battery Sizing

Battery sizing for the critical load like telecommunication equipment requires proper assumption of days of autonomy (DOA). To be in safe side we may take DOA to be 7 or even higher. In the first example (hospital) we considered DOA to be 5 only, because in that case we did have the opportunity to turn of some of the non-critical loads like TV and fan in case of continuous no sunshine days for more than 5 days. But in the present example we have only one load and turning it off means no communication at all.
The design value of ALR also becomes vital in critical load case. In the case under consideration, the ALR is:

ALR = 2.9 A x 4 peak-sun x 0.9 x 0.95 / 8.33 = 1.19

This is a comfortable figure and we can expect the batteries to be in normal state of charge after few days from the lapse of design DOA. If more reliability is the concern over the price of the system, higher capacity modules may be selected.

Finally the capacity of the battery (deep cycle) bank is:

C = (8.33 x 7)/ (0.8 x 0.9) = 80.98 Ah.

We therefore select 90 Ah, 12 V deep cycle batteries for this case. Since the system voltage is 48 V, four of these batteries have to be connected in series.

Charge Regulator Sizing

The maximum possible current from the array is the short circuit current. Assuming that the short circuit current of the selected module is 3.4 A, we may select the CR with charge current handling capacity exceeding 3.4 A.
The maximum load current drawn by the VHF set is:

I_{lmax} = 50 W/48 V = 1.04 A.

The load current handling capacity of the selected CR should exceed 1.04 A.

Finally the operating voltage of the selected CR should be 48 V. Moreover since the load is sensitive to the RFI, the selected CR must produce minimum or zero RFI.

Wire Sizing

The required size of the wires can be calculated as in the example 1.

Review Questions

1. Accurate knowledge of the load is essential in PV system design to

   a. reduce the cost
   b. increase the module power
   c. increase the cost
   d. increase the reliability

2. In solar PV system sizing, the load is expressed in

   a. Amps
   b. Watts
   c. Volts-hours
   d. Ampere-hours

3. The basic criteria for selecting number of modules to be connected in series in an array is

   a. total array power
   b. load current
   c. system voltage
   d. tilt angle

4. The required number of modules in an array is not a function of

   a. the capacity of an inverter
   b. peak sun
   c. location
   d. total load

5. While sizing the battery, the required battery capacity decreases with increases in

   a. number of autonomy days
   b. daily load
   c. allowable depth of discharge
   d. system voltage

6. One of the following is not the essential criteria for battery sizing

   a. type of the battery
   b. latitude of location
   c. surrounding temperature
   d. cost

7. The rated load current of a charge regulator is not a function of

   a. total power consumed by appliances
   b. system voltage
   c. array current
   d. all of above

8. The size of the cable increases with decrease in

   a. maximum allowable voltage drop
   b. length
   c. maximum permissible current
   d. cross sectional area

9. The daily load requirement for a remote household is 375 Ah at 48 V system voltages. If the yearly average peak sun in the locality is 6, calculate the total array size and number of module in series and parallel.

10. The distance between the array output and the charge regulator input is 10 meters; the maximum array current is 50A. Determine the size of the cable in SWG if the maximum permissible voltage drop is 3%.

CHAPTER 10

Design Aspects of Water Pumping System

Duration: 345 minutes
180 minutes (Field Visit)

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required: Catalogues of various types of modules, water pumps, wire-size tables, PV standards and a calculator. and reference material.

Procedures:

a) The instructor explains the water pumping mechanisms, decision flow charts for selecting type of energy for water pumping, guidelines for selecting pumps and water pumping system design.
b) At the end of the Chapter, visit to water pumping solar PV installation site is arranged.

Instructor: The Trainer

Reference:

1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
7.1	Introduction	Lecture	Class room	30 mins.	
7.2	Water Pumping System Configurations	Lecture	Class room	30 mins	
7.3	Water Pumps	Lecture	Class room	30 mins	
7.4, 7.5	Motors and Integrated Pump / Motor Machines	Lecture	Class room	15 mins	
7.6	Power Conditioning Circuitry	Lecture exercise	Class room	15 mins	
7.7	Array Wiring and Mounting of Water Pumps	Lecture	Class room	15 mins	
7.8	Water Pumping System Design	Lecture and Design exercise	Class roonm	225 mins	
7.9	Installation Line Diagrams	Lecture	Class room	30 mins	
7.10, 7.11	Routine and Preventive Maintenance; Monitoring and Evaluation	Lecture	Class room	30 mins	

10.1 Introduction

Potable water is the one of the most important substance for survival of a living organism. According to Maslow's hierarchy of needs, water is considered as the second most important need, after clean air, for survival of human being. According to UNEP report more than 6,000 children are killed by contaminated water everyday, 3.5 billion people, about half the world's population, will face a water crisis by 2025.

The amount of water available to human beings on earth, the so-called Water Planet, is less than widely believed. The future of human beings depends upon on whether we can use the scarce resource of water with care and efficiency.

Breakdown of Earth's Water

As per the UNEP report, breakdown of the earth's water is shown as below (chart 10.1.1):

- The Earth's total water volume: 1.4 Billion Km^3
- Out of this, sea- water is 97.5% and fresh water is only 2.5%
- Out of available fresh water, glacier and eternal snow is 68.9%,
- Ground water and frozen soil is 30.8% and
- Lakes and rivers consists of only 0.3% (0.105 Million Km^3)

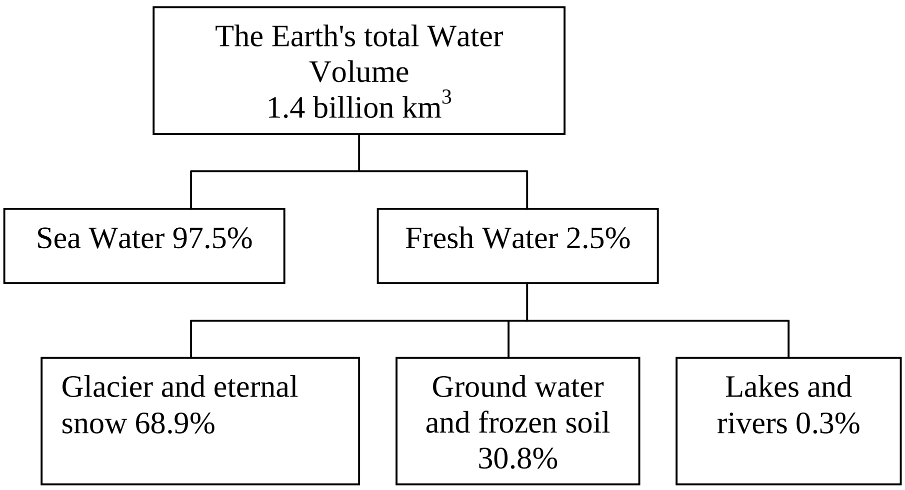


Chart 10.1.1 Breakdown of Earth’s Water

Fresh Water Scarce

Less than 0.01% of the water on the blue-clad planet is available to human being. The seawater accounts for 97.5% of the water surface and most fresh water exists in the form of polar ice or deep underground water.

It is interesting to mention that if the earth were one meter in diameter, the amount of available water would be just a spoonful.

The shortage of "sparse and valuable" water has got more acute in the 20th century as a result of the world population explosion, tripled in the past 100 years, while water consumption exploded six times in the same period.

About 2,3 billion people, or 40% of the world's population, are suffering from water shortfalls. About half of agricultural-use water, which accounts for 70% of the global usage, is wasted in evaporation and effluence.

Contaminated water causes some 80% of diseases in developing countries, and sales of mineral water are increasing sharply.

One-fourth of the world population depends on underground water. In most rural areas water scarcity is even prominent. In practice a significant amount of water is being pumped out either from underground source, or rivers or lakes or springs etc.

Nepal is not an exception. Due to its specific topography most remote areas do face scarcity of potable water resulting in more than 80% water borne diseases. One way to avail water to these areas is to pump water from appropriate sources using available electrical energy. In areas where national grid is not available and no other economic alternatives exist; Photovoltaic Water Pumping System (PVWPS) could be used. Such system is expensive, sophisticated and delicate. Therefore optimum designing of PVWPS needs critical engineering considerations. Apart from this, socio- economic analysis is a must to justify the application of chosen PVWPS in a given location for given conditions.

Water Wealth of Nepal

Nepal is rich both in surface water and ground water including springs. The estimated ground water is more than 14 billion cubic meter. There are 9 big and small basins consisting of 6000 rivers and streams totaling about 45,000 km in length. The total flow from all the basins is estimated at 6,561.36 cubic meters per second.

10.2 Water Pumping System Configurations

There is a range of possible components and configurations for photovoltaic water pumping systems, as shown in figure 10.2.1. Selection of the most suitable components and configurations for each specific application and site is critical to the economic viability and the long-term performance of the system.

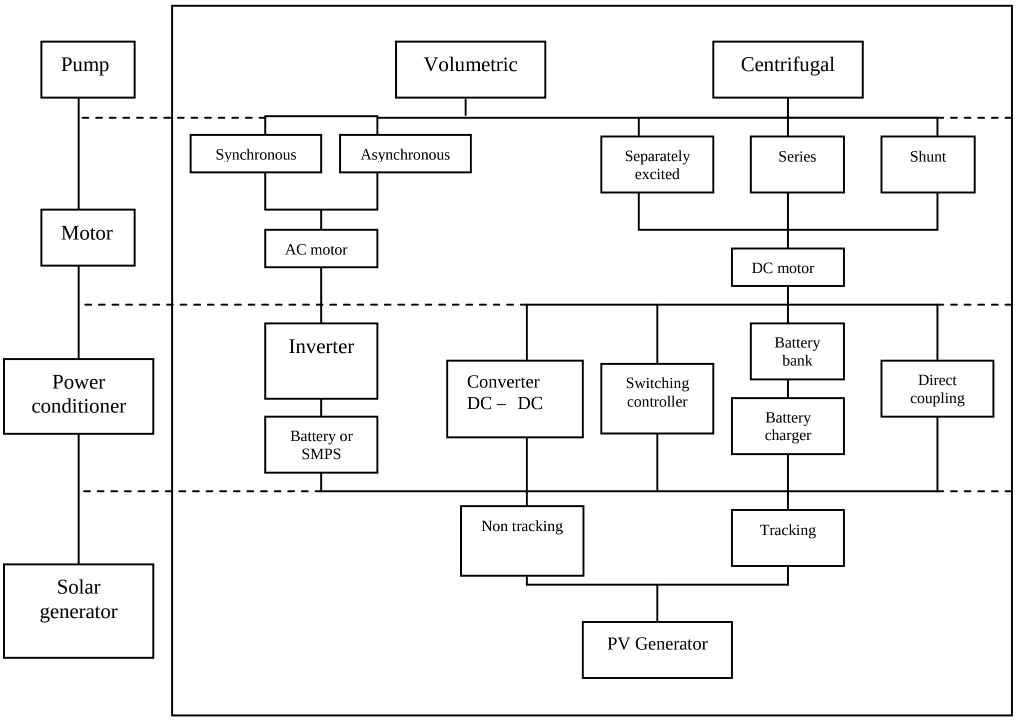


Figure 10.2.1 Photovoltaic Water Pumping System Components and Configurations

In the simplest photovoltaic water pumping systems, the solar panels are directly connected to a DC motor that drives the water pump. For such simplified systems, DC motors and centrifugal pumps are virtually mandatory, due to their ability to be matched to the output of the solar panels.

Volumetric (also known as positive displacement) pumps have completely different torque – speed characteristics and are not well suited to being directly coupled to solar panels, when volumetric pumps are used, it is therefore common for power conditioning / maximum power point tracking circuitry to be included between the solar panels and the motor / pump to convert the electrical energy into a suitable useable form. Similarly, ranges of motor types are used for water pumping systems, including DC series motors, DC permanent motor, DC permanent magnet brush less motor, AC asynchronous induction motors and AC synchronous motors.

As with the different types of pump, each motor has its advantages and disadvantages, which determine suitability to particular applications. In case of AC motors, an inverter must also be included between the solar panels and the motor.

Batteries

Batteries for energy storage are sometimes necessary in pumping systems, particularly if it is critical that pumping takes place at particular times, if pump rates exceed replenishment rates for the water source, or even to provide power conditioning for the pump / motor. Batteries have the benefit of holding the operating point of the solar panels near their maximum power points. They can thus be considered to be a "power conditioning" element in the circuit between solar panels and motor, although they may also be used to provide energy storage for a period of days during poor weather. Wherever possible, the use of batteries or other forms of storage should be avoided due to:

- their relatively short life expectancies
- requirements for maintenance
- poor reliability
- high cost
- need for protection by a voltage regulator.

In fact system becomes quite complex if an AC motor is used with a volumetric pump. Batteries or power conditioning circuitry may used to provide the high starting currents, although if batteries are used, a voltage regulator at their input and an inverter at their output, to drive the AC motor, are necessary. In addition, the speed of a volumetric pump is not well matched to that of an AC motor, thus necessitating some form of transmission wit appropriate gearing.

10.3 Water Pumps

The two broad categories of pumps are generally used for PV powered pumping systems: centrifugal and volumetric (displacement) pumps.

- *Centrifugal Pumps*

Centrifugal pumps have a rotating impeller that throws the water radially against a casing so shaped that the momentum of the water is converted into useful pressure for lifting. They are normally used for low head / low pressure applications, particularly if direct connection to the solar panels is required. They are well suited to high pumping rates and due to their compactness; wherever small diameter bores or well exists. Centrifugal pumps are characterized by the torque being proportional to the square of the speed (angular velocity of the impeller).

These pumps have relatively high efficiencies, but rapidly loose pumping performances as their speed reduces and in fact do not pump at all unless quite substantial spin speeds are achieved. This is a problem for a PV powered system when light intensity is reduced. Maximum speeds performance is achieved at high spin speeds, making them easy to match to motors, which tend to develop maximum torque (maximum efficiency) at similar speeds.

For conventional centrifugal pump designs, high efficiencies are only obtained for low pumping pressures and hence relatively small pumping heads of less than 25 meters. To overcome this limitation, either multistage or regenerative centrifugal pumps can be used. With the latter, water that leaves the pump under pressure is channeled back through cavities in the casing into an adjacent chamber, where it is pumped to a greater pressure, hence making suitable for increased pumping heads.

Efficiencies of these pumps, however, tend to be a little lower, due to leakage of water from the high-pressure chamber to the low-pressure chamber. In addition, the clearances between impellers and casing need to be substantially less to give good performance, which creates reliability problems. Another modification to suit centrifugal pumps to larger heads is to include a water injector (jet pump). However it is more common to use multistage centrifugal pumps for larger heads. These have been used successfully to pump water up to heights of 100 meters.

Other advantages of centrifugal pumps include their simplicity (with a minimum of moving parts) and corresponding reliability, low cost, robustness, tolerance to pumping particulates and low starting torque. On the other hand, another potential limitation of centrifugal pumps is their inability to be self-priming. Consequently, they are frequently used as submersible pumps, preferably in conjunction with a submersible motor.

For many years this has been a problem, since the preferred DC motors were not submersible due to the presence of the brushes. Long driving shafts were therefore necessary required between motor and pump, which in turn lead to other complications. For this reason, submersible AC motors were often used, despite their lower efficiencies and requirements for inverters.

More recently, however, submersible DC motors have become more readily available. In these, electronic commutation is used to remove the need for brushes.

Another alternative has been the use of self-priming centrifugal pumps (side pumps) where a chamber containing water at the side of the pump keeps the pump effectively submerged and hence primed.

The major trade-off involved with the design and use of centrifugal pumps is the requirement for high efficiency versus the need for an impeller with long life and good tolerance of aggressive impurities in the water. High efficiency can be obtained with small clearances and narrow passages, but this is undesirable for pump reliability ad the ability to pump liquids contaminated with particles. In addition, high efficiency can be obtained with a high speed impeller which again acts to shorten the life of the pump. In summary, pumps need to be designed and selected for specific application and environments.

- *Volumetric Pumps*

Volumetric or positive displacement pumps are the other class of pumps often used for water pumping applications, particularly for lower pump rates from deep wells or bores. Examples of volumetric or positive displacement pumps are poster pumps, diaphragm pumps, rotary – screw type pumps and progressive cavity pumps.

The pumping rate with these displacement pumps is directly related to the speed of operation, with a fairly constant torque required. The resulting flat torque / speed characteristic makes it almost impossible to drive these pumps directly from a photovoltaic source. This is because the torque developed by a motor is directly dependent on the current in the armature.

The requirement for this to remain approximately constant (to suit a constant torque pump) therefore requires an approximately constant current. This type of load is not will matched to the output of solar cells, where the current generated is directly proportional to the light intensity.

For instance, if operating torque corresponds to a current from the solar panels that closely matches their maximum power under bright sunshine, and then a small reduction in light intensity will result in insufficient current being generated to maintain the pumping speed. The pump / motor will accordingly slow down in pumping rate so as to require less current. However due to the flat torque / speed characteristic, the pump will actually cease entirely whenever the current generated drops below the critical level. To prevent this happening for the large parts of the day, a critical current would have to be selected that was well below the maximum current generated by the solar panels through the day. This means sacrificing much of the power generating capabilities of the solar panels, hence producing a system with low overall efficiency.

The other problem limiting the use of these pumps in direct connection to solar panels is the high starting (breakaway) torque associated with binding of the seals. Furthermore, the low number of strokes per unit time of volumetric pumps necessitates the use of an appropriately geared transmission to match to the speed of the motor, which adds a further complexity to the system.

In opiate of these limitations, for large heads (>20 m) the efficiencies obtainable exceed those of single stage centrifugal pumps, particular under part load conditions. Along with this benefit, it is important to understand the implications of using these pumps under part load. Under part load, these pumps require the same current but reduced voltage, due to the flat torque/speed characteristic. This is not compatible with photovoltaic output and hence power-conditioning circuitry would be required before this benefit could be utilized.

Another benefit of volumetric pumps is that they are less sensitive to head variations (seasonal and during pumping) and are self-priming, which alleviates the need for submersible motors and long driving shafts between motors and pumps.

The performance of volumetric pumps is quite poor for small heads, due to the large component of friction. The exception to this is perhaps the free-diaphragm pump, which has low internal friction and hence may be well suited to low heads.

The best-known volumetric pump is the reciprocating piston type ("bucket" pump), which is the sort, used in hand pumping. These can be powered by hand, diesel, wind or electricity, but as with other volumetric pumps, suffer from poor efficiencies below heads of 10-20 meters.

The figure 10.3.1 provides basic guidelines for selection of the pump depending upon the total system head and daily pumped volume of water.

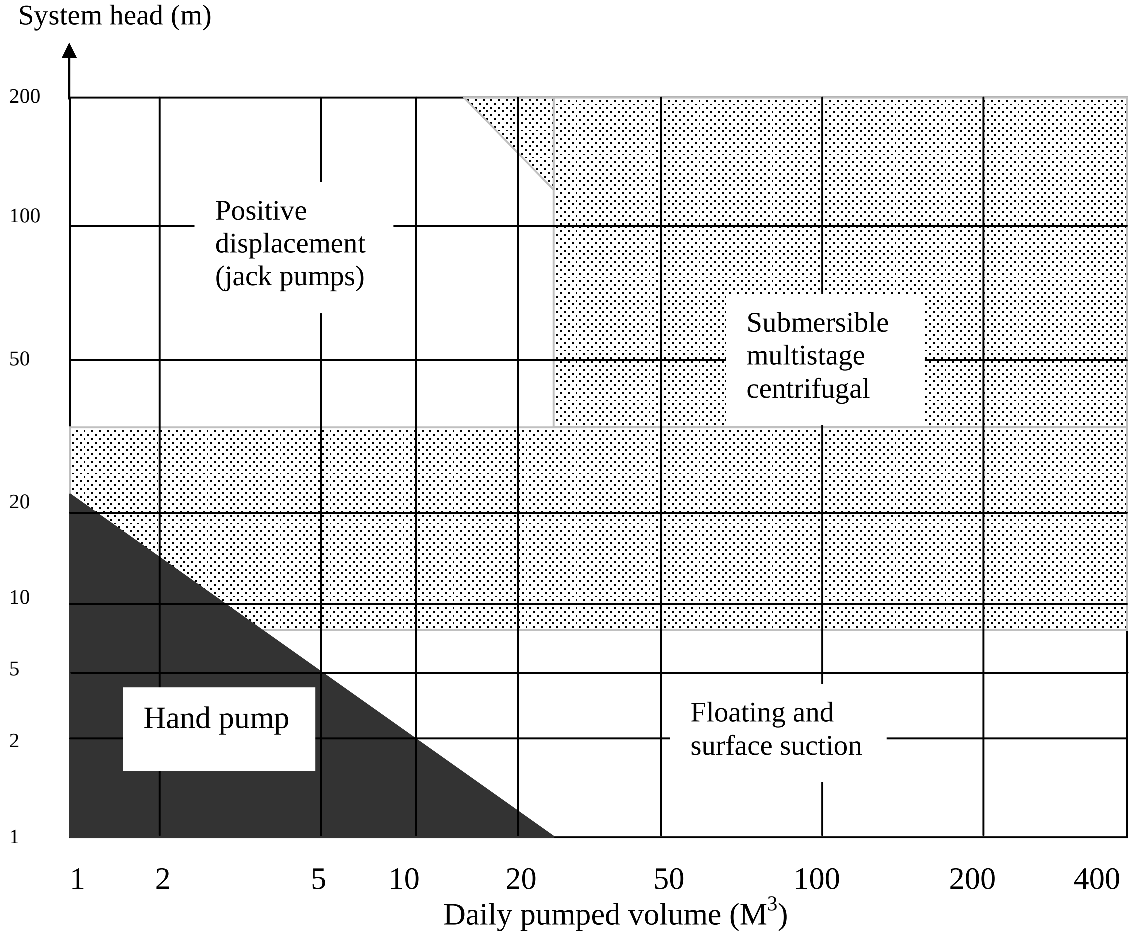


Fig. 10.3.1 Guideline chart for selection of pump

10.4 Motors

Small motors (< 2 kW) of high efficiency that are well suited to PV water pumping are still relatively rare.

Due to relatively high cost of solar panels, it is often suitable to use the more expensive DC motor to gain the efficiency advantage. However, the trend in PV is for prices to fall in coming years. This will tend to shift priorities away from efficiency as being the dominating feature in motor design, in favor of lower cost, lower maintenance machines. Other applications where DC motors are preferred are where direct coupling to the PV panels is required. However AC motors in general, tend to be cheaper and more reliable, which often complicates the choice. With current prices, AC motor are economic compared to DC motors for PV pumps where:

(Flow rate x water head) > $600m^4$ / day.

In recent years, there have been significant developments with small (typically 1-3 kW continuous rating) DC brush less permanent rare earth magnet motors. These developments have been stimulated by the demands of highly competitive, high budget, international solar car races. In the 1993 World Solar Challenge, motor efficiencies as high as 96% have been reported, although corresponding costs are high. It should be noted that heat losses and dissipation primarily determine the corresponding power handling capabilities, with the consequence that these small, high efficiency motors can handle relatively large amounts of power.

The Brush less DC Motor has the permanent magnets in the motor and electronically commutates the stator to alleviate the need for brushes. The electronic commutating circuitry constitutes a parasitic power drain, but no more than the series resistance losses of conventional brushes. These motors are commercially available but, being relatively new, still suffer from poor reliability while designs are being optimized. They also cost more, due to the need for additional windings. The major advantages of being brush less include the ability to be submersed and the potentially reduced maintenance by alleviating brush replacement.

The first three DC motor types have the severe limitation of requiring brushes. In many situations the presence of brushes is not a problem. However, for PV applications where system reliability must be extremely high and maintenance low, their use may be considered unacceptable. Brushes require periodic replacement (1-5 years) and the carbon dust from wearing brushes may cause arcing, overheating and considerable power loss. If replacement does not take place when required, serious damage may result. It is therefore essential that a failsafe brush design be employed to stop motor operation, before such damage occurs.

The other limitation of brushes is that they prevent the motors from being submersed. This restricts their use with submersible pumps except via undesirable long transmission shafts. This in itself is quite unfortunate since conventional centrifugal pumps are normally submersible and due to their torque / speed characteristics, are the most suitable of all pumps for direct coupling to PV panels.

General advantages and disadvantages of DC motor include:

Advantages:
- high efficiency
- no need for an inverter
- suitable for direct coupling to PV panels

Disadvantages:
- restricted range of brushless types available
- reliability still unproven
- brushed type not submersible
- brushed type need higher maintenance
- relatively expensive
- not readily available in sizes larger than 10 HP.

- *AC Motors*

A wide range of AC motors are commercially available, due to the wide range of applications for which they have been used for many years. However, with most of these, the emphasis has been on low cost rather than operating efficiency. In particular, small motors of about 1 kW or less suffer from very low efficiencies, making them not suitable to PV powered systems. In addition, they require costly inverters at their Inputs, which have further added reliability problems.

Furthermore, to provide the high starting current, additional power conditioning circuitry is generally required. AC motors are, however, in general very reliable and relatively inexpensive, being typically half the cost of an equivalent size DC motor.

The two basic types of AC motors available are asynchronous induction motors and synchronous motors. However, standard induction motors produced extremely low starting torques, making them suitable only for low starting torques pumps such as centrifugal pumps, unless appropriately modified to increase the torque generated at high slip frequencies.

Motor Losses

- *Support Bearings*

Friction in the support bearings has a load dependent and term and a load independent term, jointly contribute significantly to the losses in high efficiency motors.

To achieve high reliabilities and low maintenance, lubrication with grease is essential. Although expensive, high quality lubrication grease that has a temperature independent kinematic viscosity is recommended, and has been demonstrated to reduce frictional losses up to 60%.

- *Magnetic Circuit*

Imperfections in the magnetic circuit will always contribute losses although, if properly designed, should be quite small, poor motors (low efficiency) generally have losses in the magnetic circuit as the dominant cause of poor performance. Permanent magnet motors generally use Al – Ni – Co permanent magnet and need careful designing to ensure operation at the maximum of their BH product.

- *Motor Heating*

Motor heating can be a serious loss mechanism and can lead to lower reliabilities and shortened life times. As the temperature increases, the resistance of windings increases, thereby increasing the resistive losses, which in turn acts to further increase the motor temperature. It is therefore necessary to keep motors cool, both to achieve high performance and to increase reliability and lifetimes.

Submersible motors are easily kept cool, but surface mounted motors may need special attention paid to cooling, such as by a heat pipe or ventilation.

10.5 Integrated Pump / Motor Machines

As the PV powered water pumping industry develops, a wider range of motors and pumps are becoming available. It is therefore essential for an engineer designing such systems to keep up to date with new product developments and associated field-testing.

Recently, integrated pump / motor machines have become popular where the pump and motor are matched and interconnected within the same housing by the manufacturer. Such configurations act to simplify systems and provide high efficiencies when operating at or near their design point.

However, careful attention should be paid to performance losses and mismatch that results from using these machines away from the design point, such as with a different head or flow rate.

The tables 10.5.1, 10.5.2 and 10.5.3 below provides quick guide for selection of different pumps based on the merits, demerits and applications.

Table 10.5.1 Types of pumps

Centrifugal	Positive Displacement (Volumetric)
• Self-priming surface • Jet pump • Vertical turbine • Submersible • High speed impellers • Large volumes • Moderate head • Loss of flow rate with higher head • Low irradiance reduces ability to achieve head • Possible grit friction	• Helical cavity • Jack pump • Diaphragm • Volumetric movement • Lower volumes • High head • Flow rate less affected by head • Low irradiance has little effect on achieving head • Unaffected by grit

Table 10.5.2 Merits and demerits of connecting PV pumps directly to array or battery powered

Connection	Merits	Demerits
Directly coupled to array	• Simplicity • Reliability • Low maintenance • Low cost • Quick to install	• Low efficiency • No water at night
Battery powered	• Predictable supply • Higher efficiency • Supply of starting surge current • Availability of water when required	• Maintenance complexity • High cost • Charge control failure

Table 10.5.3 Merits and demerits of different types of pumps

s/n	Pump type	Merits	Demerits	Applications
1	Self-priming Surface pump	• Single impeller • Can be used with common DC motors	• Limited to atmospheric pressure for suction (maximum 7 m) • Must be primed before each start up	• flood irrigation • Moving water along the land through pipelines
2	Jet pump	• Increased effective suction head (max. 30 m) • Venturi could be place in front of the impeller chamber or at the input of the suction pipe	• Decreased net flow • Inefficient due to low net flow rate	• Surface pumping
3	Vertical Turbine pump	• Multi-stage impellers allowing deep pumping at high rates	• Head limited by shaft length • Efficiency is reduced due to twisting, friction, vibration and weight of shaft and bearings	• Used for large scale irrigation with large AC or diesel motors
4	Submersible pump	• Can pump water from high depth (300m) • Water-proof motor connected directly to multi-stage impellers • Brush less DC operation possible with electronic commutation	• Low flow at high head • AC motors require surface mounted inverter	• Drinking water supply system • Drip-irrigation system
5	Helical cavity pump	• Can move very gritty water • Can use MPPT to supply surge power • High head applications	• Torque, friction and vibration losses • Small or moderate volume of water discharge	• Drinking water supply system • Drip-irrigation system
6	Jack pump	• High head applications • Both AC and DC motors can be used	• Low discharge • Needs frequent maintenance	• Drinking water supply system
7	Diaphragm pump	• Simple to operate • Medium to high head	• Low to medium flow rate	• Small scale water supply system

10.6 Power Conditioning Circuitry

The role of power conditioning circuitry is to provide the motor/pump with the most suitable voltage / current combination, while ensuring the solar panels operate at their maximum power points. In effect, it alters the load impedance to match the optimum impedance of the array.

The circuitry of course must consume very little power to justify its inclusion, and in most systems, will typically consume 4% to 7% of total power. It is also expensive, usually costing more than the electric motor, while unfortunately often providing problems with regard to reliability.

As the light intensity falls, the current generated by solar panels falls proportionately while the voltage at the maximum power point remains approximately constant. However, for a motor / pump, as the current falls, the voltage also falls. Consequently, without power conditioning circuitry, as the light intensity falls, the solar array operates at a current and voltage progressively further and further from its maximum power point.

For instance, with centrifugal pumps, the torque is approximately proportional to the speed squared, while the torque produced by the motor will be directly related to the current flowing in the motor windings. Consequently, as the current from the solar array falls, the torque produced by the motor falls, the speed of the pump therefore decreases, the back emf produced by the motor correspondingly falls, and hence the voltage required by the motor falls. In this situation for a DC motor, the required form of power conditioning is for DC to DC converter, to effectively convert the excess voltage able to be produced by the solar panels into additional current.

For positive displacement pumps, the torque required for pumping is, in general, dependent primarily on the pumping head, pipe and pump friction, and pump pipe diameters, but depends little on the speed of pump operation if high break away torques are neglected. In this instance, a certain threshold current is required by the motor to provide the torque necessary to maintain operation of the pump. Primarily the driving voltage then determines the speed of pumping, as the pumping rate will increase until the back emf produced in the motor matches the applied voltage from the solar panels. Consequently, the motor / pump load line appears as a horizontal line when superimposed on the current / voltage characteristic of the solar panel. This is an unacceptable mechanism of operation since the falling of the array current below the required level will result in no pumping at all while current generating potential above the critical level will be wasted. Again, a DC to DC voltage converter is required and, in fact, is essential when a DC motor is driving a typical positive displacement pump.

In addition, the high starting (breakaway) torques requires high starting currents, which in general cannot be supplied by the solar panels. When starting, the speed is zero and there is no back emf produced. Consequently, a DC to DC converter can again be beneficially used to produce the high starting currents by effectively converting the excess array voltage into current. An alternative approach commonly used for providing high starting currents is through the use of a "starting capacitor" which stores sufficient charge to provide a large current burst to start the motor / pump.

Maximum power point tracking (MPPT) circuitry may be included in any system to boost efficiency. A well-designed system using a centrifugal pump will automatically have an acceptable match between the solar array and sub- system over a wide range of insolation levels. In this instance, no control circuitry is warranted, other than perhaps water level switches or pressure switches. If, however, a MPPT is to be used, ensure internal transient protection is included, to minimize the risk of damage in the event of lighting strikes.

10.7 Array Wiring and Mounting of Water Pumps

Array Wiring

Array cables should be heavy duty, with all connections in watertight function boxes with strain relief connectors. The gauge of wire should be selected so as to keep resistive losses to less than 2.5%. For reliability, splicing of the leads from the motor to the array output cable should utilize crimp-on connectors with resin filled heat shrink tubing or equivalent or equivalent, to ensure long lasting, dry connections. All wiring should be attached to support structures with nylon wire ties. PVC conduit should be used for the array output wiring to well, regulator or batteries. For a submersed motor / pump, heavy duty doubly insulated cable is essential. Also, the array and mounting frames need to be grounded using substantial copper wire. Grounding through the motor / pump and well should not be relied upon as the system may be dismantled for various reasons. Lightning protection should be considered, and bypass and blocking diodes should be included where appropriate.

Array Mounting

All support structures should be anodized aluminum, galvanized or stainless steel and need to be designed to withstand the maximum possible wind loading for the particular location. Lock washers or equivalent should be used on all bolts to remove risk of them coming loose during the subsequent 20 years. The structures should be located as close as possible to the well to minimize wire lengths, and where necessary fencing may be utilized to protect from animals, theft, vandals etc.

Tracking support structures can be useful to enable the solar panels to point more directly at the sun throughout most of the day. Motorized or passive tracking mechanisms, although cost effective in terms of electrical energy produced per unit cost, introduce considerable maintenance and reliability problems. However, a more feasible alternative is to use a manual tracking system, whereby a simple adjustment by an operator can take advantage of the changing sun position. One such regime is where a seasonal adjustment of the tilt angle is made four times each year, to compensate for the variation in the sun's angle of declination. Another form of adjustment allows for redirection of the solar panels twice a day taking greater advantage of both the morning and afternoon sun.

It should be noted that the concept of manually redirecting the solar panels is dependent upon the availability of an operator, which for some remote or inaccessible locations may not be feasible or practical. However, the studies have indicated that a simple manual tracking system requiring two adjustments per day could increase daily efficiency of the system as high as 30%.

10.8 Water Pumping System Design

PV powered water pumping is becoming very popular. The design of each system is considerably more complicated than most applications due to the large range of water sources types, consumer requirements and system configurations.

Where batteries are required for storage, design procedures are relatively straight forward and follows the design principles for "stand alone" systems. However, direct interfacing between the PV panels and the water pump motor introduces significant mismatch problems as the light intensity varies. This leads to a large variation in overall system efficiency throughout each day and between "sunny" and "cloudy" weather, making it inappropriate to assume that the power delivered to the load is directly related to the light energy incident on the solar panels. It is therefore necessary to process insolation data differently for directly coupled systems. The basic design principles are given here with some worked out examples at the end.

Basic Steps in System Design

Designing a PV water pumping system has two very important aspects:

- selection of the most suitable system component types – this is crucial in providing a low maintenance, long life system of reliability;
- matching of system components – this is a difficult area requiring considerable know-how and expertise, and will ultimately be responsible for the performance of the system with regard to efficiency of operation.

Improved matching can increase operating efficiency (18% case study) apart from 30% increase in efficiency due to manual tracking.

One of the most important questions to be asked before designing a particular system is: "what level of reliability is necessary and to what extent can maintenance be carried out?"

To answer this will indicate a bias towards either a direct-coupled system with simplicity, reliability, low maintenance and long life, or a system, which sacrifices these attributes, to an extent, in order to gain greater efficiency. The features included in the latter, which contribute to the increased complexity, higher maintenance, poorer reliability and shorter life expectancy, include power conditioning circuitry, inverters and perhaps batteries.

Other constraints influence the type of system selected, and each system needs to be designed on its own merits. No one system will be ideal for all application and of all PV applications, water pumping probably introduces the greatest variability of system design with regard to configuration and component selection.

Several computer simulation and design tools are now available to assist designers. However, their use requires a high level of water pumping knowledge and good data on site selection and component performance.

The general approach to designing a system can be summarized as follows:

- Determine the volume of water to be pumped each day,
- Determine the total head
- Calculate the pump rate from the number of sunlight hours (based on peak sun)
- Select the pump
- Calculate the torque-speed characteristic of the pump, select a motor with a compatible torque-speed characteristic;
- Select appropriate solar panels

For a system using batteries, step (f) simply involves the use of "stand-alone system" design principles.

However, prior to following these guidelines, it is useful to ascertain whether a directly coupled system (no batteries, no inverter and no power conditioning circuitry) is feasible for the particular application. If so, such a system is strongly recommended, even though its use provides little flexibility in component choice and system configuration. However, there are occasions when directly coupled systems are unsuitable. These include:

(i) When pumping heads are too large to be able to use a centrifugal pump with reasonable efficiency;

(ii) When suitable DC motors are not available, such as with some large systems (greater than 10HP) where little choice exists, or when a submersible motor is necessary and no brush less DC motors are available at a suitable price;

(iii) When the pumping rate in bright sunshine exceeds the water source replenishment rates;

(iv) When it is essential batteries be used for energy storage (i.e. where "availability" of pumped water must be very high and tank storage is unsuitable) e.g. portable units;

(v) Locations characterized by excessive cloudy weather making the poor part – load efficiencies of a directly coupled system unacceptable.

It should be recognized that the PV water pumping industry is evolving rapidly, with the potential to make any preferred design criteria obsolete in a matter of years. For instance, the preference to avoid power conditioning circuitry and the like could change if new developments, combined with field experience, indicated adequate reliability and performance could be achieved, or if a new type of positive displacement pump or AC motor prove vastly superior and more economical.

- *Design of a Directly Coupled System*

A directly coupled system is one where a low starting torque (such as a centrifugal pump) can be driven by a DC motor that receives its power directly from the solar panels. No batteries, inverters or power conditioning circuitry are used, other than perhaps safety cut-out relays activated by level, flow or pressure sensing transducers. When the sun shines brightly, the system operates and water is pumped either for storage or direct use.

An approach for designing directly coupled PV powered water pumping must include the following considerations:

(i) The volume of water to be pumped and over what period. The volume to be pumped may vary significantly throughout the year and in fact may be entirely non-critical for some months of the year, as for some irrigation applications. This will have important implications regarding array tilt angles.
For instance:

(a) if the demand profile throughout the year is reasonably constant (such as for a domestic water supply) , a tilt angle in the vicinity of latitude +20º will be necessary to give the most uniform insolation levels throughout the year falling on the solar panels ;

(b) if the amount of water to be pumped out is to be uniform throughout the year , but with a definite bias towards summer months (such as for drinking water) , a tilt angle in the vicinity of latitude +10º will probably be desirable ;

(c) if the annual amount of water to be pumped is to be maximized (such as with a large storage reservoir) a tilt angle in the range latitude -10º to latitude should be used :

(d) if the water pumped during summer months is to be maximized (such as for some irrigation applications) a tilt angle in the vicinity of latitude -20º will be preferable, to ensure the solar panels point directly at the summer sun. In general, increasing the tilt angle will provide more uniform pumping throughout the year.

(ii) The pumping head and its seasonal variations must be known and where possible, information regarding water source replenishment rates should be obtained.

(iii) The inclusion and economics of water storage should be considered in conjunction with consumer needs.

(iv) Any available insolation data should be obtained and (used in conjunction with the local conditions e.g. for determining the light intensity incident on the solar panels at certain angle during morning, noon or afternoon).

(v) Select a pump to suit starting torque requirements, the range of operating heads, and physical dimension constraints imposed by the application and one that will pump the required volume of water when operating at its maximum efficiency point. It is essential the torque / speed characteristics of the selected pump to be known, to facilitate system matching.

(vi) Select a motor with a torque / speed characteristic compatible with that of the pump. It is important that the motor operate near maximum efficiency when producing the necessary torque, to drive the pump at its design speed.

(vii) Appropriate sizing of the PV system will enable overall system specifications to be met, while simultaneously maximizing overall system efficiency. For this, both the voltage and current at maximum power point need to be optimized. Unfortunately, little choice exists with regard to the voltages available on standard commercial modules. They are normally designed for 12-volt systems (including considerable excess voltage capacity to allow for battery charging, regulation, blocking diode etc.) and can be connected in series to increase system voltage to multiples of 12 volt. In comparison, a reasonable choice in short circuit currents exists, due to the range of solar cell sizes and technologies used by different manufacturers.

Array sizing

For a simple schematic shown in figure 10.8.1 the hydraulic energy in kWh/day needed to pump water at a volumetric rate V is given by formula 10.8.1:

$$E_H = \rho V g H / \eta_p \qquad (10.8.1)$$

Where is:

- V - is the total volume required per day
- H - is the total dynamic head
- ρ - is the density of water,
- g - is the acceleration due to gravity, and
- η_p - is the pump efficiency.

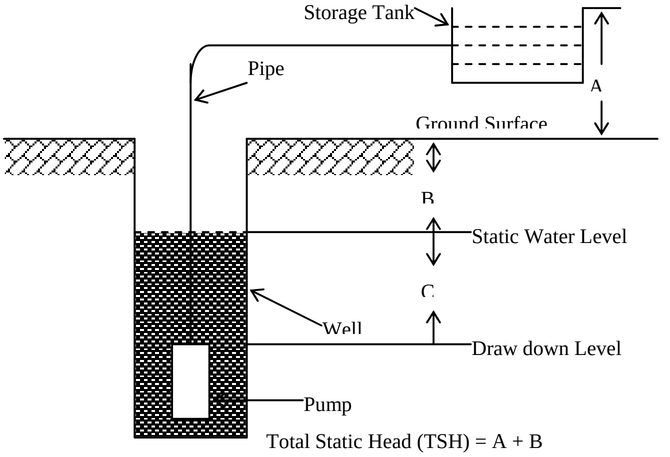


Fig.10.8.1 Schematic diagram of water pumping system

Example10.8.1
Problem

Calculate hydraulic energy required to pump 1000 litres/day from a depth of 35 meters. Assume pump efficiency to be 100%.

Solution

Hydarulic energy E_H can be calculated using formula 10.8.1:

$E_H = \rho \text{ x } g \text{ x } V \text{ x } h$, Joules ($\eta_a = 1$)

Where,

ρ - density of water, 1000 kg/m^3
g – acceleration due to gravity, 9.81 m/sec^2
V - required volume of water 1 m^3/day
h – total head to be pumped, m.

Substituting the above values,
$E_H =$ 1000 kg/m^3 x 9.81 m/sec^2 x 1 m^3 x 35 m = 0.343 MJ = 95 Wh
(1 kWh = 3.6 MJ)

The pump efficiency η_p is a function of the load (head and flow-rate) and is available as a characteristic curve from the manufacturer. For general design purposes typical values given in Table 10.8.1may be used. The table lists two basic types of pumps, centrifugal and positive displacement. These pumps can be driven by AC or DC motors. DC motors are preferable for the PV applications, because they can be directly coupled to the PV array output. Centrifugal pumps with submersible motors are the optimum for PV applications because of their efficiency, reliability and economy. However, for deep wells

Jack pumps may be necessary. Jack pumps are the piston type of positive displacement pumps that move chunks of water with each stroke. However they require very large currents, therefore they are connected through batteries.

Table 10.8.1 Typical Range of Pump Performance Parameters

Head(m)	**Pump Type**	**Wire to water efficiency (%)**
0-5	Centrifugal	15-25
6-20	Centrifugal with Jet	10-20
	Submersible	20-30
21-100	Submersible	30-40
	Jack pump	30-45
>100	Jack pump	35-50

The array size in kWp now be calculated using the following formula 10.8.2

$$P = (E_H) / (S \times F_m \times F_t) \qquad (10.8.2)$$

Where is,

- E_H - Hydraulic Energy required in kWh / day
- S - Average daily solar insolation – peak sun in hours
- F_m - array / load matching factor, generally Fm = 0.8
- F_t - temperature derating factor for array power loss due to heat; generally 0.8 for warm climate and 0.9 for cool climate.

Pumping Design Based on Pump Manufacturers Data

Most of the renowned and reliable pump manufacturers provided very reliable chart for the selection of appropriately rated motor/pump combination. The only input required is the yearly average peak sun for the given locality, daily water requirements (m^3) and the total dynamic head. The manufacturers provide the system performance and instantaneous output graphs as illustrated in fig. 10.8.2 below.

Similar charts are available for pumps of various capacities meeting the daily water requirements and pumping head.

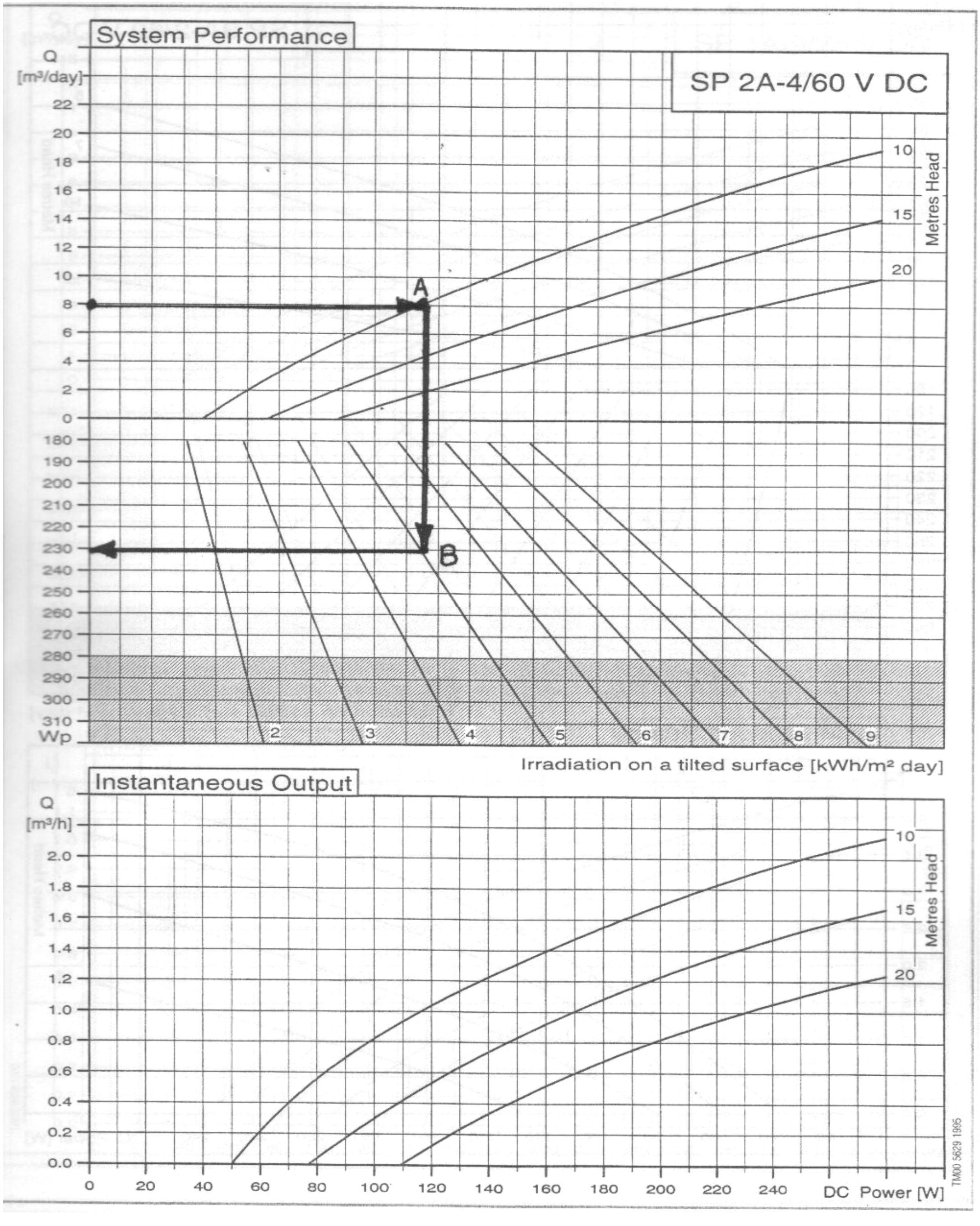


Fig. 10.8.2 System Performance and Instantaneous output chart

The steps in selecting appropriate pump would be as follows:

- consider the upper graph of the sample figure 10.8.2
- draw a straight line from the point in m3/day axis until it intersects with the curve with the required head in meters

- from the point of intersection A draw straight line down until it meets with the curve for given peak sun of the locality (intersection B)
- Finally draw horizontal line from B to the Y axis with Wp indication. And the reading in this axis is the required array power in Wp.

The example in the figure 10.8.2 is for daily water requirement of 8 m^3 with total dynamic head of 10 m in a locality with 5 peak sun. In this case the required array power is 230 Wp.

Now if the water requirement or the total height is greater than that mentioned in the curve, select the curve for higher capacity pump.

The results obtained from the manufacturers chart must also be verified by the results of calculations based on previously described formula. Alternately, the results of the calculation may also be verified using manufacturers charts.

Example 10.8.2

Problem

Select an appropriate PV pump and design PV array system for a water supply system for a village with following data:

Population:	250
Number of cattle head:	50
Average water consumption (human):	25 litres/day/person
Average water consumption (cattle):	40 litres/day/cattle
Monthly average solar insolation at optimum tilt:	5.5 kWh/m^2/day (Jan-May and Oct-Dec) 4.5 kWh/m^2/day (June-Sept)
Ambient temperature at pumping site:	warm
Pipe friction loss (equivalent):	1 m
Static head:	30 m
Draw down level:	5 m
Water source:	Dug well (with sufficient yield)
Coordinates of the site:	86^0 E, 28^0 N

Solution

A. Daily volume of water required = 250 people x 25 lts. + 50 cattle x 40 lts. = 8.25 m^3

B. Total dynamic head = static head + friction loss + draw down = 30+1+5 = 36 m

C. Design solar insolation = 4.5 kWh/m^2/day (minimum value selected for worst case)

D. As the site is in warm place, the temperature derating factor F_t can be taken to be equal to 0.8 (The exact value of drop in power can be calculated once the PV modules are selected and exact temperature variation is known).

E. For safe side operation, select mismatch factor between the array and pump Fm =0.9 (the exact mismatch factor can be calculated but the calculation is very complicated). When MPPTs are used, Fm can be taken as unity. MPPTs are costly and normally cannot be repaired in rural conditions. Therefore in most of the remote applications MPPTs are excluded.

F. Maximum discharge of water from the selected pump should therefore be equal to: total volume of water required/minimum available peak sun (in hours) = 8.25 m^3 / 4.5 = 1.83 m^3/hours, say 2 m^3/hour.

G. Now consult available PV pump catalogue and select the best pump to meet the discharge requirements. For example, Grundfos submersible solar pump 400 meets our requirement. This pump is designed for domestic water supply systems with a maximum head of 40 m and maximum discharge rate of 5.8 m^3/hour at 400 Wp PV power. Since the head required in our example is 36 m and the discharge rate is 2 m^3/ hour, Grundfos solar pump 400 would be appropriate one.

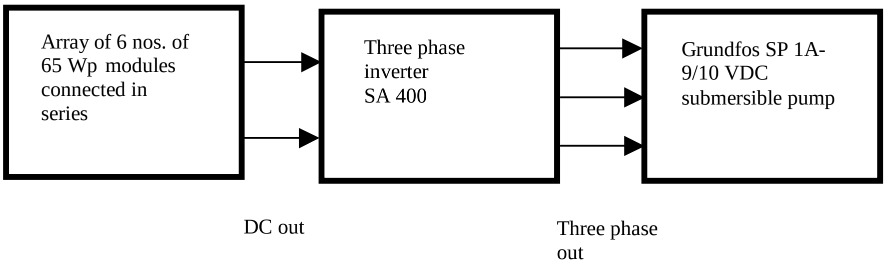
H. PV array power can be calculated once the head (36 m), flow rate (2m^3/ hour) and solar insolation (4.5 kWh/m^2/day) are known, Using Grundfos catalogue for solar pump 400 model SP 1A-9/10 V DC, we find the required array power to be 350 Wp.

I. The Grundfos solar pump 400 is powered by an inverter with nominal input DC voltage of 75V (minimum 63 V and maximum 83 V). The SA400 three phase inverter recommended by the pump manufacturer should be selected to operate the pump.

J. The total array power required is 350 Wp. The nominal voltage required is 75 V DC. If the output of a PV module is considered to be 12 V DC, then the number of PV modules to be connected in series will be equal to 75/12 = 6.25 or say 6.

K. Since total array power is 350 Wp and 6 modules are to be connected in series to achieve the voltage matching the inverter input, the peak power of each module should be equal to 350 Wp/6 = 58.3 Wp. We can select any module with peak watt not less than this value. Suppose a module rated at 65 Wp with Imp = 4 A and Vmp = 16.3 V is selected. Six number of these modules will provided a total of 391 Wp (4 A x 16.3 V x 6 nos.) which is greater than 350 Wp and hence meets the design requirement.

L. Finally, the installation line diagram would be as shown below:



The above design was based on the curves provided by the manufacturer of the pump. We can check the reliability of the design (i.e. array sizing) by applying simple calculations.

Hydraulic energy E_H calculated using formula 10.8.1:

E_H = (1000 x9.81x8.25x36)/ 3.6 x 10^3 = 0.8 kWh

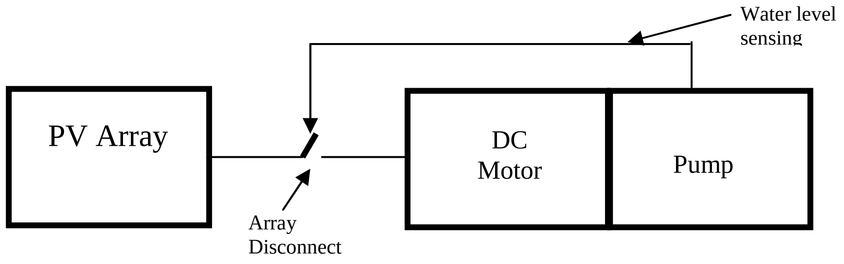
Peak PV power required is then

P = EH /(η x Fm x Ft x peak sun) = 0.8 / (η x 0.8 x 0.9 x 4.5) = 0.249/η kWp

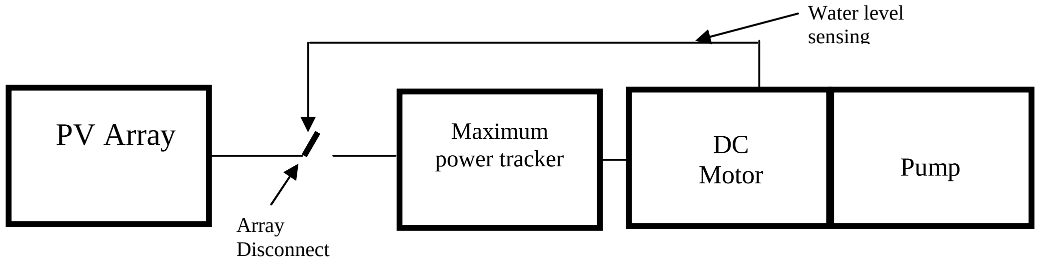
where η - Efficiency of the pump.
Now if η is taken as 70%, peak power of array would be 356 Wp which is close to our findings from the Grundfos pump design nomograms. In reality efficiency of submersible pump may not be as high as 70% and could be considerably less, in which case power calculated from Grundfos design nomograms may be increased for reliability of the design.

10.9 Installation Line Diagrams

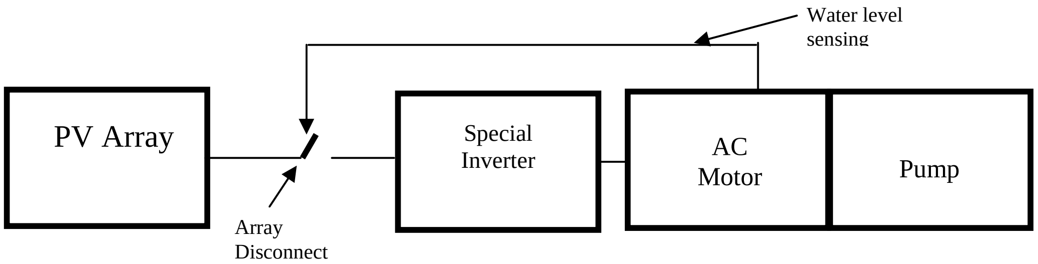
The schematic diagram for water pumping system can be prepared in similar manner as done with non-pumping applications. However, additional safety device like water level sensor has to be installed in the system. Moreover, the power conditioning devices such as maximum power tracker, if required by the pump, may be installed in the system. The suggested installation line diagram for various configurations is given in fig. 10.9.1 below.



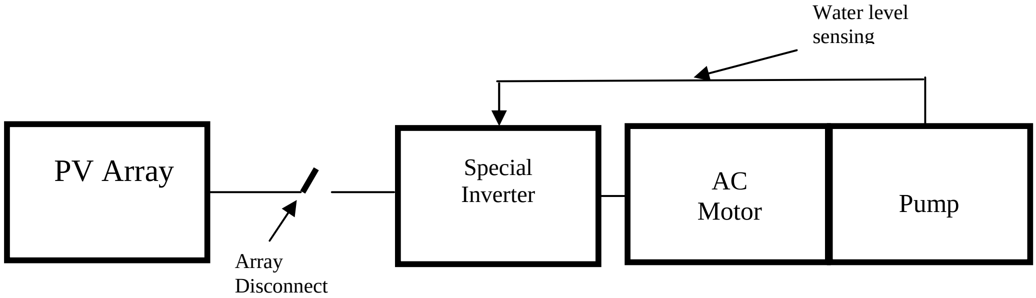
Directly coupled DC motor/pump



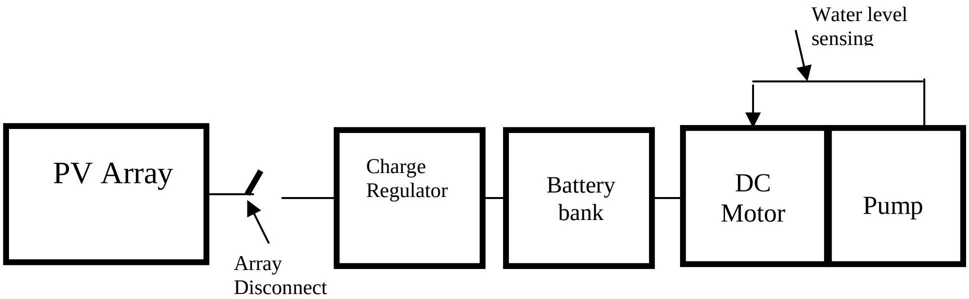
Directly coupled DC motor/pump with
Maximum power tracker



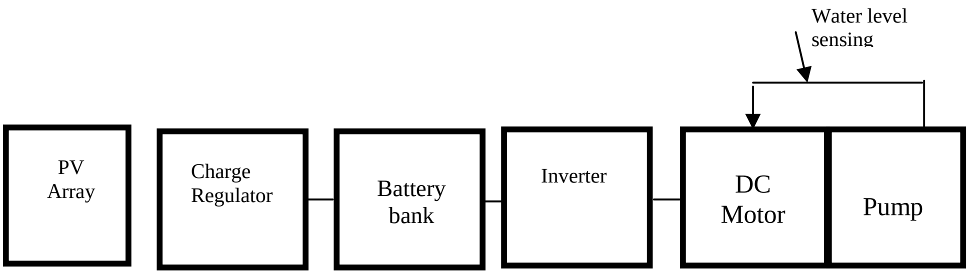
AC motor/pump with specially designed
inverter



AC motor/pump with specially designed inverter



DC motor/pump coupled through battery bank



AC motor/pump coupled through battery bank

Fig.10.9.1 Line diagrams for various combinations of system component

10.10 Routine Maintenance and Preventive Maintenance

While installing PVWPS every care must be taken to minimize the cable losses as far as possible by keeping pump and PV arrays as close as possible. The PV array is to be installed carefully at a proper location to avoid shadowing of any part of the array or other obstructions throughout the year. The array should be inclined facing south in case of Northern Hemisphere.

Solar pumps should not normally require more than a simple maintenance, which only demand rather basic skills. The main problem with them is lack of familiarity. The " black box" nature of solar pump components makes their function appear mysterious and may discourage local technicians from repairing it.

PV Array:

- Clean bird droppings if seen any time
- Clean array with water at least once a week
- Clean array with a damp cloth at least once a month

In some dusty areas more frequent cleaning may be necessary for increasing array efficiency.

***Pump*:**

- In case of submersible pump electrical connections have to be checked at least once every six months
- The brushes, if any, are to be changed after six months of continuous use.
- The inverter connected to the pump has to be checked at least once a month for proper operation.

Besides there are a number of simple faults that can arise which needs immediate corrections:

- Poor electrical connection caused by dirty, wet or corroded terminal or plugs
- Blocked strainers and filters on the pump
- Failure of suction pump due to loss of prime caused by faulty foot-valve or air leaks in suction line (specially in case of surface pump)
- Leaking pipe and hose connections
- Leaking pump gland seal
- Some pumps need frequent replacement parts as suggested by its manufacturers
- In case of positive displacement pumps, loosening of belts and chains may occur hence requiring tension adjustments.

In many cases the manufacturers may have special recommendations for routine and preventive maintenance. These recommendations have to be strictly followed for proper and safe operation of the complete system.

In each station there must be card mentioning the dates when routine and preventative maintenance are carried out. If any fault has been observed it must be registered in this card. This card must be accessible all the time at the site.

10.11 Monitoring and Evaluation of Installed water pumps

The purpose of Monitoring and Evaluation (M&E) is to make sure that the system works properly and satisfy the users as foreseen in the design phase and in the long run it becomes sustainable.

Monitoring and evaluations of installed pumps should be carried out after one month of complete and successful installation to answer the following questions:

- Is the system performing as per the specification of supplier (this may include parameters like discharge of water at specified total dynamic head, ambient temperature and insolation)?
- Has the system brought positive social changes in the area?
- Have the suggestions and comments of users group been incorporated?
- Have the users paid back the loan component in time if any?

The same procedure mentioned above should be repeated after six months, twelve months after a complete successful installation. Then after, monitoring and evaluation be carried out once every six months.

Review Questions

1. Which of the following is an important application of PV water pumping in remote locations?

    (a) Irrigation for paddy field with high head.
    (b) Drip-irrigation for cash crops with limited land area.
    (c) Drinking water supply system for population more than 10,000.
    (d) Drinking water supply system when required volume of water is less than $1m^3$

2. The power needed to pump water at a volumetric rate V does not depend on:

    (a) The pump efficiency
    (b) Frictional head loss in the pipe
    (c) Density of water
    (d) Constant drawn down

3. Lakes and rivers on earth contain

    (a) 0.105 million km^3 of fresh water
    (b) 3.5 million km^3 of fresh water
    (c) 1.05 million km^3 of fresh water
    (d) 0.75 million km^3 of fresh water

4. Which one of the following is not an disadvantage of diesel powered water pump?

    (a) Fuel shortages are common in many places
    (b) Good maintenance is difficult to obtain in remote areas
    (c) Portable
    (d) Relatively short useful life.

5. Which of the following pump is known as displacement pump?

    (a) Centrifugal
    (b) Volumetric
    (c) Diesel pump
    (d) Hand pump

6. Useful hydraulic energy is

    (a) Always less than mechanical energy
    (b) Always more than mechanical energy
    (c) Independent of mechanical energy
    (d) Equal to mechanical energy

7. Solar pumps are need when available solar insolation is

    (a) 1.5 kwh/m^2/day
    (b) 2 kwh/m^2/day
    (c) Greater than 2.8 kwh/m^2/day
    (d) Constant throughout the year

8. Any power required for solar pump does not depend upon

    (a) Temperature derating factor
    (b) Array lead matching factor
    (c) Number of peak sun available
    (d) Location of site with fixed coordinates

9. Find out the daily energy required to pump water for drinking purpose in a village with 100 people. The following data are available

    (a) Average water consumption: 20 litres/day/person
    (b) Static head: 40 meters; Maximum Drawn down: 3 meters
    (c) Equivalent friction loss in the pipe and the bends: 2 meters
    (d) Average efficiency of pump: 0.4
    (e) Water source: Dug well

10. Design a PV system to pump water in a village with data given in problem number 9. Additional Data:

    (a) Site: 85^o 45' (Long.); 28^o 30' (Lat.)
    (b) Ambient temperature variation: 10^oC to 35^o C
    (c) Peak Sun: 5.0 (Jan.-May, Oct.-Dec.) and 4 (June –Sept.)

CHAPTER 11

Socio - Techno Economic Feasibility Study

Duration: 335 minutes

Physical Facilities required: Class room with white board and multi-media projection facility.

Materials required: Catalogues of various types of modules, water pumps, wire-size tables, PV standards and a calculator. and reference material.

Procedures: The instructor/s explains the technical and financial feasibility analysis principles of solar PV systems

Instructor: The Trainer

Reference:

1. Solar Photovoltaic System Design Manual for Solar Design Engineers, AEPC/ESAP

Lesson Plan

Sub-chapter	Lesson details	Teaching Methodology	Facilities required	Duration	Remarks
9.1-9.4	Introduction, basic principles of feasibility study etc.	Lecture	Class room	30 mins.	
9.5	Financial Analysis	Lecture	Class room	180 mins	
9.6,9.7	Sensitivity analysis, Repayment schedule	Lecture	Class room	30 mins	
9.8	Cash flow analysis	Lecture	Class room	60 mins	
9.9,9.10	Tables and feasibility study formats	Lecture	Class room	35 mins	

10.1 Introduction

Project or scheme of any type involves investment and other resources and has to borne risk. So before putting the investment resources into the new projects, technical as well as economic/financial study is generally undertaken at the very out set to see if they are feasible for investment. This is nothing but the techno-economic /financial evaluation or assessment of the project before actually going into action. Such study is necessary to minimize the risk of investment and maximize the benefit from the scarce investment resources.

An solar PV system (SPS) as well as PV pumping system (PVPS) project needs sufficient amount of investment and is expensive. Such project involves risk because most of the cost must be met at the beginning. It is but natural that the promoter of the project needs to convince the investor as well as financers (a private individual, funding agency, or rural development bank like Gramin Bank) that the project is technically sound and economically /financially feasible and the investment is therefore safe.

The duty of the project designer or project formulator is therefore to identify schemes/projects that may likely to fail and warn the prospective investor about poor financial potential of such unfeasible project.

9.2 Basic Principles of Feasibility Study

The basic principles of techno-economic feasibility studies are to evaluate the schemes/projects on technical, economical and financial ground with the objective of offering alternatives if possible. There are projects, which may be technically very sound and attractive but from economic or financial ground may be very expensive and the price of the products from such projects may be beyond the reach of the people. The purpose of such study is to avoid heavy loss and minimize the risk, which the investor as well as the financer of the project may have to incur, if implemented.

It is to be noted that the investor will not be an engineer and as such, he/she may not be interested in engineering design studies. But he/she will understand very well the need for good management, training schedules for the operators of the project, good planning of maintenance, and so on. He/she will also understand certain financial indicators, and certain types of financial projections.

The plant factor and unit energy cost are the two basic indicators which provide lot of information and are important and useful, simply because they can be quickly calculated at a very early stage of planning a project (the pre-feasibility stage) to predict financial viability. They are helpful to make initial comparisons with alternative energy/power sources. Often a proposed SPS/PVPS scheme can be compared with a petroleum product based electricity plants like diesel or kerosene, if required. An essential part of economic/financial study is also to provide analysis of rival power sources using standard comparative indicators.

Besides plant factor and unit energy cost, other indicators of project viability are net present value (NPV), internal rate of return (IRR), pay back period, etc. The calculation of simple and discounted payback periods of the project investment is also useful to give the idea of within how many years the investment will be realized. As a matter of fact, these economic and financial indicators will assist the investor in deciding whether the project is worth doing; the motive may be to find the most profitable project, or the safest and most financially self-sustaining.

The cash flow analysis is another important tool, which is a more detailed future projection of the likely financial performance of the proposed project on a year-by-year or month-by-month basis. Take for example, the project may require bank loan, and repayment will be needed in future years. Or it may also happen that the demand for the services provided by the proposed project is expected to grow over the first five years of operation, and that in the first five years the demand will be too small for the project to be immediately viable. In such circumstances, external funds will be required both for initial capital costs and to cover operational costs during these five years. Naturally, investor will also be interested to know whether in later years sufficient funds are generated to repay loans, replace worn out equipment and cover for contingencies like the replacement of equipment unexpectedly damaged (by natural calamities, e.g., landslide, flood, etc.) So, year by year or month by month forecast of money flows into project account, and out of it, is an essential planning activity for project formulator as well as to the investor.

11.3 Technical Aspect of Feasibility Study

Technical viability comes first in feasibility study. Nothing can be done so long as the project is technically viable. Therefore it is necessary to justify that the proposed project is technically sound.

In the present context of SPS and PVSP projects, technical viability is largely influenced by sufficient availability of sunshine. The location of the proposed project must have plenty of sunshine. If the location is covered by fog over 100 days in a year or is in the northern part of a mountain or in the shade of trees, which result in less than 5 hours' sunshine in a day of a year, the message will be that the location of the proposed project may not be technically suitable.

As indicated, it is to be noted that the range for the sizes of the arrays or the institutional PV systems is 100 to 1,000 Wp. The smaller end of the systems close to 100 Wp will be generally DC systems, and the larger systems may have a DC/AC inverter to supply to AC loads. The appliances should be the most energy efficient and required to follow general guidelines in selecting appliances and electrical equipment prescribed for ISPS.

The beneficiaries as well as end-uses of the proposed SPS / PVPS project need to be considered for ascertaining the installed capacity. The more numbers of direct beneficiaries, better the project will be for support. The minimum beneficiaries required are 50 beneficiaries. The indirect beneficiaries are also to be considered, for simple reason that such indirect beneficiaries will add more value to the project.

PV Pumping Systems (PVPS) are used for lifting water from source to storage with the electricity needed for operating a motor-pump unit powered by PV panels. Usually PVPS projects are used in locations where the hydraulic energy equivalent ranges 25 m4/day to 2000 m4/day. Different configurations of PVPS are possible in power conditioning (DC/DC systems and DC/AC systems, pump-set location (e.g., submersible, floating pump, surface-mounted pump) and type (e.g., centrifugal pump, piston pump and progressive cavity pump), storage and distribution system.

11.4 Energy Demand Analysis

For determining the optimum capacity of the SPS/ PVPS project, the estimation of energy demand is to be explored. So, existing level of energy consumption is to be assessed and also has to project the energy demand for planned power consumption. In addition, power factor efficiency of existing as well as proposed end use appliances are to be listed and on that basis estimation of energy requirement at the site is to be made.

11.5 Financial Analysis

If the project is seen feasible from the technical side, then the question is whether the project is financially also sound and the end-use services are within the reach of the beneficiaries. So, different financial aspects of the project are to be looked into for exploring its financial viability.

*Project Costing***:** In order to do the financial analysis of the project, total cost of the project is to be known. Total cost comprises of expenditures to be incurred in different components of the systems such as equipment, construction, transportation, erection, commissioning and also training, if required. Detail listing of the equipments and other items is to be prepared for costing. The costing of equipment should be based upon quotation received from companies.

*Projection of Income and Expenditure***:** It is necessary to project the income as well as expenditure to be incurred for the period of next 10 years after commissioning of the project. The expenditure should include the salaries of directly involved people, even if they are part-timers for the project. The expenditure is to be divided at least into two broad headings---investment cost and operational cost.

*Financial Feasibility Analysis***:** The detail financial feasibility is difficult and may not require for projects like ISPS/PVPS project. Therefore, the focus of the financial study for such project, among other, should be to study cash flow analysis to see availability of fund for its operation and maintenance and for debt servicing, loan is being taken.

The economic and financial viability can also be seen by employing the tools like the Net Present Value (NPV) and the Internal Rate of Return (IRR) along with profit and loss, rate of return on investment, pay back period.

Description of Tools / Methods with Illustration:

- *Profit and Loss Method*: By using profit and loss method one can decides whether to make investment in the project or not. For this the estimation of annual income and expenditure of the project are required. On the income side, one should know about the annual income from, say solar PV pump or institutional solar PV system scheme/project. The income or benefit from the solar PV pump project may be its water charges for irrigation or drinking water. On the expenditure side, annual discount of project equipment, interest, salary of the staff, repair and maintenance and other miscellaneous expenses of the project. The profit (loss) can be calculated using the following simple formula 9.5.1:

Profit (or Loss) = Annual income – Annual Expenditure (11.5.1)

Example 9.5.1

To clarify Use of Profit and Loss Method, the example of the PVPS project, which is used for lifting water from river/stream or ponds/spring for drinking and irrigation purpose is given below:

Annual Income:			**Rs.418,800**
Water charges for irrigation:		Rs.102,000	
Water Charges for drinking:		Rs.316,000	
Annual Expenditure:			**Rs.375,983**
Annual discount:	Rs.109,633		
Annual interest:	Rs.152,950		
Annual salary:		Rs. 24,000	
Annual maintenance:		Rs. 87,400	
Contingencies:		Rs. 2,000	
Profit:			**Rs.42,817**

Profit = Annual Income - Annual Expenditure
= Rs.418, 800 - Rs.375, 983
= Rs.42, 817

- *Return on investment Method:* As a matter of fact, the annual rate of benefits or income received from the investment in the project is what is called as return on investment. The rate of investment can be derived by using the formula 11.5.2 given below:

$$\text{Return on Investment} = \frac{\text{Net Profit} + \text{Interest}}{\text{Investment}} \qquad (11.5.2)$$

Example 11.5.2

Using the number / amount of earlier above example and assuming total investment as Rs.1, 748, 000, the return on investment has been worked out for illustration as given below.

$$\text{Return on Investment} = \frac{\text{Rs.42, 817+ Rs.152, 950}}{\text{Rs.1748, 000}} \times 100$$

$$= 11.2\ \%$$

Frankly speaking, 11.2% return on investment is low and decision of taking up of the project is therefore to be made by comparing it with market rate of interest and with other investment projects.

Let us assume that government has provided subsidy for investment in solar PV pump project. The amount of subsidy provided is 25% of total cost of project. If the subsidy were deducted total investment would come to Rs.1, 311, 000 only. Then the rate on investment would be increase to 14.9%. Although the rate of investment has increased as compared with the earlier 11.2%, the project may not be financially feasible if the market rate of interest is higher than this.

- *Pay Back Period Method*: The investment recovery period is called as pay back period of the project. For calculating the pay back period, one has to have following data associated with the project:
  - Total Investment Cost
  - Subsidy provided
  - Annual Income
  - Annual Expenditure including repair and maintenance expenses

The formula 11.5.3 used for calculating the pay back period is as follow:

$$\text{Pay back period} = \frac{\text{Investment Cost -Subsidy}}{\text{Annual Income – Annual Expenditure}} \qquad (11.5.3)$$

The method of calculating pay back period is presented below for illustration.

Example 11.5.3

Say, the estimated cost of proposed PVPS project is cost Rs.1, 748, 000 and subsidy is provided to the tune of Rs.437, 000. The annual income estimated from the project is Rs.418, 800 while the annual expenditure is estimated at Rs.113, 400.

$$\text{Pay back period} = \frac{\text{Rs.1, 748, 000} - \text{Rs. 437,000}}{\text{Rs.418, 800} - \text{Rs.113, 400}}$$

$$= \frac{\text{Rs.1311, 000}}{\text{Rs.305, 400}} = 4.29 \text{ years}$$

That is to recover the investment made in the proposed project can be backed in 4 years and 3 months. In case the subsidy is not provided to the project, then it would require 5 years and 9 months to get investment back.

$$\text{Pay back period} = \frac{\text{Rs.1, 748,000}}{\text{Rs.418, 800} - \text{Rs.113, 400}}$$

$$= \frac{\text{Rs.1, 748, 000}}{\text{Rs.305, 400}} = 5.72\text{years}$$

From this illustration, it will be clear that the pay back period will be less if there is subsidy, if not period will be longer.

- *Net Present Value (NPV) Method:* The NPV method helps to assist in making decision on the choice of two different projects having different service periods and different investment sizes or cost by way of comparison. Generally speaking, the expenditure of the project will be high in the first few years or initial period of investment and after the completion of the project, the annual expenditure either goes on decreasing, remain constant or increasing. It will have no meaning if the income and expenditure incurred in different years of operation as it is or without bringing them into base year money value, since they cannot be compared. In order words they are not comparable. The money value differs from time to time. The weightage is given to present expenditure than spending in future. That is why it is necessary to bring expected income and estimated expenditure of future into present value, i.e., base year and for this discount rate, with discount factor is to be used. Discount rate in fact reflects time value of money, i.e., if a persons has to spend money in the present year than in the coming years, he or she will feel much burden, for the simple reason that he or she can get income by investing out of that expenditure. Likewise, there is advantage to get future income in the present year in advance. If discount rate is high, it means expected income from alternative investment is high. Similarly, to compensate inflation i.e. rising prices discounting of money is required.

While undertaking the exercise of Net Present Value (NPV), it is necessary to understand the concept of time value of money as well.

- *Time Value of Money*: While undertaking any type of financial and economic assessment or evaluation of the project, it is but necessary to have some insight in time value of money. What is it after all? It can be explained with the proverb, which goes like this. " A bird in the hand is worth two in the bush". It gives the idea of time value of money. As such, the proverb expresses the concept of discounting. A project is expected to achieve financial benefits in the future. But these benefits are not worth the same as if they were securely in our hands now. Consequently it will be discounted. It can be clarified with an example. Let us assume that one expects to get Rs.1,000 in one year's period, but its worth will be Rs.800 only in the hand now. Likewise, another person may be happy to accept as little as Rs.600 now as equivalent to Rs.1,000 in a years' time It means the second person has a higher personal discount rate.

Discount rate can also be expressed as a fraction, e.g., Rs.1,000 divided by 1.25 is Rs.800. the discount rate is 0.25, or 25%. If it is for two years time, it will be discounted twice.

$$\text{Present value (PV)} = \frac{\text{Rs.1000}}{1.25*1.25} = \text{Rs.640}$$

The general formula 9.5.4 for discounting is

$$PV = \text{Future value} / [(1+m)^n] \qquad (11.5.4)$$

Where n is number of time periods (usually years - but sometimes months) into future that the future value is expected to arise, and m is the discount rate over the period (years or months)

The reasons for discounting future sum of money are: a) There may be event to stop enjoying our future sum of money, b) Expectation of some financial compensation if some one else is using money and c) Inflation, i.e., prices tend to go up at a general inflation rate.

Say, the general inflation rate in the country is 10%, and we are offered Rs.1,000 in one year's time. This sum will be equivalent to receiving (Rs.1000/1.1=) Rs.909 now.

The general formula 11.5.5 for inflation (f) is:

$$PV = \text{Future value} /(1+f) \qquad (11.5.5)$$

Referring to first example above Rs.1, 000 in one year's time was considered to have the same value as Rs.800, because the discount rate applied was 25%. Again, the discount rate would have allowed for the inflation rate of 10%, i.e., it takes into account that the Rs.1, 000 would only be worth Rs.909. The real discount rate was therefore the conversion of Rs.909 then to Rs.800 now. The real discount rate becomes 13.6 % (since Rs.909/1.136=Rs.800).

The symbol used for real discount rate is 'r' here. This will distinguish discount rate 'r' from 'm', the market discount rate. The real discount rate 'r' takes care of inflation. For most purposes it is permissible to convert quickly by subtracting inflation from the market rate, i.e., r = m - f. Strictly the real rate is found from the formula 11.5.6 below:

$$1+r = (1+m)/(1+f) \qquad (11.5.6)$$

A short cut is the annuity equation. An annuity is a constant annual sum. The formula 11.5.7 of annuity equation is as follow:

$$\text{Total Present Value (PV)} = \text{Discount factor (A)} = [(1+r)^n - 1]/[r(1+r)^n] \qquad (11.5.7)$$

Example 11.5.4

In the example, with a discount rate of 12%, and annuity of Rs.1,000 for 15 years:

$$PV = 1,000 \text{ X } \frac{(1.12)^{15} - 1}{0.12\,(1.12)^{15}} = 1,000 \text{ X } 6,8109 = \text{Rs.}6,800$$

We have calculated that at a discount rate of 12%, annual revenue of Rs.1,000 over the next 15 years is equivalent to Rs.6,800 in hand at his moment.

Application of Net Present Value: NPV (r%)

An SPS / PVPS project is expected to bring in revenue/income in future years, and also will have to incur running costs. The NPV is simply the PV of all revenues minus the PV of all running and capital costs. The annual revenue/income and the running costs are estimated to be respectively, Rs.2,400 and Rs.1,000 per year. The net annual revenue/income would be Rs.1,400 per year. This can now be discounted for each year to its present value, and all the present value added together. The result is the total present value of the project net earnings. If the project life is expected to be 15 years and the discount factor 12% then, in the example, the total PV would be:

$$PV(r=12\%) = A * \text{discount factor}$$
$$= \text{Rs.}1,400 * 6.8109$$

= Rs.9,500

The project will create future wealth equivalent to having Rs.9,500 in hand at the present moment, given a 12% discount rate. But how much will it cost to set-up the project? It will only be a worth while project if it earns more than its costs. The net present value (NPV) is the present value of net earnings (PV) with the present value of project cost (C) deducted.

If we suppose that the project in this example cost Rs.8,000 to implement, then:

NPV (r = 12%) = PV - C = 9,500 – 8,000 = Rs.1,500.

The investor now understands that at the stated discount rate of 12%, the project will earn more than it costs. Of course there is always a chance that he will think the adopted discount rate is too low, and it is a good practice to check the robustness of the investment by doing two or three NPV calculations at different test discount rates. Always specify the discount rate used for particular calculation. (See quick calculation of NPV, example in Annex table 3 (a) (b) for more example of NPV calculation)

In the project like PVPS or I PVS, sufficient investment would require in the first year or during the period of first few years. On the other hand, the income or benefits from the proposed project will continue to flow over the period of project service life. Therefore, before making investment decision, expected income and expected expenditure are to be compared by discounting the value of money. In the terminology of financial analysis or economic analysis, it is known as the net present value (NPV) of the project. The numerical example will help to understand this more precisely.

Use of discounting factor: If you seeks Rs.115 for Rs.100 you loans today or this year, it means you are demanding 15% interest minimum. The 15% is the discount rate. The number which is used in multiplying Rs.100 to get Rs.115 is called discounting factor.

One can use discounting table to find out discounting factor for multiplication to bring expected income and expenditure of various years by using different discount rates with the help of discounting factors into present value. It is also to be noted that with the same discount rate, as the future years increases discounting factor will go on decreasing.

In simple term, by net present value (NPV), it means saving or deficit of income derived from the sum total of expected annual income and annual expenditure anticipated during the period of project life and discounted. In fact, NPV is the discounted cash flow. Illustration of NPV for calculation is provided below:

Let us assume the service life of the Photovoltaic Pumping System (PVPS) project is 12 years (its life may be more than this in practice). The total investment required is estimated at Rs.1, 311,000 and annual expenses amount to Rs.113, 400 and annual income estimated ranges from Rs.3,49,000 to Rs.4,18,800. The Net Present Value of the project at the discount rate of 17.5% would be as shown in table 11.5.1 below.

Table 11.5.1 Simple Method of Calculating Net Present Value (NPV)

In Rs. '000

Year	Annual Expenditure	Annual Income	Net Income Flow	Discounted rate (17.5%)	Annual NPV
Starting year, 0:	1311.0	0	-1311.0	1.00	-1311.00
1st:	113.4	349.0	235.6	0.85	200.26
2nd:	113.4	383.9	270.5	0.72	194.76
3rd.:	113.4	401.4	287.0	0.62	177.94
4th.:	113.4	418.8	305.4	0.52	158.81
5th.:	113.4	418.8	305.4	0.45	137.43
6th.:	113.4	418.8	305.4	0.38	116.05
7th.:	113.4	418.8	305.4	0.32	97.73
8th.:	113.4	418.8	305.4	0.28	85.51
9th.:	113.4	418.8	305.4	0.23	70.24
10th.:	113.4	418.8	305.4	0.20	61.08
11th.:	113.4	418.8	305.4	0.17	51.92
12th.:	113.4	418.8	305.4	0.14	42.76

The net annual income will be received by subtracting annual expenditure from annual income. The annual present value will get by multiplying each net income by discounting factor. The addition of all annual present values will be the NPV. In the above example Rs.83, 490 amount is the NPV.

***The Steps of NPV Exercise**:*

While doing exercise of NPV following steps are to be kept in mind.

- Make a list of estimated income /benefits expected over the period of project life and put in the income stream column of the table.
- Generally, the annual income estimated for the first year can be taken for rest of the years.
- In the expenditure column, the investment of the first year is to be put and then after, i.e., from second year onward by adding up all annual operational expenditure including annual salary of the staff, repair and maintenance expenses, miscellaneous expense etc. the lump sum figure is to be put.
- Multiply particular year of annual income and expenditure by the same year of the discount factor and place the results under the related columns of the table. This will give discounted income and expenditure.
- Subtract discounted annual expenditure from discounted annual income. This is call discounted net cash flow. The sum of this column will give net present value of the project.

Following conclusions can be drawn from the exercise of NPV.

- If the NPV is positive, the project is feasible and investment can be made in the project
- If the NPV is negative, the project is infeasible.
- If the NPV is zero, the project is neither feasible nor infeasible. But in such case also generally it will not be wise to invest in such project.

- ***Benefit Cost Analysis Method*:**

This method is generally used to find out the relationship between investment cost of the project and the benefit produced by the unit of investment. In order words, how much income or benefit will get from one rupee investment or cost. Benefit/cost method is mostly used in the economic and financial analysis of the projects.

The total discounted income or revenue divided by total discounted cost will give benefit /cost ratio of the project.

Let us take the previous example used in NPV calculation to calculate benefit/cost of the project. Here the initial investment cost of the Solar PV pump project is assumed to be Rs.1, 311, 000 , the annual expenditure expected to be incurred is Rs.113,400 and annual expected income from the project ranges from Rs.349,000 to Rs.418,800 . The discount rate is taken as 17.5% (table 11.5.2).

Table 11.5.2 Simple Method of Calculating Benefit / Cost Ratio of the Project

In Rs. '000

Year	Annual Expenditure	Annual Income	Discounted rate (17.5%)	Discounted Expenditure	Discounted Income
1st.	1311.0	0	1.00	1,311	0.00
2nd:	113.4	349.0	0.85	96.39	296.65
3rd:	113.4	383.9	0.72	81.65	276.41
4th.	113.4	401.4	0.62	70.31	248.87
5th.	113.4	418.8	0.52	58.97	217.7
6th.	113.4	418.8	0.45	51.03	188.46
7th.	113.4	418.8	0.38	43.09	159.14
8th.	113.4	418.8	0.32	36.29	134.02
9th.	113.4	418.8	0.28	31.75	117.26
10th.	113.4	418.8	0.23	26.08	96.32
11th.	113.4	418.8	0.20	22.68	83.76
12th.	113.4	418.8	0.17	19.28	71.20
13th.	113.4	418.8	0.14	15.88	58.63
Total	-	-	-	1,864.39	1,948.50

From the above exercise these things will be clear.

- The annual expenditure multiplied by discount factor of related year will be the discounted expenditure of that year. Sum total of annual discounted expenditure is Rs.1, 864, 390 as shown in the table 11.5.2.
- The annual income or revenue multiply by discount factor of related year will be discounted income of that year. Sum total of annual discounted income is Rs.1, 948, 500 as shown in the table 11.5.2.
- Total discounted income divided by total discounted expenditure is 1:05 in the case of above table. This is called Benefit/Cost Ratio. It means in this project if Rupee one is invested the income will not be less than Rs.1.05. So it is feasible

The following conclusion can be drawn from the benefit/cost analysis;

- If benefit /cost ratio is less than one, while dividing benefits by the cost, it means project expenditure is greater than the expected income or benefit. So the project will not be financially or economically viable.
- If benefit/cost ratio is greater than one, it means benefits will be more than the cost incurred. The project will yield more income or benefit and will be viable.
- If benefit /cost ratio is one, benefit from the project will be equal to cost of the project.

The projects whose benefit/cost ratio is greater than1 will be feasible for undertaking according to this method.

*Internal Rate of Return Method***:** The internal rate of return is the discount rate at which NPV =0. At this rate, discounted annual expenditure and discounted annual income will be equal. In order words, internal rate of return (IRR) will indicate expected maximum interest rate from the investment.
Method of calculating IRR**:** It is required as in the case of NPV to derive cost stream and revenue stream. Exercise has to find out the discount rate, which will make NPV equal zero.

The following steps are to be followed while preparing IRR of the project.

Step 1: Choose a discount rate. Looking at the previous example, a positive NPV was achieved using a discount rate of 12%, which indicates that a value higher than 12% is needed to achieve a NPV value of zero. Let us try 15%.
Step 2: Draw up a cash flow table as shown below for the project. Calculate NPV, using the first guess discount factor of 15%. In this case we find the NPV is Rs.13, 000, 000 (see table 3 below)
Step 3: Now apply the principle: "If NPV is more than zero, increase the discount rate until NPV is as near to zero as you can get, using whole numbers for discount rates. If NPV is less than zero, increase the discount rate" Doing this (see table 3 below) we find in the first step at 15% discount rate the NPV will be Rs.13, 000. In the second step at 17% discount rate NPV will be Rs.4, 000, 000. If discount rate is increased to 18%, NPV will be zero (Table 11.5.3).

Table 11.5. 3 Calculating Internal Rate of Return (IRR) of the Project

In Rs.'000

Years	0	1	2	3	4	5	6	7	8	9	10	11	12
1.Expenditure:	-100	-15	-5	-5	-5	-5	-5	-7	-7	-7	-37	-7	-7
2. Income:	0	28	28	28	30	31	31	31	31	31	25	31	31
3. Annual net earning	-100	13	23	23	25	26	26	24	24	24	-12	24	24
4. Discount Factor 1st. guess discount rate 15%	1	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29	0.26
5.Annual present value	-100	11.3	17.4	15.1	14.3	12.9	11.2	9.0	7.8	6.8	-3.0	5.2	4.5

6.NPV= -100+113= Rs.13, 000 (discount rate 15%)

4. Discount Factor 2nd. guess discount rate 17%	1	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29	0.26
5.Annual present value	-100	11.1	16.8	14.4	13.4	11.9	10.1	8.0	6.8	5.8	-2.5	4.3	3.6

6.NPV= -100+104= Rs.4, 000 (discount rate 17%)

4. Discount Factor 3rd. guess discount rate 18%	1	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29	0.26
5.Annual present value	-100	11.0	16.5	14.0	12.9	11.4	9.6	7.5	6.4	5.4	-2.3	3.9	3.3

NPV=-100+100=Rs.0 (discount rate 18%)

Step 4: The IRR is the discount rate at which NPV is nearest to zero. Therefore in this case IRR is 18%.

Comparison of NPV and IRR:

In the below table comparison of NPV method and the IRR method is presented.

Net Present Value (NPV)	Internal Rate of Return (IRR)
1. Discount rate ' r' needs to be chosen before calculation	1. Discount rate 'r' is not needed for calculation
2. Calculation is to perform	2. Calculation is not easy except for the simplest types of projects.
3. Cannot be used directly for ranking projects of different lengths.	3. Can be used for ranking projects of differing lengths.
4. Final value depends on the size of the project. (This may be a help of course)	4. The best indicator if you are poor and have a high time preference discount rate.
	5. Will provide a guide as to the maximum interest rate at which monies can be borrowed to finance the project.

11.6 Sensitivity Analysis:

Sensitivity analysis is undertaken to how much risk will be there if changes occur in some of the items of the benefit/ cost or IRR analysis. The future is quite uncertain. The cost and interest may go up due to various reasons. Demand of service or goods may go down. These things may naturally have impact upon economic and financial feasibility of the project. What will happen internal rate of return, if the project cost increases than earlier estimate. In such situation the estimated IRR goes down and IRR will then be less than market rate of interest. Then the project will be risky.

11.7 Repayment Schedule:

The entrepreneur/or investor also borrows money from the bank or financial institutions for the project for the period of 10 years. In such a case, repayment schedule will help how much principal and interest and from what date for how many years loan have to be paid on installment basis. Repayment has to be made out of the annual income of the project. It will tell the owner if it is possible or not to pay from its annual income. The under mentioned formula (11.7.1) will have to be used.

$$\text{Annual Installment} = \text{Total Loan Amount} \times \frac{\text{Interest rate } (1+r)\ n}{(1+r)n-1} \qquad (11.7.1)$$

$$\text{Annual Installment} = \text{Rs.}874,000 \times \frac{0.175\ (1+.175)\ 10}{(1+0.175)\ 10-1} = \text{Rs.}152,950$$

$$= \text{Rs.}191,032.84$$

The owner if he could make repayment Rs.191,032.84 annually, at the 10th year all principal and interest will be paid.

Example 11.7.1 Method to be used to derive interest on borrowed money

Of total cost of the PVPS project, say 25% is subsidy, 50% is financed by loan and 25% is equity. The loan amount is let us suppose Rs.874, 000 for which 17.5% interest rate is charged. The annual repayment can be calculated as follow:

$$\text{Annual installment} = \text{Rs.}874,000 \text{ X} \frac{0.175\ (1 + 0.175)\ 10}{(1 + 0.175)\ 10-1}$$

$$= 874,000 \text{ X } \frac{0175 * 5.016}{4.016}$$

$$= \text{Rs.}191,032.84$$

If repayment is made at the rate of Rs.191,032 each year within 10 years principal with interest will be paid.

11.8 Cash Flow analysis:

In a pre-feasibility study expenditures and income are often estimated as constant each year, but in a full feasibility study it is accepted that they will vary with time, and it is useful to prepare a table predicting this variation. One of the main purposes of the cash flow analysis is to reveal working capital requirement.

In order to explain the cash flow analysis three different cash flow situations is presented in three tables 11.8.1 (a), (b) & (c) below.

Just for example sake, the presented cash flow analysis is for the solar PV pumping system project. Its investment cost is assumed to be Rs. 100,000 and has annual expenditures and revenues as predicted by Tables 4 (a), (b) &(c) below. It is to be noted that presented tables should be used to help plan a scheme and to assist negotiations for a loan and a suitable repayment schedule. In addition, they should also be used to help a potential investor evaluate the future viability of the schedule. It assumes zero inflation.

Table 11.8.1 (a) Cash flow situation of Solar PV Pumping Project without loan repayments

(Rs. in thousand)

Year	**Expenditure**	**Revenue**	**Annual net cash flow**	**Simple running total**
0	-100	0	-100	-100
1	-15	28	13	-87
2	-5	28	23	-64
3	-5	28	23	-41
4	-5	30	25	-16
5	-5	31	26	10
6	-5	31	26	
7	-7	31	24	
8	-7	31	24	
9	-7	31	24	
10	-37	25	-12	
11	-7	31	24	
12	-7	31	24	

The table (b) is prepared for the same project but with loan of Rs.100, 000 and the schedule consists of constant annual repayments of Rs.18, 000 as installment for the period of 10 years, calculated from the annuity equation for an interest rate of 12%. In this case you will find a cash flow problem in year 1 which indicates that either the repayment schedule is unacceptable or additional external funds must be introduced. The shortfall in year 10 shows a working capital requirement of Rs.30,000 which could be covered by previous accumulation of funds.

Table 11.8.1 (b) Cash flow for same project including a proposal for a loan repayment schedule without loan repayments (Rs. in thousand)

Year	**Expenditure**	**Repayment of Loan**	**Revenue**	**Annual net cash flow**	**Cumulative cash flow**
0	-100	0	100	0	0
1	-15	-18	28	-5	-5
2	-50	-18	28	5	0
3	-5	-18	28	5	5
4	-5	-18	28	7	12
5	-5	-18	30	8	20
6	-5	-18	31	8	28
7	-7	-18	31	6	34
8	-7	-18	31	6	40
9	-7	-18	31	6	46
10	-37	-18	25	-30	16
11	-7	-0	31	24	40
12	-7	-0	31	24	64

Table 11.8.1 (c) Cash flow with revised repayment schedule to overcome negative cash flow in year 1 (Rs. in thousand)

Year	**Expenditure**	**Repayment of loan**	**Revenue**	**Annual net cash flow**	**Cumulative cash flow**
0	-100	0	100	0	0
1	-15	-10	28	3	3
2	-5	-21	28	2	5
3	-5	-21	28	2	7
4	-5	-21	30	4	11
5	-5	-21	31	5	16
6	-5	-21	31	5	21
7	-7	-21	31	3	24
8	-7	-21	31	3	27
9	-7	-21	31	3	30
10	-37	0	25	-12	18
11	-7	-0	31	24	42
12	-7	-0	31	24	66

From the above table 11.8.1 (a), (b) & (c), it will be clear that in the first year of operation, predicted expenditure on operation and maintenance, i.e., O+M is high (Rs.15,000) because of training and initial management costs. The O+M expenditure then settles down to steady Rs.5,000 per year. In the 7th year O+M expenses are predicted to rise to Rs.7,000 per year to take account of increased wear and tear on machinery, rising operator wage, extension of new services to customers, and increase in the spare parts. It is considered likely that in the 10th year complement refurbishment of the pumps and other equipment will be required at a cost of Rs.30,000. Mean while revenue is fairly steady, rising from Rs.28,000 per year to Rs.31,000 expect for a drop while refurbishment takes place.

In the example the 'annual net cash flow' is calculated- this is the money remaining in hand each year once expenditure has been subtracted from revenue/income. It is evident from the table 11.8.1 (a) that in 0 year (the 'start –up' year) and in the 10th year (the refurbishment year) the net cash flow is negative. In such situation, some form of external investment may be required to cover the start-up cost; this may be a loan with interest. It may be that only a portion of the initial cost needs to be raised as a loan, and some of it can be found from the investor's own resources. The question is, will the money earned in other years be sufficient to recover this investment, and secondly, will revenues cover for the negative balance of Rs.12,000 in year 10.

A quick way to answer the first question is to calculate a 'simple running total' for each year—this is the sum of the annual net cash flows of previous years. This can also be referred to as the cumulative net cash flow, but the term 'simple' is a useful remainder that the time value of money is not yet taken into account. The simple running total calculated in the example shows that the investment could be recovered within 5 years.

The second question, how to cover for shortfall in year 10, is not so easily answered. If calculated for the whole period the simple running total will show a healthy accumulation of funds in year 9 which would easily finance the refurbishment costs in year 10, but no conclusions should be drawn from this, since the real (time value) cost of finance is not considered. A second table 11.8.1 (b) is needed before a realistic assessment of accumulated funds can be made.

The second table 11.8.1(b) has drawn up by guessing, or by discussing with a bank/financial institution, a possible loan and repayment schedule for same project. It is assumed here that the full start-up cost of Rs.100,000 is procured as a loan on the basis of constant annual repayments. It would be equally possible to borrow another sum, say Rs.60,000, and leave – Rs.40,000 in the net cash flow column for year 0, representing an investment of internal resources.

Table 11.8.1 (a) indicates that a loan repayment period of about 10 years is probably necessary, since this is twice the simple payback period. Using the annuity equation for a bank interest rate of 12%, the result is an annual repayment of Rs.18, 000. Now consider if this is a sensible sum – can the project afford it? Since the net cash flows are around Rs.23 to Rs.26,000, it is an affordable sum. A shorter period than 10 years could be chosen and the annuity equation used to calculate a higher repayment sum. Conversely, if the repayment is too high for revenue to cover it, choose a longer period. It is important to leave net cash flow figures of about Rs.3,000 since this provides a safety margin in case the predictions turn out to be inaccurate.

Annual net cash flow figures are calculated for Table 11.8.1 (b) exactly as in table 11.8.1(a), but this time loan repayments are included as expenditures. The result is that we again find negative cash flows occur, this time in year s 1 and 10. These are unacceptable, since they imply that the project will not be able to meet its operating costs, and will therefore be forced to stop, failing to generate the planned revenue.

The shortfall in funds in 10th.year indicates that there is a need for 'working capital' – this is the phrase used to refer to requirement of additional finance, which has appeared on a cash flow table.

Accumulated fund, or 'cumulative cash flow', is a running total, calculated in the same way as in the previous table. The cumulative cash flow in 9th.year on table 9.8.1(b) is Rs.46,000 which is sufficient to cover for the refurbishment costs the following year. The positive cumulative sum of Rs.16,000 the following year demonstrates this. The problem arising from negative cash flow in the 9th.year will be solved, the required working capital having been found from accumulated funds. It should be remembered that the investor also regards accumulated cash as a 'cushion' or safety margin protecting against unexpected problems or errors in prediction, so it would not be acceptable to use all of the accumulated funds as working capital.

The problem showing on table 11.8.1 (b) of negative cash in year 1 can be solved by revising the repayment schedule. To do this, consider the year 1 cash flow show on table 11.8.1 (a). Since this is Rs.13,000 it is clear that loan repayments in year 1 should not exceed Rs.10,000.This would allow a Rs.3,000 safety margin. The original loan to cover start up cost is Rs.100,000. Suppose Rs.10,000 is repaid at the end of year 1, and that this is regarded as a payment of principal only, with no allowance for interest. The remaining principal is then Rs.90,000. Interest of Rs.12,000 (12% of Rs.100,000)will also be owed for the first year. Total remaining debt is therefore Rs.102, 000. This could be paid off with a constant annual repayment over the following 10 years. Following the annuity equation, it can be calculated that a constant annual repayment of Rs.19,000 would be needed for the next 9 years. Often an investor has more confidence in a scheme with as short as possible loan repayment period. An eight years period would demand a constant repayment of Rs.21,000 each year (calculated from the same annuity equation).

Anything shorter than this would create cash flow problems in the first few years of operation, but of course it would be possible to negotiate further 'soft-start options' with the lender. As one example of several possible solutions, table 11.8.1(c) shows an eight year constant repayment following 'soft – start' in the first year. It is noticeable that the loan is cleared one year earlier than in table 11.8.1 (b), so that the refurbishment in 10th.year takes place without the extra burden of loan repayments; consequently the net cash flow deficit in 10th year is less severe. As in table 11.8.1 (b) accumulated funds are required to accommodate the 10th year deficit.

Note: These things are to be considered while preparing cash flow analysis tables.

- Is the expected life of the machinery a realistic estimate? Are replacement costs included and increasing O+M costs as the age of the machinery begins to tell?
- Training costs. New operators will need further training. Are these cists included?
- End-use equipment. Initial purchase, replacement and maintenance of wires, lights, etc. will need finance.

- Has the cost of organizing and managing the end-use equipment and appliances been properly included?
- Are subsidies or grants involved? These can be subtracted from the costs.

11.9 Tables and Formulas for Quick Reference

Table 11.9.1 Discount factor for single sums at different discount rates

Period (year, n)	10%	12%	14%	15%	16%	17%	18%	19%	20%	24%
1 yr.	0. 909	0. 893	0. 877	0. 870	0.862	0.855	0.847	0.840	0.833	0. 607
2 yr.	0. 826	0.797	0.769	0. 756	0.743	0.731	0.718	0.706	0.694	0. 650
3 yr.	0. 751	0.712	0. 675	0. 658	0.641	0.624	0.609	0.593	0.579	0.524
4 yr.	0. 683	0. 635	0. 592	0.572	0.552	0.534	0.516	0.499	0.480	0.423
5 yr.	0. 621	0. 567	0. 519	0. 497	0.476	0.456	0.437	0.419	0.402	0.341
6 yr.	0. 564	0. 507	0. 456	0. 432	0.410	0.390	0.370	0.352	0.335	0.275
7 yr.	0. .513	0. 452	0. 400	0. 376	0.354	0.333	0.314	0.296	0.291	0.221
8 yr.	0. 467	0. 404	0. 351	0. 327	0.305	0.285	0.266	0.249	0.233	0.179
9 yr.	0. 424	0. 361	0. 308	0. 284	0.263	0.243	0.225	0.209	0.194	0.144
10 yr.	0. 386	0. 322	0. 270	0. 247	0.227	0.208	0.191	0.176	0.162	0.116
11 yr.	0. 350	0. 287	0. 237	0. 215	0.195	0.178	0.162	0.148	0.135	0.094
12 yr.	0. 319	0. 257	0. 208	0. 187	0.168	0.152	0.137	0.124	0.112	0.076
13 yr.	0. 290	0. 229	0. 182	0. 163	0.145	0.130	0.116	0.104	0.093	0.061
14 yr.	0. 263	0. 205	0. 160	0. 141	0.125	0.111	0.099	0.088	0.078	0.049
15 yr.	0. 239	0. 183	0.140	0. 123	0.108	0.095	0.084	0.074	0.065	0.040
16 yr.	0. 218	0. 163	0.123	0. 107	0.093	0.081	0.071	0.062	0.054	0.032
17 yr.	0. 198	0. 146	0.108	0. 093	0.080	0.069	0.060	0.052	0.045	0.026
18 yr.	0. 180	0. 130	0. 095	0. 081	0.690	0.059	0.051	0.044	0.038	0.021
19 yr.	0. 164	0. 116	0. 083	0. 070	0.060	0.051	0.043	0.037	0.031	0.017
20 yr.	0. 149	0. 104	0. 073	0. 061	0.051	0.043	0.037	0.031	0.026	0.013

Note: In the financial analysis, discounting factor will have to use the same as that of interest rate. Say, if 14% discount rate is used for financial analysis, discounting factor for first, second, third year will be according to above table as follow:

Year	14%
1	0.877
2	0.769
3	0.675

Table 11.9.2 Recovery Factor Table

Interest Rate

Year	10%	12%	14%	15%	16%	18%	20%
1	1.100	1.120	1.140	1.150	1.160	1.180	1.200
2	0.576	0.592	0.607	0.615	0.623	0.639	0.655
3	0.402	0.406	.0.431	0.438	0.445	0.460	0.475
4	0.315	0.329	0.334	0.350	0.357	0.372	0.386
5	0.264	0.277	0.291	0.298	0.305	0.320	0.334
6	0.230	0.243	0.247	0.264	0.271	0.286	0.301
7	0.205	0.219	0.233	0.240	0.248	0.262	0.277
8	0.187	0.201	0.216	0.223	0.230	0.245	0.260
9	0.174	0.188	0.202	0.210	0.217	0.232	0.248
10	0.163	0.177	0.192	0.199	0.207	0.223	0.239
11	0.154	0.168	0.183	0.191	0.199	0.215	0.231
12	0.147	0.161	0.177	0.184	0.192	0.209	0.225
13	0.141	0.156	0.171	0.179	0.187	0.204	0.221
14	0.136	0.151	0.167	0.175	0.183	0.200	0.217
15	0.131	0.147	0.163	0.171	0.179	0.196	0.214
16	0.128	0.143	0.160	0.168	0.176	0.194	0.211
17	0.125	0.140	0.157	0.165	0.174	0.191	0.209
18	0.122	0.138	0.155	0.163	0.172	0.190	0.208
19	0.120	0.136	0.153	0.161	0.170	0.188	0.206
20	0.117	0.134	0.151	0.160	0.169	0.187	0.205

Note: If loan is taken for 15 years at the rate of 15%, according to above recovery table the recovery factor will be 0.199.

Table 11.9.3 (a) Examples for Quick Calculation of NPV

A pre-feasibility study makes quick estimation of the finances for ISPS/PVPS project as follows:

Income: Rs.20,000 each year for 15 years
Expenditure: Start-up cost Rs.120,000 and Yearly Expenditure: Rs.8,000.

Calculate the NPV for the project assuming a12% discount factor, and comment.

The annual net income is Rs.12,000. The total present value (PV) of receiving this annuity each year for n years is:

$$PV = \text{annuity X} \frac{(1 + r)^{n}-1}{(1 + r)^{n}} = \text{Rs.12,000 X} \frac{(1.12)^{15}-1}{0.12\ (1.12)^{15}} = \text{Rs..81,600}$$

Note that discount factor 6.8 can be found from discount factor table (or by using a calculator)

The net present value of the project is this present value sum of earnings (Rs.81,600) with the original investment of Rs.120,000 subtracted:

NPV (r = 12%) = PV – Investment = Rs.81,600 – Rs.120,000 = - Rs.38,400

The conclusion is that the project is not viable from the investor's point of view, since the NPV is negative.

Table 11.9.3 (b) Example Quick Calculation of NPV

Calculate the Net Present Value of a project, which has annual expenditures and income as presented below (Units are in Rs.000). The start-up cost of the project is presented as a Rs.100,000 expenditure in year 0. In this case a lifetime of only 12 years is assumed.

Year	**Expenditure**	**Income**	**Annual Net earnings**	**Discount factor (discount rate 12%)**	**Annual present values**
0	-100	0	-100	1	-100
1	-15	28	13	0.89	11.6
2	-5	28	23	0.80	18.3
3	-5	28	23	0.71	16.4
4	-5	30	25	0.64	15.9
5	-5	31	26	0.57	14.8
6	-5	31	26	0.51	13.2
7	-7	31	24	0.45	10.9
8	-7	31	24	0.40	9.7
9	-7	31	24	0.36	8.7
10	-37	25	-12	0.32	-3.9
11	-7	31	24	0.29	6.9
12	-7	31	24	0.26	6.2

Table 11.9.4 Estimation of Investment (Start-up) Cost of the SPV/ PVPS

SN	**Description**	**Amount**	**Remarks**
1.	Land & Building		
2.	Construction of storage tanks, canals, etc.		
3.	Solar Panels, Battery, Inverter, wires, etc.		
4.	Appliances—TV, radio, refrigeration, Computer, Video, etc.		
5.	Transport and installation charges		
6	Miscellaneous		
7.	Pre-investment expenses		
	Total		

Table 11.9.5 Method of calculating Annual Salary of the staff (Operator and other) of the ISPV/ PVPS

Suppose the project needs 2 persons (operator and supervisor) to run the project office. The monthly salary is Rs.2,000 , then annual salary expenses will be calculated as below:

2 persons X Rs.2,000 per month X 12 month = Rs.48,000. It means Rs.48,000 annual salary for the project staff.

Table 11.9.6 Method of calculating Annual Interest on loan of the ISPV/ PVPS Project

Suppose the project has taken loan of Rs.874,000 at the interest rate of 17.5%, interest will be calculated as follow:

$$\text{Annual Interest Payment} = \frac{\text{Rs.874,000 X 17.5}}{100} = \text{Rs.152,950}$$

Note: Annual interest amount will goes on decreasing along with the reduction of principal amount.

Table 11.9.7 Method of calculating Annual Expenditure of the SPV/ PVPS project

SN	Description	Amount(Rs.)
1	Salary of the staff	
2	Depreciation	
3	Annual Repair and Maintenance	
4	Annual Interest on loan	
5	Other miscellaneous	
6.	Total	

Table 11.9.8 Method of calculating Depreciation Asset of the SPV/ PVPS project

a. Construction cost of storage tanks, etc: ………Rs.510,000
b. Solar Panels……………………………………Rs.493,000
c. Other equipment……………………………… Rs.48,000
d. Appliance & other………………………………Rs.697,00

Annual depreciation :

- The life of storage tanks, etc. is 20 years (suppose)

  Then, Rs. 510,000 / 20 years == Rs.25,500

- Life of Solar Panels is, say, 15 years

  Then, Rs. 493,000 / 15 years = Rs.32,866.67

- Life of Other equipment is, say,10 years,

  Then, Rs. 48,000/10 yrs= Rs. 4,800

- Life of Appliance & other, say, 15 years,

  Then, Rs. 697,00/15 yrs = Rs.46,466.67

Thus, total sum of depreciation = Rs.25,500 + Rs.32,866.67 + Rs. 4,800 + Rs.46,466.67 = Rs.109,633.30

Note: There will be no depreciation of land.

The calculations related to economic feasibility can be performed easily by using spreadsheet software like MS Excel. Simple programs written in MS Excel could be very handy in performing multiple calculations.

11.10 Suggested Formats Relating to Feasibility study of SPS and SPVS project/Scheme

1. Technical assessment:
   For SPVS project
   a) Installed electricity generation capacity: Wp
   b) Water lifting capacity of the pump: m^3/day
   c) Proposed irrigation Land area: ha

d) Drinking water requirement: liter/day
e) Population / ward coverage:
f) Other technical details (if any)

Form for listing of equipments and materials including construction

SN	Description	Qty
1.	Solar Panels (no.x Wp)	
2	Solar pump (no. x….)	
3.	Poles (no. X….)	
4.	Conductors (meters)	
5	Battery (AMP) No.	
6.	Construction of storage/tanks	
7.	PVC pipes	
8	Miscellaneous	

2. Investment Cost estimation:

S.N	Description	Amount
1.	Land purchase:	
2.	Construction of Pond/Water storage and cannels, etc.:	
3.	Solar PV pump Equipment: 3.1Solar panels: 3.2 Submersible pump, etc.: 3.3 Pipes and conductors: 3.4 other (controller, poles, etc.):	
4.	Transportation and porter age charges:	
5.	Pre-investment expenses:	
6.	Total:	

Note: This form has to be filled up on the basis of quotation furnished by the companies or organization.

3. Annual expenditure (O + M) Estimation

S.N	Description	Amount
1.	Annual salary of Operator(s):	
2.	Depreciation of equipments:	
3.	Repair and maintenance:	
4.	Annual interest on loan	
5.	Other expenses:	
6.	Total:	

4. Income/benefits estimation of PVS project format

a. **For drip / sprinkle irrigation:**

Description of crops	Annual Production in Kg	Estimated income from sale or income at market price in Rs.	Remarks
1. Vegetable crops 2. Seedling 3. Nursery 4. Other			

b. **For drinking water supply**

Description of items	Annual water supply in 000 liter.	No. of households	Population	Estimated income (Rs.)
VDC / Wards				

The ISPS services and capacity estimation

Items	Units	Power consumption	Total power require	Remarks (No. of beneficiaries)
1. Electric bulb (lighting)				
2. Computer				
3.Television sets				
4.Radios				
5.Cassette player				
6.Vaccine refrigerator				
7. Other (specify)				

5. Financial Analysis format:

a. **Net Present Value table:**

Year	0	1	2	3	4	5	6	7	8	9	10	11
Annual expenditure:												
Annual income:												
Discount factor(in interest rate %)												
Annual net present value (NPV)												

b. **Benefit/ Cost Ratio table:**

Year	0	1	2	3	4	5	6	7	8	9	10	11
Annual expenditure:												
Annual income:												
Discount factor (in interest rate %)												
Discounted expenditure												
Discounted income												

c. **Internal Rate of Return Format**:

Interest rate %	Year	Invest. Cost	R & M Exp.	Depreciation	Total Exp.	Total Income	Discount factor	Total Discounted cost	Total Discounted income	Net Cash flow
		1	2	3	4(1+2+3)	5	6	7(4*6)	8(5*6)	9(8*7)
	0									
	1									
	2									
	3									
	4									
	5									
	6									
	7									
	8									
	9									
	10									
	11									
	12									

Review Questions

1. Why techno-economic feasibility study of SPS / SPVS project is necessary?

   i. Minimize the risk and maximize the benefit
   ii. Assist investor to decide whether the project is worth doing
   iii. Motivate to find out most profitable project,
   iv. Find out safest and most financially self-sustaining projects

2. What are basic principles of feasibility study for project?

   i. Evaluate the schemes/projects on technical,
   ii. Evaluate the schemes/projects on economical,
   iii. Evaluate the schemes/projects on financial ground
   iv. Evaluate the schemes/projects on all of the above.

3. Why feasibility study of scheme/project is necessary?

   i. Minimize heavy losses
   ii. Maximize profit
   iii. Reduce financial risk
   iv. Convince the investor and financers for investment.

4. What are the basic indicators for quick calculation of techno-economic viability at a very early stage of project planning?

   i. Plant factor of the scheme/project
   ii. Unit energy cost of the scheme/project
   iii. Plant factor and unit energy cost of the scheme/project
   iv. Low operation cost of scheme/project

5. What are the indicators of project viability?

   i. Net present value (NPV),
   ii. Internal rate of return (IRR),
   iii. Pay back period,
   iv. Profit and loss of the beginning years

6. What are the factors necessary to determine optimum capacity?

   i. The estimation of energy demand
   ii. Existing energy consumption level
   iii. End use appliances
   iv. Non of the above

7. What are the basic factors influencing technical viability?

   i. Sufficient availability of sunshine
   ii. Cover project site fog over 100 days in a year
   iii. Northern part of a mountain or in the shade of trees,
   iv. More than 5 hours' sunshine in a day of a year

8. What are necessary to include in project investment costing?

   i. Cost of machinery and equipment,
   ii. Expenses incurred on civil construction,
   iii. Operation and maintenance expenses
   iv. Pre-investment expenses

9. What are the tools of economic financial analysis?

   i. The Net Present Value (NPV)
   ii. The Internal Rate of Return (IRR)
   iii. The Profit and Loss,
   iv. The rate of return on investment,
   v. Pay back period

10. Which are correct in project feasibility?

   i. If the NPV is negative, the project is feasible
   ii. If the NPV is positive, the project is infeasible.
   iii. If the NPV is zero, the project is neither feasible nor infeasible.
   iv. It is wise to invest if the NPV is zero.

11. Which one is not correct?

   i. The internal rate of return is the discount rate at which NPV =0
   ii. The investment recovery period is called as pay back period of the project
   iii. The purpose of the cash flow analysis is to reveal working capital requirement.
   iv. Sensitivity analysis is undertaken to how much risk will be there if changes occur in some of the items of the benefit/ cost or IRR analyses

12. Calculate the Net Present Value of the water pumping PV project, which has yearly expenditures and revenues as presented in Table below with the following data, assuming annual expenditure after year 0 and annual income same as appeared in the table.

   i. The start-up cost Rs.150,000 as expenditure of 0 year
   ii. Discounting rate 15 % (use discount table)
   iii. Project life 10 years

Year	Expenditure (Rs. 1000)	Income (Rs. 1000)	Annual Net earnings (Rs. 1000)	Discount factor (discount rate 12%)	Annual present values (Rs. 1000)
0	**-100**	**0**	**-100**	**1**	**-100**
1	**-15**	**28**	**13**	**0.89**	**11.6**
2	**-5**	**28**	**23**	**0.80**	**18.3**
3	**-5**	**28**	**23**	**0.71**	**16.4**
4	**-5**	**30**	**25**	**0.64**	**15.9**
5	**-5**	**31**	**26**	**0.57**	**14.8**
6	**-5**	**31**	**26**	**0.51**	**13.2**
7	**-7**	**31**	**24**	**0.45**	**10.9**
8	**-7**	**31**	**24**	**0.40**	**9.7**
9	**-7**	**31**	**24**	**0.36**	**8.7**
10	**-37**	**25**	**-12**	**0.32**	**-3.9**
11	**-7**	**31**	**24**	**0.29**	**6.9**
12	**-7**	**31**	**24**	**0.26**	**6.2**

Note: Change where necessary

13. Calculate the Net Present Value (NPV) for the ISPV project assuming a 12% discount factor, with the following data and comment.
    i. Income: Rs.20,000 each year for 15 years
    ii. Expenditure: Start-up cost Rs.40,000 and
    iii. Yearly Expenditure: Rs.8,000.

14. Considering the income of the project is Rs.20,000 yearly for 15 years and start-up cost (investment) is Rs.120,000, yearly expenditure Rs.8,000 . The NPV was calculated at a discount rate of 12%. What is the IRR of this project?

Note: The IRR will be equal to equal to the discount rate at which NPV is zero. Simply, try various values of discount rate, until the annuity is Rs. 12,000.

"If NPV is more than zero, increase the discount rate until NPV is as near to zero as you can get, using whole numbers for discount rates. If NPV is less than zero, increase the discount rate" Doing this (see table 3 below) we find in the first step at 15% discount rate the NPV will be Rs.13, 000. In the second step at 17% discount rate NPV will be Rs.4, 000, 000. If discount rate is increased to 18%, NPV will be zero.

Table 3 Calculating Internal Rate of Return (IRR) of the Project

In Rs.'000

Years	0	1	2	3	4	5	6	7	8	9	10	11	12
1.Expenditure:	-100	-15	-5	-5	-5	-5	-5	-7	-7	-7	-37	-7	-7
2. Income:	0	28	28	28	30	31	31	31	31	31	25	31	31
3. Annual net earning	-100	13	23	23	25	26	26	24	24	24	-12	24	24
4. Discount Factor (1st. guess discount rate 15%)	1	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29	0.26
5.Annual present value	-100	11.3	17.4	15.1	14.3	12.9	11.2	9.0	7.8	6.8	-3.0	5.2	4.5

6.NPV= -100+113= Rs.13, 000 (discount rate 15%)

4. Discount Factor 2nd. guess discount rate 17%	1	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29	0.26
5.Annual present value	-100	11.1	16.8	14.4	13.4	11.9	10.1	8.0	6.8	5.8	-2.5	4.3	3.6

6.NPV= -100+104= Rs.4, 000 (discount rate 17%)

4. Discount Factor 3rd. guess discount rate 18%	1	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29	0.26
5.Annual present value	-100	11.0	16.5	14.0	12.9	11.4	9.6	7.5	6.4	5.4	-2.3	3.9	3.3

NPV=-100+100=Rs.0 (discount rate 18%)

Step 4: The IRR is the discount rate at which NPV is nearest to zero. Therefore in this case IRR is 18%.