AMELIORATION OF SOLAR PHOTOVOLTAIC PERFORMANCE WITH MATLAB/SIMULINK

A DISERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
CONTROL & INSTRUMENTATION

Submitted By

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CERTIFICATE

This is to certify that Major Project-II report/dissertation entitled **AMELIORATION OF SOLAR PHOTOVOLTAIC PERFORMANCE WITH MATLAB/SIMULINK** is a bona fide record of the work carried out by **Mr. Manish Kumar Sharma**, bearing Roll No. **2K14/C&I/502**, submitted to Electrical Engineering Department of Delhi Technological University under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in "**Control & Instrumentation**".

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DECLARATION

I, hereby declare that the work which is being presented in this dissertation entitled **Amelioration of Solar Photovoltaic Performance with MATLAB/Simulink** is my own work carried out under the guidance of **Mr. A. R. Kulkarni**, Assistant Professor, Electrical Engineering Department, Delhi Technological University.

I further declare that the matter embodied in this dissertation has not been submitted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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ABSTRACT

Solar energy, a boon for mankind is available in abundance on earth. To drive & improve the quality of human life, energy security is a prima facie requirement, due to which research on solar photovoltaic technology is growing steadily liaising with implementation of solar power plants across the world. In this dissertation extensive study is given to review the solar photovoltaic module efficiency & ameliorate the optimized output of $500kW_P$ solar power plant by flexible tuning of distinct parameters and plant's operation strategy dealing with the site topography, environmental considerations and cost reduction. Explicitly it is step by step analysis of solar photovoltaic cells/modules/arrays and their operating characteristic with Matlab/Simulink. The variation of physical parameters in real time & efficiency of solar photovoltaic system for different operating conditions is analyzed using experimental method to optimize solar photovoltaic efficiency, whereas striving for cost reduction with O&M activities. Real time experimental results further reveal that an increase of 3.7% in annual energy output is achieved over conventional flat system.

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ABBREVIATIONS

SPV	Solar Photo Voltaic
MPP	Maximum Power Point
NOCT	Normal Operating Cell Temperature (˚C)
STC	Standard Test Conditions
POA	Plane of Array
LDR	Light Dependent Resistor
w.r.t.	With respect to
AR	Anti-Reflection
FF	Fill Factor
AC	Analog Current (Amp)
DC	Direct Current (Amp)
η_{SPV}	SPV Module Efficiency (%)
V_{OC}	Open Circuit Voltage of SPV (Volt)
V_{PV}	Output Voltage of SPV (Volt)
V_{SYS}	Rated System Voltage (Volt)
V_{MOD}	Nominal Module Voltage (Volt)
V_{ROC}	Reference Open Circuit Voltage at STC (Volt)
V_{MP}	Voltage at Max Power (Volt)
V_D	Discharging Voltage (Volt)
V_C	Charging Voltage (Volt)
I_{SC}	Short Circuit Current of SPV (Amp)
I_{PV}	Output Current of SPV (Amp)
I_{MP}	Current at Max Power (Amp)
I_{PV}	SPV Load Current (Amp)
I_S	Solar generated or Photon Current (Amp)
I_{RSC}	Reference Short Circuit Current at S.T.C. (Amp)
I_D	Diode Current (Amp)
I_{SAT}	Reverse Saturation/Scale Current (Amp)
I_c	Constant Charge Current (Amp)
I_d	Constant Discharge Current (Amp)
dI	Change in current

R_S	SPV Cell Series Resistance (Ω)
R_{SH}	SPV Cell Shunt Resistance (Ω)
P_M	Maximum Power (kW)
P_{DC0}	Nameplate DC Rating (kW)
T	Operating Temperature of SPV (˚C)
Ta	Ambient Temperature (˚C)
T_R	Reference Temperature of SPV (25˚C)
N_{MS}	No. of Panel in Series
N_{MP}	No. of Panel in Parallel
N_P, N_S	No. of SPV Cell in Parallel & Series
L_{AD}	Average Daily Load (kW)
A/L	Array to Load Ratio
S_H	Sunshine Hours at Site
K_I	Short Circuit Current Temperature Coefficient at I_{RSC}
τ	Transmittance of Glazing
α	Absorptance of SPV layer
U_L	Thermal Loss Coefficient (W/m^2K)
N_s	No. of Stator Phases or Stacks
N_r	No. of Rotor Teeth (or Rotor Poles)
ΔT_C	Charging Time Duration
ΔT_D	Discharging time duration
Q	Electron Charge ($1.6x10^{-19}$)
ß	Surface Tilt
γ	Surface Azimuth
γ_{SUN}	Solar Azimuth
$Ø_{SUN}$	Solar Zenith
I_B	Incidence Beam
$I_{D, SKY}$	Sky Diffuse on Surface
$I_{D, GROUND}$	Ground Reflected Irradiance
G_{TR}	Transmitted POA Irradiance (W/m^2)
G	Irradiance on SPV (W/m^2)
G_R	Reference Solar irradiance ($1000W/m^2$)
K	Boltzmann Constant ($1.3805x10^{-23}$ J/K)

L	Inductance(H)
C_{OUT}	Output capacitance
f_s	Switching frequency
D	Duty cycle for boost converter
mm	Micro meter

CHAPTER-1

INTRODUCTION

World has recognized India as a fastest growing economy and a developing country having great energy demand of which nearly 70% need is fed by non-renewable fossil fuels, which may result into main issues like future energy crisis, climate change and environmental disasters. Thus, it has become a global challenge to reduce CO_2 emission and sustain clean & affordable energy by means of renewable energy sources. With frightening rate of depletion of major energy reserves like Coal, Natural Gas, Petroleum and elephantine increase in energy demand worldwide, it has become a clamant necessity for renewable energy resources to feed world energy need through Biomass, Geothermal, Nuclear, Ocean, Solar, Wave and Wind. Among them, Solar photovoltaic (SPV) is the dominant contestant, advantageous in terms of being pollution free and requiring little maintenance, with high cost of installation and need of an converter/inverter for integration of load. Future demand of renewable energy resources with their potential is plotted in Fig. 1.1[Source: Wikipedia]

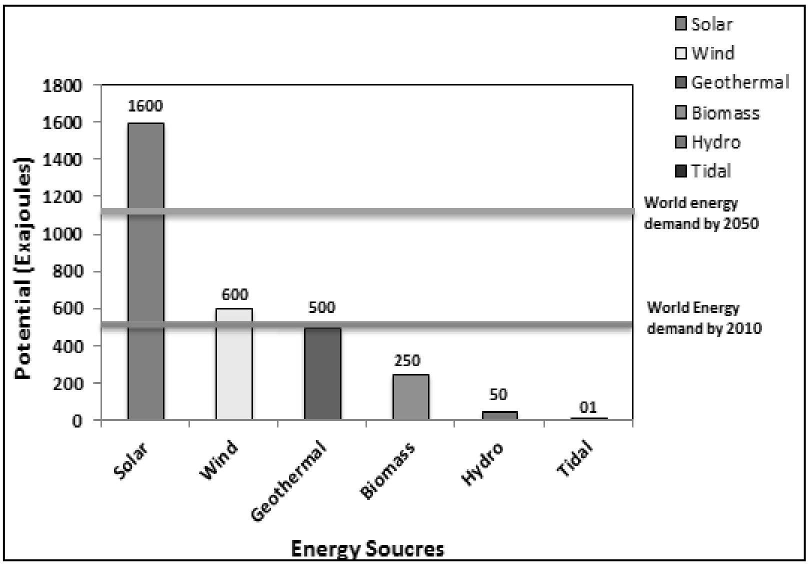

Fig. 1.1 Potential for Renewable Energy Sources

On the recommendation of Prime Minister of India, Ministry of New & Renewable Energy (MNRE) is implementing Jawaharlal Nehru National Solar Mission, which will empower India to become self-sustainable in solar power; year wise target to achieve 100GW by year 2022 is given in Table 1.1 [1].

Table 1.1 Future target of Ministry of New & Renewable Energy

Year	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	2021-22	Total
Rooftop (GW)	0.2	4.8	5	6	7	8	9	40
Ground mounted (GW)	1.8	7.2	10	10	10	9.5	8.5	57
Total (GW)	**2**	**12**	**15**	**16**	**17**	**17.5**	**17.5**	**97**

Being in developing phase with dense population, the energy sector of India is facing critical situation where load demand is rising round the clock irrespective of increased energy production over the years. Urban areas with almost stable power supply are still facing load shedding at peak time, whereas rural areas are affected by unstable power supply due to inadequate energy production. As per the statistics of Ministry of Power on May 2017, Total generation capacity of Indian power sector is nearly 330.2GW whose graphical representation is shown in Fig. 1.2[1]

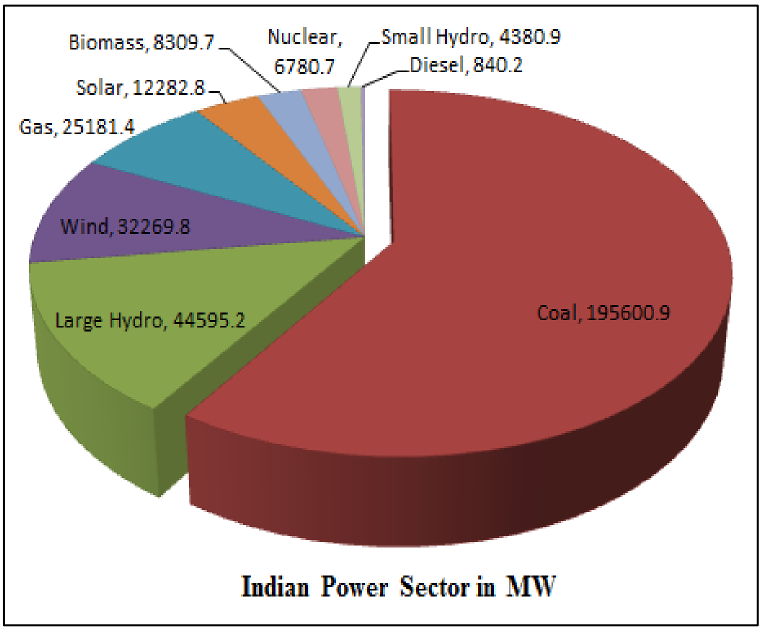

Fig. 1.2 Indian Power Sector in MW Capacity

With great downfall in cost & rising efficiency limits, SPV cell has emerged as an attention grabber of world's power sectors to generate electricity, which is a tremendous approach to make solar energy feeding future electricity demand by solar photovoltaic & solar thermal technology.

1.1 DIFFERENT SOURCES OF RENEWABLE ENERGY

1.1.1 Wind Energy

As per law of motion any moving object possesses kinetic energy, similarly wind flow around the earth also possesses kinetic energy which is called wind energy. It is an indirect manifestation of sun's energy as uneven heating of earth surface due to sun creates flow of wind in our atmosphere. About 1-3% solar energy falling on earth surface gets converted into wind energy. Worldwide several MW capacity wind turbine is used to harness wind energy that is nearly now of 100GW capacity. As per global wind energy council 2006 report, wind energy installations have grown at rate of nearly 27.9%

1.1.2 Solar Energy

Energy from solar radiation is profusely available on earth that has made it possible to harvest & utilize solar energy in form of solar photovoltaic & solar thermal technology. It can be used to produce electricity in rural & hilly areas, where availability of grid supply is a major challenge. The conversion of solar energy into electricity with nil impact on climate & environment can be achieved with the help of SPV cells.

1.1.3 Tidal Energy

Tides in a sea are the result of gravitational pull between moon & earth that causes rise & fall of water level, which is used for energy conversion process with the help of turbine. The effectiveness of energy conversion purely depends upon the maximum height the water level can achieve due to tide. As per world energy council draft report worldwide potential of tidal energy is about 63,800MW.

1.1.4 Geothermal Energy

Geothermal energy as name suggests energy available from the molten interior inside the earth. As we move inside earth towards the center, average temperature increases by about 30˚C per kilometer. As earth is round & due to this at some places hot spot is just beneath the surface and we found steam produced from reservoirs of hot water couple of miles or more below the earth's surface & that steam is used for generating capacity. As per world energy council draft report worldwide potential of geothermal energy is about 62,500MW. This energy comes from the decay of radioactive nuclei with long half-lives that are embedded within the earth, some energy is from residual heat left over from earth formation and rest of the energy comes from meteorite impacts.

1.1.5 Nuclear Energy

The energy content of a nucleus of an atom is converted into electrical energy by fission reaction in which a nucleus splits into smaller nucleus & results into release of energy called nuclear energy. The fuels used in fission reaction are U^{235}, U^{238} and Th^{232}. As per world energy council draft report worldwide potential of nuclear energy is about 3,70000MW.

1.2 MOTIVATION

Today SPV technology has become a burning research field for scientists & research scholars. Worldwide nations are investing in renewable & clean energy sources for developing their power sector due to limited sources of conventional energy. Even in the India, central & state governments are also implementing strategic plans to utilize renewable energy to cope up with raising energy demand. Electricity conversion from SPV module by the photovoltaic effect is a foremost effective technique that has enough space for research. As solar power generation has low efficiency and high installation cost therefore our target should be to increase system efficiency and reduce capital investment. Researchers are continuously developing efficient solar cell material and operation & maintenance activities to minimize the cost for consumers of solar systems.

1.3 SCOPE OF WORK

Operation & maintenance activities with correlated physical parameters & environmental factors like solar irradiation, temperature, season changes etc. adversely affect the SPV performance. Thus, it is interesting to analyse SPV performance under different environmental conditions & also track the maximum power point (MPP) using MPPT technique. Hence this dissertation is aimed to analyze & simulate SPV system with MPPT for improving the efficiency. The main objective of this dissertation work is:

1.3.1 Study & analyze annual performance data of 500kW_P solar power plant.

1.3.2 To design & develop Matlab/Simulink model of 250W SPV panel & 5kW_P SPV array.

1.3.3 Study of micro inverter application on performance of 500kW_P solar plant.

1.3.4 Performance analysis of Maximum Power Point Tracking (MPPT) for 5kW_P array.

1.3.5 Develop the simulation model for single phase SPV system with P&O MPPT technique and analyze the results.

1.4 ORGANIZATION OF DISSERTATION

For discussion purpose, the dissertation contemplates to solar photovoltaic terminology is systematized in the following manner:

CHAPTER-1 The chapter introduces renewable energy resources along with MNRE future strategy.

CHAPTER-2 The chapter contains literature survey on SPV technology.

CHAPTER-3 The chapter contains an overview & designing of SPV system that brief various topologies affecting SPV system efficiency.

CHAPTER-4 The chapter briefs sun tracking approach in SPV technology.

CHAPTER-5 The chapter contains an overview to converter, inverter & battery system.

CHAPTER-6 The chapter describes MPPT technique for SPV system.

CHAPTER-7 The chapter contains modeling & simulation of SPV system.

CHAPTER-8 The chapter describes optimum strategy & simulation results.

CHAPTER-9 The chapter conveys conclusion & future scope in SPV technology.

CHAPTER-2
LITERATURE REVIEW

Solar photovoltaic (SPV) modules with life span of 25-30 years have comparatively low conversion efficiency but serves as the most promising technology with steady development being clean, reliable, silent, minimal maintenance cost and ecological impact. It is estimated that sun, our natural power resource, will keep on shining for an estimated 4 billion years. The amount of solar energy that earth receives from sun in an hour has a potential to feed global energy demand for a year [2]. Due to continuous shift in relative position of earth & sun, irradiation on fixed SPV panels changes steadily and arrives a point where SPV surface receives maximum irradiation to grant max output.

As per geographical location of India we gain solar radiation almost 300 days a year. Utmost places receive 4.7kWh of solar radiation/m^2/day. Every year India gains nearly 3000 sunshine hours, that is equivalently above 5000 trillion kWh [3]. Thus with benefits of cost effectiveness, grid parity, self-consumption, greenhouse gas reduction and energy payback solar power is an optimistic future option of energy whose quinquennial iteration is plotted in Fig. 2.1

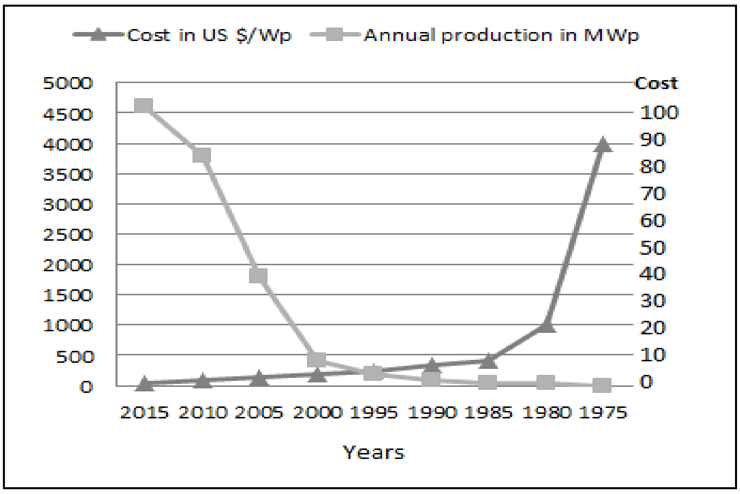

Fig. 2.1 Worldwide annual production of SPV modules & annual average cost in US$/$W_p$

With technology evolution, efficiency of SPV panel has increased dexterously, but it still limits up to 15% for common ones. An unceasing way to convert sun energy directly into electricity is not new topic, but the efficiency enhancement of SPV conversion is still of prime importance for many academic & industrial research groups round the globe. This dissertation work will present the highlights of O&M technology and methods implemented during program for efficiency enhancement.

Solar energy, a boon for mankind on earth may be utilized with the help of thermal & photovoltaic technology. Because of limited research and implementation programs by Govt. of India, thermal technology for electricity generation still is in reserve phase; whereas photovoltaic technology is in advance phase of implementation & utilization for both household & commercial purposes.

2.1 MODELING, DESIGN AND SIMULATION OF SPV ARRAY

SPV cells in a panel are connected in series/parallel configuration whose combination designs an array. The array size depends upon the load requirement in connection to converter, inverter, DC/AC load or grid supply that can be simulated in Matlab/Simulink.

Chetan singh solanki[2] presented complete detail about solar photovoltaic system, fundamental technology behind its functioning & applications in various sectors.

N. Rakesh[4] et al., proposed a new technique to enhance output power from solar array under different partial shaded conditions. SPV output dependency upon power mismatch, shading, solar irradiance & temperature is analysed.

R. Seyezhai & R. Ramaprabha[5] described solar energy conversion process in Renewable Energy Systems. It explains SPV system with converter, inverter, MPPT and solar tracker applications.

S. K. Parida & R.k.Behera[6] analyzed the effect of parasitic resistance in solar photovoltaic panel under partial shaded condition. Result of series & shunt resistances affecting SPV performance under differential shading condition were plotted.

E. V. Paraskevadaki & S. A. Papathanassiou[7] presented evaluation of maximum power point voltage & power of multicrystalline silicon SPV modules under partial shading condition.

Habbati Bellia[15] presented detailed modeling & simulation of temperature & irradiance effect on the current & voltage output of the SPV panel using Matlab/Simulink. Proposed single diode working model with both series & shunt resistors yields good accuracy.

Natrajan Pandiarajan[16] et.al., presented a complete model of SPV power system. The mathematical equations of currents are modeled & simulated in Simulink. SPV model in connection to the converter and inverter with P&O MPPT technique is analyzed and P-V, V-I curves are plotted for various temperature and irradiance.

Ram Krishan[17] et.al shows the performance of SPV array with variable temperature and irradiance. The P-V & V-I curves are analyzed with different temperatures and irradiance using MATLAB/Simulink.

2.2 DC-DC CONVERTER INTERFACING

SPV DC output level is very low, which is unable to feed load demand. So to make it in a desirable range, converters are used in boost, buck, half bridge, push pull, fly back, full bridge and buck-boost modes.

B. Sree Manju[18] proposed SPV charge control phenomena in battery storage system with Matlab/Simulink. A boost converter is more efficient than buck-boost converter, applicable where battery voltage is greater than SPV module voltage in connection to charge controller to increase battery life.

A.N. Natsheh, J.G. Kettleborough[19] describes the control of behavior of buck-boost converter used to provide an interface between SPV arrays and batteries for renewable energy sources.

2.3 MAXIMUM POWER POINT TRACKING ALGORITHMS

MPPT is the technique to maximize output power from SPV panel by various MPPT methods as discussed in chapter-6.

Bidyadhar Subudhi[20] presented the classification of different MPPT techniques based on their control variables. MPPT comparison is done on the basis of circuit cost and selection for a specified application.

F. Z. Hamidon[21] et.al., presented SPV array model with most widely used P&O MPPT algorithm to obtain SPV array characteristics for different irradiance, temperature, series & shunt resistance and series parallel combination of SPV modules.

2.4 CHARGE CONTROLLER OF BATTERY

A charge controller/battery regulator limits the charging & discharging current in the batteries. It also acts as a safeguard of battery against overcharging, overvoltage and deep discharging that reduces life & performance of battery and may adhere to safety risk.

Sherif Imam[22] et.al., design different operating & design parameters on sizing and economics of SPV system for residential utilization and define component size and cost of energy with effect of battery bank voltage, solar irradiation and Demand of discharge.

2.5 INVERTER CONTROL TECHNIQUE

S. Yousofi-Darmian & S. Masoud Barakati[23] proposed a new four-level transformer-less single phase inverter design with low cost and high efficiency for residential use. In these inverters leakage current flows through stray capacitors which is harmful, cause losses and electromagnetic interferences. This inverter works on non-unity power factor done by switching control strategy and has low leakage losses.

CHAPTER 3

AN OVERVIEW & DESIGNING OF SOLAR PHOTOVOLTAIC SYSTEM

3.1 TECHNICAL SYNOPSIS OF 500kW$_p$ SOLAR POWER PLANT

3.1.1 Efficient generation at consumption center, small transmission & distribution losses & low cost production (500kW$_p$ @ 4.0cr with financial assistance from GOI of 15% of total cost)

3.1.2 Small gestation time (approximate 1 month) with optimal use of land (500kW$_p$ @ 1.5-2.0 acre for crystalline & 2.5-3.5 acre for thin film technology)

3.1.3 Energy storage either scaled up (Ideal) or grid connected.

3.1.4 Site selection in Delhi with latitude of 28.59°N, Ground reflectivity of 0.2, Maximum sunshine hours/day at location, Maximum plane of array incident radiation.

3.1.5 Power plant capacity of 500kW$_p$ (100 arrays of 5kW$_P$), standard wafer based crystalline silicon (C-Si) of 15-19% commercial efficiency, normal operating cell temperature(NOCT) of 47˚C, maximum power point (MPP) tracking control option, inverter rating of 500kW with 96% efficiency, location average radiation of 5.09kWh/m^2, ambient temperature of 25.1˚C, temperature coefficient -0.45%/˚C and No. of modules are 2100 approx.

3.1.6 Panel orientation on site with latitude of 28.59˚N, longitude of 77.046˚E, summer angle will be 13˚, winter angle will be 43˚ & optimum tilt (angle from horizontal of SPV module in array) of 28.59˚.

3.1.7 Monthly solar radiation on site for solar plant is shown in Fig. 3.1

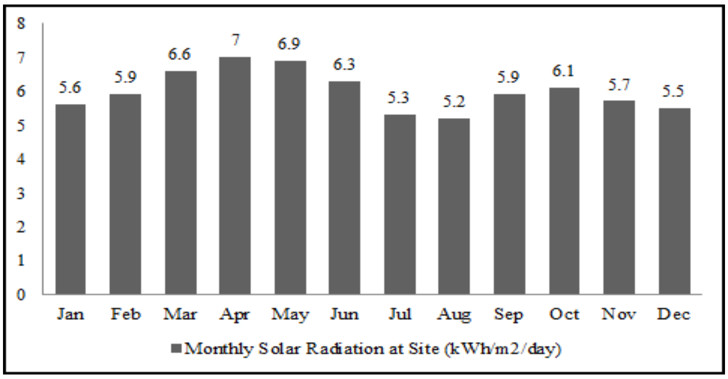

Fig. 3.1 Monthly solar radiation at plant site

3.1.8 Specification of Tata BP solar panel at standard test conditions(STC) of $1000W/m^2$ solar irradiation, NOCT of 25˚C, average wind speed of 1m/s and at zero electrical loads are listed in Table 3.1

Table 3.1 SPV panel specifications at standard test condition.

P_M	250W
V_{OC}	37.38V
I_{SC}	8.71A
V_{MP}	31.5V
I_{MP}	7.94A
R_S	0.55Ω
R_{SH}	1000Ω
Panel Efficiency	15.3%
Solar Cell Efficiency	17.2%
Size & Life with Guarantee	$1.637m^2$, 10 years@90% & 25 years@80%
Operating Temperature	-40˚C to 85˚C
Weight	17kg
Max output	2000kWh in Summer 1250kWh in Winter

3.1.9 Azimuth angles as per headings for fixed SPV are listed in Table 3.2

Table 3.2 Azimuth angle with heading

0˚	45˚	90˚	135˚	180˚	225˚	270˚	315˚
North	North-East	East	South-East	South	South-West	West	North-West

3.1.10 Monthly POA irradiance on site for solar plant is shown in Fig. 3.2

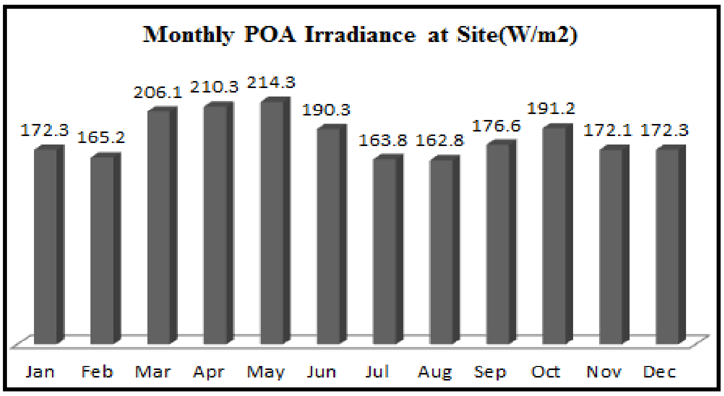

Fig. 3.2 Monthly POA irradiance at plant site

3.1.11 Annual performance of 250W SPV panel is shown in Table 3.3

Table 3.3 250W SPV panel month wise performance data

250W Solar Panel Monthly Performance Data (Jan-2015 to Dec-2015)				
Location				DELHI
Latitude (degree N)				28.59
Longitude (degree E)				77.25
Elevation (m)				216
DC System Size (W)				250
Module Type				Standard
Array Type				Fixed (open rack)
Array Tilt Angle (degree)				28.59
Array Azimuth Angle (degree)				180
System Losses (%)				11.42
Invert Efficiency (%)				96
DC to AC Size Ratio				1.1
Month	**AC system output (kWh)**	**Solar Radiation (kWh/m^2/day)**	**Plane of Array Irradiance (W/m^2)**	**DC array Output (kWh)**
Jan	25.3	4.16	129.02	26.50
Feb	28.96	5.41	151.54	30.21
Mar	36.4	6.45	200.01	37.90
Apr	36.12	6.83	204.81	37.68
May	33.15	6.06	187.83	34.61
Jun	29.24	5.44	163.06	30.57
Jul	26.8	4.62	143.18	28.03
Aug	28.9	4.92	152.40	30.20
Sep	31.14	5.58	167.45	32.51
Oct	33.51	5.86	181.80	34.94
Nov	28.23	4.93	147.85	29.43
Dec	25.9	4.29	132.96	27.04
Total	**363.65**	**64.55**	**1961.91**	**379.62**

3.1.12 Annual performance of $5kW_P$ SPV array is shown in Table 3.4

Table 3.4 5kW SPV array month wise performance data

$5kW_P$ SPV Array Monthly Performance Data (Jan-2015 to Dec-2015)				
Location				DELHI
Latitude (degree N)				28.59
Longitude (degree E)				77.25
Elevation (m)				216
DC System Size (kW)				5
Module Type				Standard
Array Type				Fixed (open rack)
Array Tilt Angle (degree)				28.59
Array Azimuth Angle (degree)				180
System Losses (%)				14.08
Invert Efficiency (%)				96
DC to AC Size Ratio				1.1
Capacity Factor (%)				16.6
Month	**AC system output (kWh)**	**Solar Radiation (kWh/m^2/day)**	**Plane of Array Irradiance (W/m^2)**	**DC array Output (kWh)**
Jan	491.36	4.16	129.02	513.90

Feb	561.71	5.41	151.54	586.07
Mar	705.30	6.45	200.01	735.31
Apr	700.63	6.83	204.81	730.90
May	642.93	6.06	187.83	671.46
Jun	567.09	5.44	163.06	593.14
Jul	519.11	4.62	143.18	543.78
Aug	559.99	4.92	152.40	585.93
Sep	603.95	5.58	167.45	630.61
Oct	649.97	5.86	181.80	677.89
Nov	547.54	4.93	147.85	570.93
Dec	502.27	4.29	132.96	524.53
Total	**7051.85**	**64.55**	**1961.91**	**7364.45**

3.1.13 Annual performance of 500kW$_P$ SPV plant is shown in Table 3.5

Table 3.5 500kW SPV plant month wise performance data

500kW$_P$ Solar Plant Monthly Performance Data (Jan-2015 to Dec-2015)				
Location				DELHI
Latitude (degree N)				28.59
Longitude (degree E)				77.2
Elevation (m)				216
DC System Size (kW)				500
Module Type				Standard
Array Type				Fixed (open rack)
Array Tilt Angle (degree)				28.59
Array Azimuth Angle (degree)				180
System Losses (%)				12.75
String Inverter Efficiency (%)				96
DC to AC Size Ratio				1.1
Capacity Factor (%)				18.6
Month	**AC system output (kWh)**	**Solar Radiation (kWh/m^2/day)**	**Plane of Array Irradiance (W/m^2)**	**DC array Output (kWh)**
Jan	67698.7	5.56	172.29	70631.47
Feb	63834.9	5.90	165.23	66567.10
Mar	77625.5	6.65	206.11	80996.66
Apr	76918.3	7.01	210.29	80257.81
May	76681.4	6.91	214.34	80041.72
Jun	68364.7	6.34	190.28	71444.48
Jul	59792.9	5.28	163.82	62576.58
Aug	59931.0	5.25	162.84	62685.92
Sep	64829.3	5.89	176.60	67711.33
Oct	70165.6	6.17	191.25	73218.62
Nov	64507.5	5.74	172.16	67287.55
Dec	66052.1	5.56	172.33	68884.94
Total	**816401.9**	**72.26**	**2197.54**	**852304.18**

The entire structure in Fig. 3.3 is rigid mounted flat SPV system of 500kW$_P$ capacity (differentiated in 100 arrays of 5kW$_P$ rating) with tilt angle of 28.59° in northern hemisphere faced southward (azimuth angle= 180°) with competency to shift locus as season changes, so that it can acquire ameliorated output with attention to extrinsic factors that a solar planner can't control such as solar irradiation, day temperatures, number of sunny days and air mass. The output also rely upon some intrinsic factors that a solar planner can control such as site selection, solar tracking option, tools & material quality, operation & maintenance activity, artisanship of engineering procurement & construction planner.

Fig. 3.3 500kWp solar photovoltaic plant at Dwarka

SPV output mostly depends upon power mismatch, shading, solar irradiance and temperature [4]. Keeping tilt angle as site latitude will not necessarily enhance annual output, but if we keep tilt angle greater than latitude in winter (on the risk of wind damage to array and rise in cost of pallet racking and mounting hardware) and less than in summer, it surely enhance annual output, thus lower tilt angle is preferred. For our system increasing azimuth angle boosts afternoon energy production and decreasing azimuth angle boosts morning production.

An array area of approximate 3333.3m^2 is required, which is not entire plant area but might include space for modules, inverter and assembly obtained from equation (3.1).

Plant Rating (kW) = *SPV Area* (m^2) x 1kW/m^2 x *Panel Efficiency* (%) (3.1)

[500kW ÷ 1kW/m^2 ÷ 15% = 3333.3m^2 (35879.67ft^2)]

(3.1) may be expressed as:

Plant Rating (kW) = *Panel Nameplate* (W) x *No. of Panels* ÷ 1000W/kW (3.2)

3.2 CLASSIFICATION OF DIFFERENT CELLS & MATERIALS

Enhancement in passivation of contacts & surface region of cells has significant impact on efficiency of solar cell & material. Various factors to be considered for efficiency improvement of solar cell are listed as:

3.2.1 Diversity in Si material like mono crystalline, multi crystalline, cast-mono & amorphous structure.

3.2.2 Diversity in substrate material like a-Si, Cd-Se, Cd-Te, Ga-As, Ga-Se & CIGS.

3.2.3 Diversity in semiconductor structure like organic material, liquid interface & intermediate transitions (phosphors).

3.2.4 Diversity in junction type like direct & indirect band gap structure, homo & hetero junctions, metal-insulator junction, metal-semiconductor junction, Schottky barrier junction.

3.2.5 Diversity in cell fabrication like PERL, PERC, reflecting & textured surface, sliver & stacked cells, thin film cells, vertical multi junction cells [5].

Optically reduced reflection by improved anti-reflection (AR) coating, improved trapping of light by surface texturing in cell & reduction of volume in heavily doped material in cell have great impact to increase efficiency to confirmed value up to 24%. Efficiency improvement in future as a function of time is plotted in Fig. 3.4(Source: Wikipedia)

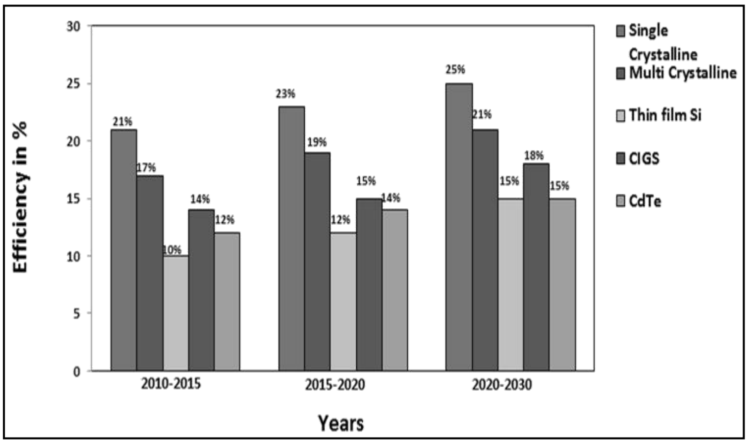

Fig. 3.4 Expectation of SPV efficiency improvement in future.

Mostly solar cells are made up of crystalline silicon(C-Si) wafers of 160mm to 240mm thickness. Having all advantage of thin film technology, the material quality of hydrogenated amorphous silicon (a-Si:H) for solar cell production is better than pure amorphous silicon (a-Si). Installed solar panel is 15-19% efficient which accounts for larger module area as 3333.3m^2 (35879.67ft^2) but if we use Premium wafer based crystalline silicon (C-Si) of commercial efficiency 19-24%, temperature coefficient of -0.35%/°c with AR module cover, the required area is only 2631.6m^2. [500kW ÷ 1kW/m^2 ÷ 19% = 2631.6m^2 (28326.3 ft^2)].

Thus optimum use of land with cost reduction. Other than crystalline Si wafer, thin film technology also now mercantile cultivated which consist of a-Si, Cd-Te, CIGS. Distinct semiconductor materials with their efficiency limit & band diagram of solar cell is plotted in Fig. 3.5 & 3.6

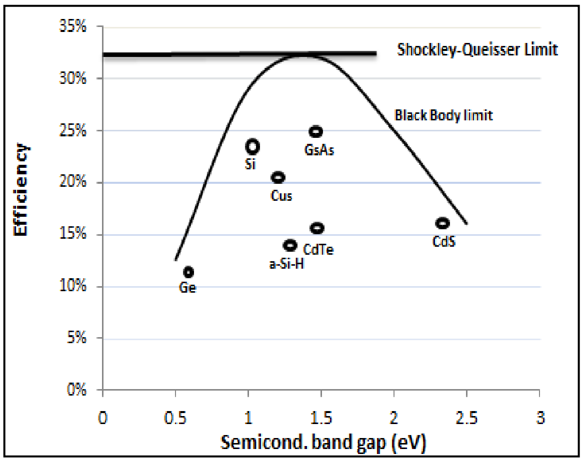

Fig. 3.5 Distinct semiconductor materials

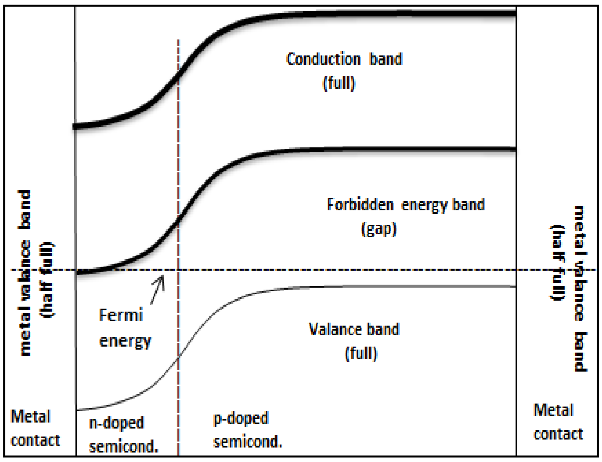

Fig. 3.6 Band diagram of solar photovoltaic cell.

3.3 OPEN CIRCUIT VOLTAGE (V_{OC}) & SHORT CIRCUIT CURRENT (I_{SC})

Open circuit voltage (V_{OC}) is the maximum voltage obtained from SPV cell when its terminals are left open means load current is zero. Whereas maximum current induced by SPV cell when its terminals are short circuited is termed as short circuit current (I_{SC}) as shown in Fig. 3.7.

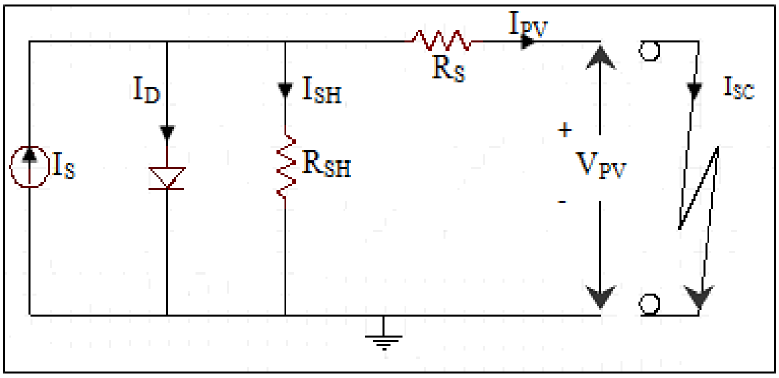

Fig. 3.7 SPV Cell Equivalent Circuit

SPV cell equivalent circuit shown in Fig. 3.7 can be modeled mathematically as given in equations (3.3) - (3.10).

$$I_S = I_D + I_{SH} + I_{PV} \tag{3.3}$$

$$I_{PV} = I_S - I_D - I_{SH} \tag{3.4}$$

$$I_S = [I_{RSC} + K_I (T-T_R)\, G/G_R] \tag{3.5}$$

$$I_{SC} = \mathrm{I}_{RSC} [1+K_I (T-T_R)] \tag{3.6}$$

$$I_{PV} = I_S - I_D - V_{OC}/R_{SH} \tag{3.7}$$

Since diode current (I_D) and ground leakage current (I_{SH}) are too small to be neglected under short circuit condition. Thus with this criterion:

$$I_{SC} \approx I_{PV} = I_S \quad (3.8)$$

Where I_D is given by Shockley diode equation as:

$$I_D = I_{SAT}\,[\exp\,(QV_{OC}/AKT\text{-}1)] \quad (3.9)$$

$$V_{OC} = V_{PV} + I_{PV}\,.\,R_{SH} \quad (3.10)$$

V_{OC} from Fig. 3.8 is:

$$V_{OC} = E_g/q - (kT/q)\ \ln(J_{sc}/J_{oc}). \quad (3.11)$$

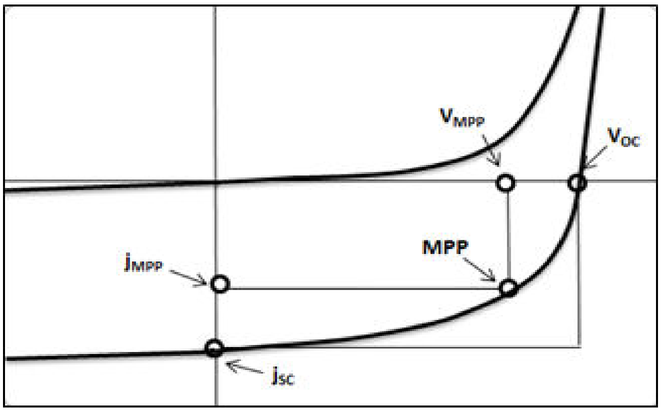

Fig. 3.8 Open circuit voltage & Short circuit current

Higher band gap material may consume less photon in comparison of lower band gap material. Thus I_{SC} will increase and V_{OC} will decrease with decrease in band gap energy. SPV cell generates V_{OC} near around 0.5-0.7V based on the semiconductor material & SPV cell construction. To raise panel voltage, cells must be connected in series configuration. Larger the band gap, higher is the V_{OC} of SPV cell as analyzed from Fig. 3.8. Since band gap of silicon is 1.1ev thus maximum possible V_{OC} may be 1.1V [6].

3.4 VOLTAGE-CURRENT CHARACTERISTICS

Extracting maximum power (P_M) from SPV panel is difficult due to nonlinearity of voltage-current (V-I) characteristic plotted in Fig. 3.9

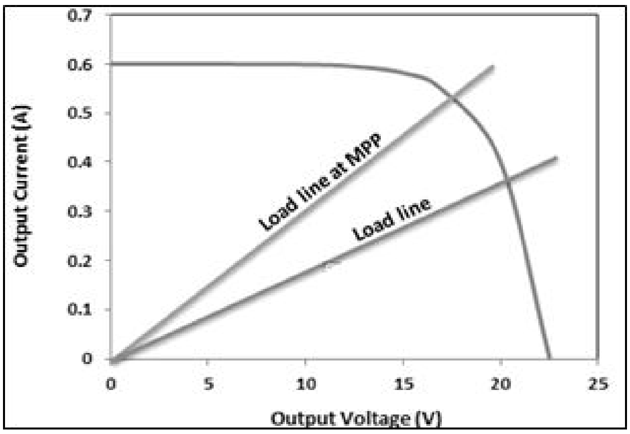

Fig. 3.9 V-I Characteristic of SPV cell

During assessment it was examined that SPV output voltage (V_{PV}) varies with temperature variation and SPV output current (I_{PV}) changes in accordance with irradiation change. As illumination rises, I_{PV} increases and load line tangent moves up. In Fig. 3.9 load line tangent over V-I curve decides MPP to deliver P_M for liable temperature & irradiation. The necessary & sufficient condition for stable operation of SPV panel is $(dp/dv)_{\mathbf{Load}}$ must be greater than $(dp/dv)_{\mathbf{Source}}$.

3.5 FILL FACTOR (FF)

It is squareness of V-I curve that regulates P_M of solar cell liaising with product of V_{OC} & I_{SC}. It is principally allied to resistive loses in solar cell. Ideally it is 100% but it's not feasible to have square curve shown in Fig. 3.9. Due to losses present FF value reduces. Premium solar cell has FF value more than 0.89.

3.6 SOLAR CELL EFFICIENCY

SPV cell is generally of 10x10cm, protected by AR transparent film, which produces around 0.5v depending upon design & material of cell. SPV cell conducts forward biased under uniform radiation but with variation of radiation, some SPV cell conducts reversed biased and dissipates as heat. SPV cell can permit I_{PV} flow below its I_{SC} capacity for liable solar radiation but when I_{PV} more than I_{SC} flows, SPV cell by-pass diode activates and short circuit particular SPV panel, due to which power curve incur multiple peaks [7].

I_{PV} depends primarily on SPV cell area and incident radiation. With band-gap extension I_{SC} of SPV cell decreases and V_{OC} increases, thus an optimum band-gap must lay to achieve max solar cell efficiency. Optimization of solar cell parameters I_{SC}, V_{OC} and FF must be higher to get high efficiency. SPV cell max efficiency Vs energy band gap is plotted in Fig. 3.10

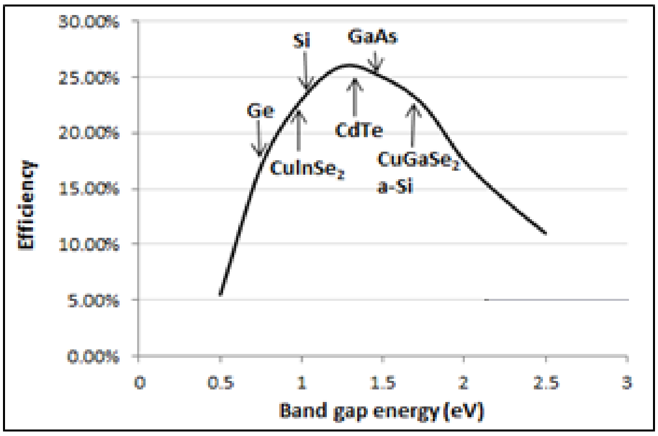

Fig. 3.10 SPV cell max efficiency Vs Energy band gap

3.7 SOLAR PANEL EFFICIENCY

At noon on the equator, 1000 W/m^2 of sun energy touches the ground of which only 20% can be transferred into consumable energy. The photon can either be absorbed, reflected or pass through the semiconductor, of which pass through & reflected must be diminished to increase no. of photons absorbed, ultimately increasing efficiency of solar panel. To reduce percentage of reflected photons, AR coating is planted over semiconductor material. Photons in sunlight having energy less than band-gap and different wavelength overleap the semiconductor without creating electron-hole pair. A highly efficient SPV panel can be designed by cascading semiconductor material with distinct band gaps to perfectly match light spectrum, despite its requirement of infinite amount of semiconductor material and different crystal structure which makes it utterly complicated and intensely difficult as one crystal structure may be more efficient, but expensive to consider. Rather than focusing on issues recite to design and semiconductor physics behind solar panels, this dissertation work focus more on ameliorating the features that control the output of solar panels. SPV panel output variation also depends on certain ambient weather conditions such as temperature, illumination, how clear the sky is.

3.8 LOSSES IN SOLAR CELL

It refers to loss of photon energy due to fundamental & technical reasons as discussed below:

3.8.1 Transmission Loss: Photons having less energy than band gap energy don't get assimilated in material and do not contribute to generation of electron hole pair referred as transmission losses and virtually nears to 23% for single junction solar cell.

3.8.2 Loss due to glut energy of photon: If photons having energy greater than band gap, the excess energy is termed as glut energy which gives off heat to the material almost near to 33% of single junction solar cell.

3.8.3 Fill factor (FF) loss: The V-I curve of ideal SPV cell is square (FF=1), but the real one has exponential behavior (FF= 0.89). This type of loss arises from parasitic series (R_S) & shunt (R_{SH}) resistance shown in equivalent circuit of P-N junction solar cell, Fig. 3.7. Parasitic resistance principally affects SPV performance whereas more effect is due to R_S in solar cell, which reduces FF, I_{SC} and SPV panel efficiency. Worst value of R_S is 1Ω as ageing tends to increase it and decrease FF & I_{SC}, so it is desirable to have small R_S and high R_{SH}.

Above losses are fundamental which cannot be avoided or minimized beyond their fundamental limits.

3.8.4 Loss by reflection: A fraction of incident photons reflected from cell surface can be attenuated by using AR coating or surface texturing. An AR of silicon nitride is typically deposited using chemical vapour deposition (CVD) process. Precursor gases of Silane (SiH_4) & Ammonia (NH_4) are fed into a chamber & break down due to temperature (LPCVD) or plasma enhancement (PECVD). Other systems use microwaves to provoke the Silane/Ammonia reaction to take place. The complete reaction is:

$$4NH_3 + 3SiH_4 = 12H_2 + Si_3N_4 \quad (3.12)$$

Earlier SPV cells design used TiO_2 to provide AR coating which was easy in application but unable to procure surface passivation. With given angle of incidence (Θ_1) & Snell's law, Angle of refraction (Θ_2) into AR coating is:

$$\Theta_2 = arc\sin\left[(\eta_{air}/\eta_{AR})\sin(\Theta_1)\right];\ \eta_{air}=1, \eta_{glass}=1.526 \quad (3.13)$$

The AR coating anticipates slightly higher output compared to standard glass due to improved angular response.

3.8.5 Loss due to incomplete absorption: It refers to the loss of photons having enough energy to get absorb but not due to finite solar cell thickness which can be deprecated by light trapping scheme as anti-reflection coating, surface texturing.

3.8.6 Loss due to manufacturing imperfections between panels that causes marginally different V-I characteristics & differences between field measurements of SPV panels & name plate ratings.

3.8.7 Loss due to temperature variation & inverter conversion.

3.8.8 Resistive loss in inverter, electrical connecters, DC/AC wires connecting panels.

3.8.9 Loss due to scheduled/unscheduled system shut down for maintenance, grid outages and other operation & maintenance reasons.

3.8.10 Loss due to light induced degradation which reduces array output power during initial phase of operation just after installation. After certain period of operation module output stabilizes and follows long term degradation over life time from installation (≈0.5%/year). Due to peculiar material and construction, premium wafer crystalline silicon panel experiences lower degradation losses as compare to standard wafer crystalline silicon panel.

3.8.11 Loss due to dust, dirt & other foreign particles on SPV panel surface preventing solar radiation reaching cells. Such loss is weather cum location dependent, stands high in traffic & polluted areas with infrequent rain.

3.8.12 Loss due to metal coverage: Metal contact to the front side of cell is made in form of finger & bus bar, which shadows some light on SPV panel nearly up to 10% that can be reduced by using one sided contact cell.

3.8.13 Recombination loss: All electron–hole pairs do not contribute to I_{PV} & V_{PV}, as recombination loss affects both current collection & forward injection current in solar cells. To reduce, both surface & bulk recombination must be minimized, which can be done by appropriate surface passivation technique using Silicon Nitride that passivates surface and reduces surface recombination. Heavy doping under contacts & rear of SPV cell keeps minority carriers away from high recombination front & rear contact.

Total losses (L_{Total}) encountered here is not sum of individual losses; it can be estimated by multiplying reduction due to each loss L_i (%) as:

$$L_{Total}\,(\%) = 100\,[1 - \Pi_i\,(1- L_i/100)] \tag{3.14}$$

All above losses (system loss nearly 12.75%) can be minimised beyond their fundamental limits by AR coating, surface texturing & passivation and rest techniques discussed in this work & shown in Fig. 3.11 (By application system loss reduces nearly up to 12.30%).

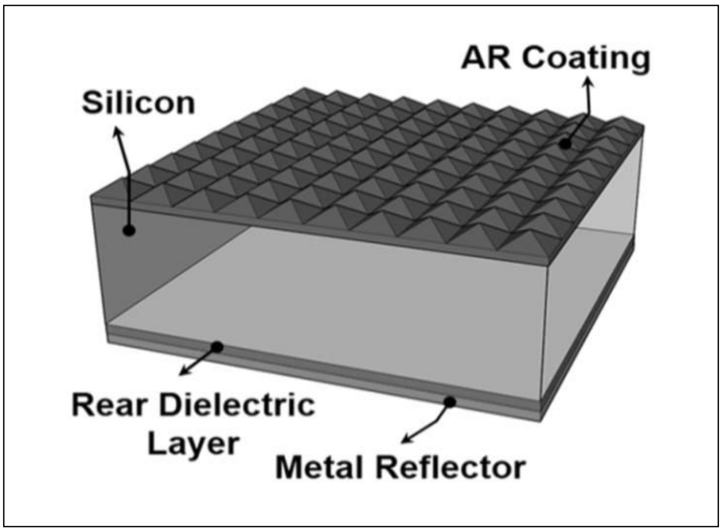

Fig. 3.11 AR coating with surface texturing & passivation

3.9 MODULE SIZE INDEPENDENCE & INSTALLATION FLEXIBILITY

In parallel solar paradigm shown in Fig. 3.12, SPV technology of module no longer matters, because each SPV module operates independently among its adjacent modules.

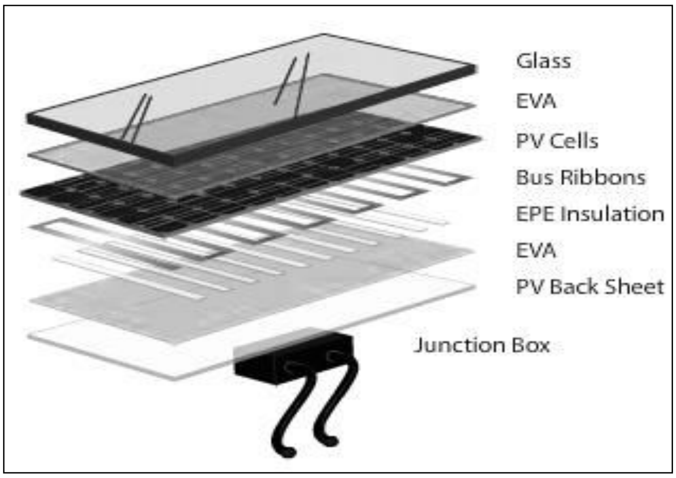

Fig. 3.12 Solar photovoltaic module

Variable sized panels ranging from 200W to 31KW of any manufacturer can be put to use in SPV plant, which needs different azimuth & tilt angle as per aesthetics of the plant. It empowers installer to utilize entire space at fortification site. To simplify calculation of configuration loads during SPV plant design, parallel configuration reduces influence of factors such as V_{OC}, temperature drift, upper limit of charge controller and its restriction on the number of module which can be wired together. If load demand rises, without disturbing existing setup we can simply expand solar plant rating by adding SPV panels in parallel.

3.10 CABLE THICKNESS

Electrical home appliances rated at 220V is significantly higher compared with SPV voltages of 48, 24 & 12V. For similar rating much higher current is involved in SPV system, which introduces resistive losses in configuration. Cable with $1.5mm^2$ cross section has resistance of nearly 0.012Ω/m of wire length. So a 10m long wire between panel & charge controller will offer resistance of $10 \times 0.012 = 0.12\Omega$. For 12V, 10A system, voltage drop across this wire is 1.2V. Thus final voltage at cable end is 1.2V (10% drop) less than panel output voltage which is objectionable.

For $6mm^2$ cross section cable, having resistance of 0.003Ω/m, 10m long wire will offer resistance of $10 \times 0.003 = 0.03\Omega$. For similar 12V, 10A system, drop across wire end is 0.3V (2.5% drop) that might be acceptable on ground of cost increment. To decrease resistive losses we can also raise system voltage say 24V that will deliver same output. [24V × 5Amp = 120W] thus voltage drop reduces $1/4^{th}$ times, if we double system voltage. With configuration all around, resistive drop has immense effect on plant efficiency thus cable configuration requires utmost scrutiny at planning & designing level of solar plant. MNRE standards for cable is IEC 60227 / IS 694 or IEC 60502 / IS 1554 [1].

3.11 TEMPEATURE EFFECT

Under steady state condition operating cell temperature (T_C) is:

$$T_C = T_a + (\tau\alpha)\,(G/U_L)\,[1- \eta_{SPV}/\tau\alpha] \tag{3.15}$$

$\eta_{SPV} = 0$ for zero electrical loads, under NOCT condition:

$$U_L = (\tau\alpha)\,G_{NOCT}/(T_{NOCT} - T_{aNOCT}) \tag{3.16}$$

Thus final operating cell temperature is:

$$T_C = T_a + (G_T/G_{NOCT})\,(T_{NOCT} - T_{aNOCT}) \tag{3.17}$$

With temperature rise, I_{SC} of the cell increases, whereas V_{OC} decreases shown in Fig. 3.13

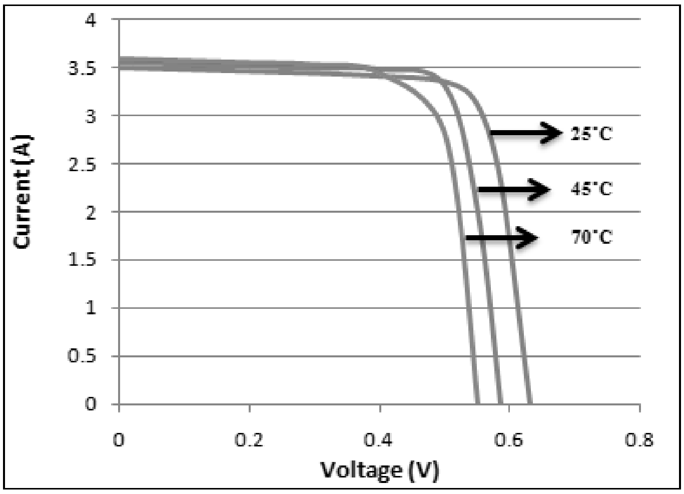

Fig. 3.13 Temperature effect on SPV cell

If T_C is increased by ΔT then new I_{SC} & V_{OC} is:

$$I_{SC} = I_{RSC}\,(1 + K_I \Delta T) \tag{3.18}$$

$$V_{OC} = V_{ROC}\,(1 - K_V \Delta T) \tag{3.19}$$

The power is:

$$P = V_{ROC}\,(1 - K_V \Delta T) \times I_{RSC}\,(1 + K_I \Delta T)$$

$$P = P_O\,[1 + (K_I - K_V)\,\Delta T] \tag{3.20}$$

With each degree temperature rise above T_R, SPV cell output power deteriorates, since increase in I_{SC} is much less then decrease in V_{OC} as shown in Fig. 3.13, the net effect is decrease in power at high temperature. Panel behavior rated for 25˚C might be differential from outside situation because cold climate insist SPV panel for optimized output rather than hot. Above 25˚C for each degree temperature rise, output of SPV panel decline nearly 0.26% in case of amorphous cell fabrication & 0.5 to 0.6% in case of crystalline cell fabrication.

During humid summer temperature of SPV may rise up to 60˚C & even more, due to which panel may decay up to 25% less power compared to their rating. Thus a 1000W array will give 750W only, as output during May, June, July in utmost part of Delhi where temperature may rise up to 48˚C & beyond in summer with high electricity demand. Conditions for SPV open circuit cells in an array to achieve NOCT are: Air temperature (≈20ºC), Wind speed (≈1m/s), Irradiance (≈800W/m^2). SPV array is open back rigid mounted & susceptible to air flow from back to serve cooling purpose. Best quality panels have NOCT value of 35±2˚C & worst have 56±2˚C. With low NOCT value, higher is the expectation by SPV panel to perform in hotter climates.

3.12 SHADING

Ideally there should be no shadow on SPV panel as it can have explicitly weird effect on the output because shadow of objects like bird's shit, cloud, falling leaves, man-made structure and tree may reduce radiation that SPV panel receive, inevitably resulting in lower system efficiency. Ordinarily series connected cells in a panel get disturbed due to shading on a single cell which affects the complete current flow and deterioration of output occurs if such infected panel gets connected in a string. Thus, during installation modules with parallel configuration is preferred over series configuration & partial shading effect must be examined during designing & planning stage. Efficiency depreciation as a result of shading in string connection & appreciation with micro-inverter connection is shown in Fig. 3.14

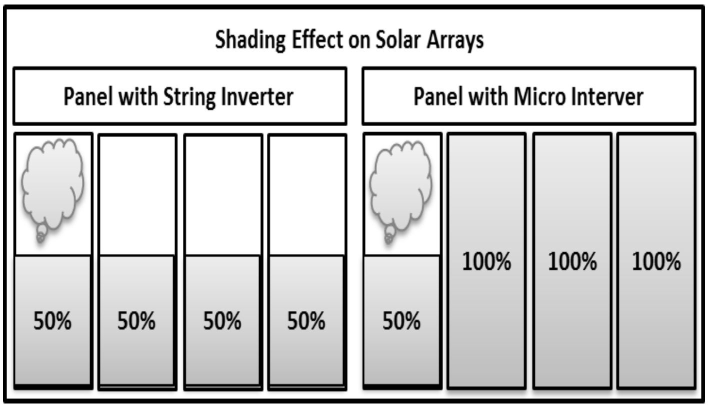

Fig. 3.14 Shading impact on SPV array

In case of series connected SPV modules, real time field result reveals how giant, asymmetric loss can occur due to shading in Table 3.6

Table 3.6 Shading effect on SPV output power

% of Array shaded	3%	6.5%	9%	13%
Power loss due to shading	25%	44%	54%	44%

Shading derate factor is a function of ground cover ratio (GCR), which is the ratio of array area to ground area occupied by an array. Derate factor close to one means less shading loss, more space between module rows & smaller GCR. Keeping smaller tilt angle, less row space & larger GCR we can achieve derate factor closer to 1, i.e. less shading losses in our system.

3.13 PARALLEL CONFIGURATION CONCEPT

Conventionally SPV modules in series configuration to achieve desired voltage level, endow efficient operation of charge controller, but due to high sensitivity for operating voltages, it suffers major swings in efficiency with input voltage variation. Larger the variation, harder is the optimal efficient operation. A potent clue is to connect each SPV module in parallel. Mismatch in series & parallel configuration occur due to difference in V_{OC} and I_{SC}. But in parallel configuration, mismatch of current is not a concern. As current will be the sum of individual solar cell current & the mismatch in open circuit voltage results in loses which is less harmful in parallel in spite of series configuration. So, designing of solar cell with series parallel combination is preferred. During design, number of solar cells in a panel, wattage of panel, fabrication of panel, ratings of panel, V-I & power curve of panel, effect of temperature are the considerable factors. Number of modules in series (N_{MS}) & parallel (N_{MP}) configuration w.r.t. system losses can be calculated from equations (3.21)-(3.22).

$$N_{MS} = [V_{SYS} / V_{MOD}] \tag{3.21}$$

$$N_{MP} = [(L_{AD}\ \mathrm{A/L})/(1\text{-}loss)\ S_H I_{MP}] \tag{3.22}$$

Array to Load (A/L) ratio must be taken as 1.1/1.2 for noncritical loads with high solar irradiation site & 1.3/1.4 for critical loads with low solar irradiation site. In parallel configuration, SPV array comprised parallel string of serially connected SPV panels where each string is connected independently to common bus with MPPT controller delivering efficient DC output. In series configuration little shading may spark huge deterioration in efficiency & even complete ceasing of plant, which may be ward off with parallel connected SPV. If one cell underperforms then to prevent failure of whole string, the installation must be accoutered with bypass/detour diodes, which can deviate current flow over underperforming cell as shown in Fig. 3.15

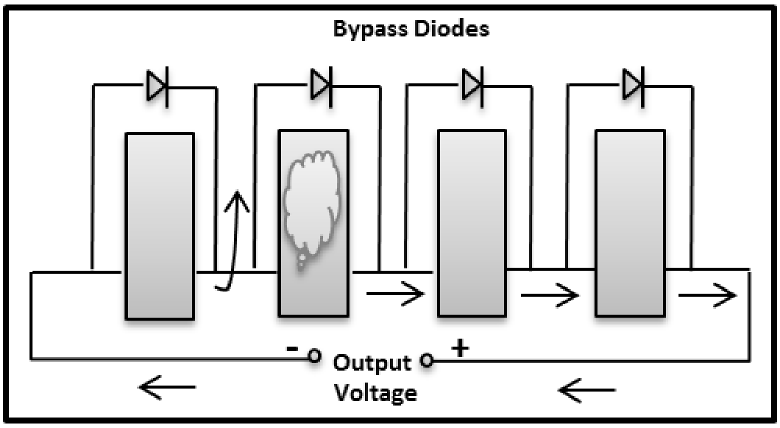

Fig. 3.15 Bypass diode function in SPV array

Voltage difference across various panels induce energy of weaken string to fall-off around zero; such loss may be neutralized by parallel configuration in string. In series configuration, the voltage of module drives the system and therefore leads to economic installation, where as in Parallel configuration constant voltage permit system to operate by current thus total generated power magnified by over 20% with parallel configuration in SPV in spite of series.

3.14 SPV PANEL CLEANING

Dust deposition in Delhi is about 35.28gm/m^2/year & many countries like Canada, USA, Mexico, Egypt, UAE, Iran, Afghanistan, China, and Russia are facing critic conditions during solar implementation. A dust layer of 4gm/m^2 can decrease solar power conversion by 40%, so depending upon the weather conditions, manual periodic (daily/weekly/monthly) cleaning is often required and economical compared to any other technological cost. If somewhere self-regulating cleaning option is must then solution is to scale solar cells by electrodynamics transparent screen composed of Optoelectronic material as Indium Tin Oxide(ITO) or Aluminum doped Zinc Oxide(AZO) or Indium doped Zinc Oxide(IZO) which induce dust-repelling electrical charges over surface to remove dust. When energized, the electrodes produce electrostatic travelling waves with electrophoretic forces that can remove 90% dirt & dust out of surface and transit them towards Panel fringes in less than 60sec.

CHAPTER 4
SUN TRACKING APPROACH

Solar tracker is an active device fitted with solar panels tracking motion of sun across the sky and tries to navigate through the path; ensuring maximum sunlight strikes the panels throughout the day. The prime implementation of system relies on sensors or photo resistors which feed microcontroller to adjust position accordingly. Light dependent resistor (LDR) or Photo resistor as shown in Fig. 4.1, is fabricated of high resistance semiconductor in which resistance value decline with high frequency light application to act as sensor.

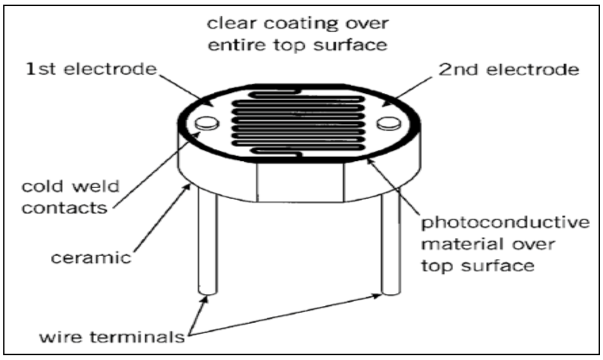

Fig. 4.1 Light Dependent Resistor

Whereas microcontroller is the brain of control system which determines input from light processing circuit & gives output pursuant to required movement for the system. Automatic tracking needs it to decide which way to rotate whole system in order to track sun efficiently that can be achieved by using a microcontroller from AVR ATMEL family named AT89S52 whose Pin diagram is shown in Fig. 4.2

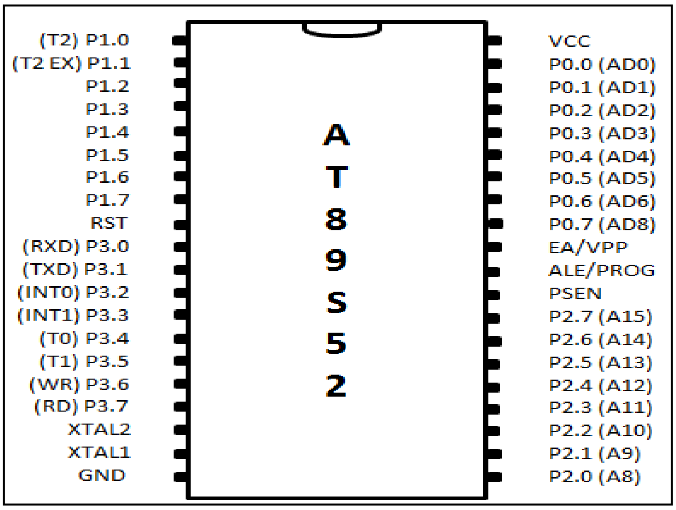

Fig. 4.2 ATMEL 89S52 Chip

For each axis movement two sensors are liable so total four sensors required. Their sensitivity is so adjusted that when concentrated beam of light hit sensors then system can move is desired direction, else panel will adjust automatically depending on quadrant where light beam is concentrated. Circuit diagram of solar tracker based system is shown in Fig. 4.3

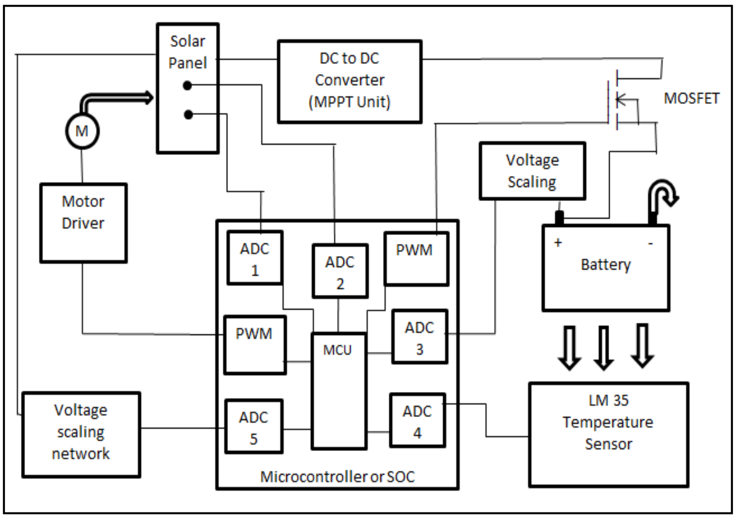

Fig.4.3 Circuit diagram of solar tracker system

DC power (P_{DC}) from solar array w.r.t reference irradiance is:

$$P_{DC} = (G_{TR}/1000)\, P_{DC0}\, [1+\gamma\, (T - T_R)] \quad (4.1)$$

Panel is free to rotate from 0 to 180° in order to track sun throughout the day. Both the motors used for tracker have resolution of 1.8°/step.

Magnitude of Step angle is = *360 degree/* $N_s\, N_r$ (4.2)

(5.2) may be expressed as:

$$(N_s\text{-}N_r/N_s\, N_r) \times 360^\circ \quad (4.3)$$

4.1 MANUAL TRACKING

Weather economic & capital investment don't applaud for automatic tracking option but still it is optimal to achieve maximum efficiency in spite of manual tracking, but on cost effective basis it may be sufficient to adjust solar panel manually in which SPV array seats on galvanized iron frame and having provision of 3-dimensional manual adjustment for tilt angle as per site latitude. Monthly SPV angle layout can also be fastened on frame to empower a workman to set required tilt angle manually.

4.2 AUTOMATIC TRACKING

Conventional automatic tracking system utilizes photo-resistors shown in Fig. 4.3, as sensing medium to follow sunlight on brighter sunny days but it directs to oscillate continuously in hunt of sunlight on rainy, foggy & dusky day.

Sometimes on cloudless sunny days ultraviolet radiation distracts sensing to make tracker behave like visionless and halt tracking ultimately. A solution is to implement digital solar timer or solar switch in spite of photo-resistors to track sun in day time and park in a horizontal position at night that can eliminate the need of a photo-resistor. For tracking implementation calculation of various factors in our fixed system:

Angle of incidence (α_{FIXED}) is:

$$\alpha_{FIXED} = \text{Cos}^{-1}[\text{Sin}(\varnothing_{SUN})\ \text{Cos}(\gamma\text{-}\gamma_{SUN})] \cdot [\text{Sin}(\beta) + \text{Cos}(\varnothing_{SUN})\ \text{Cos}(\beta)] \quad (4.4)$$

Plane of array (POA) beam is:

$$I_{POA} = I_B + I_{D,\ SKY} + I_{D,\ GROUND} \quad (4.5)$$

Average incident POA irradiance (in kW/m^2/day) for n months:

$$POA_n = (0.001\text{x}\Sigma_m POA_h)/(\text{No. of days in 'n' month}) \quad (4.6)$$

There are two prime approaches to appreciate solar panel efficiency, first is to flourish SPV cell material and second is implementation of tracking option. Ultimate consumer desires for tracking option rather than fixed system to hike their earnings because:

4.2.1 Automatic tracking option can raise system efficiency by 30-40%

4.2.2 Automatic tracking option requires less space for same output.

4.2.3 With increased system efficiency time of investment return is reduced.

4.2.4 Automatic tracking option amortizes itself nearly within 4-5 years.

CHAPTER 5

AN OVERVIEW TO CONVERTER, INVERTER & BATTERY SYSTEM

5.1 CONVERTER

Converter is a vital part of an SPV system which is the grit of SPV plant to extract sun energy effectively and expected to have conversion efficiency at least 95% in all working conditions. SPV panel in parallel configuration along with individual power optimizer and efficient convertor & inverter deliver optimized output. With variation in radiation SPV module operation point varies, which is decided by connecting load. The mechanism of an MPPT electronic circuit is shown in Fig. 5.1.

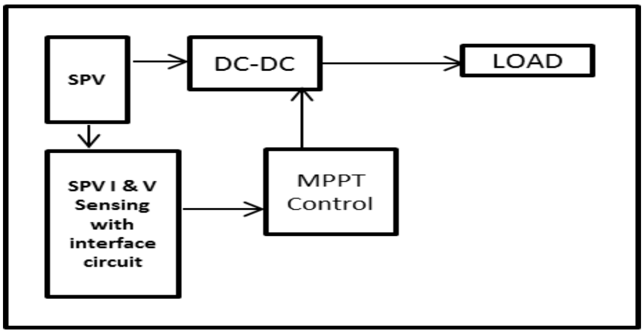

Fig. 5.1 Circuit diagram of MPPT based SPV system

This mechanism is based on principle of impedance matching between load & module using DC-DC converter which ensures correct switching of converter for drawing optimum current from SPV. The duty cycle of switching signal is influenced & controlled by relevant control algorithm that competes for optimum voltage & current required for operation at MPP. DC–DC converter is used to interface the SPV array to DC bus to perform three major functions including step up/step down the SPV voltage, regulate varying DC output voltage of SPV array and implement MPPT on SPV array to ensure operation at maximum efficiency. However, there are various topologies of DC-DC converter including buck, boost, push pull, half bridge, full bridge, flyback, buck-boost etc. The choice of topology depends on system requirements and its applications. A boost converter is designed to step up a fluctuating or variable input voltage to a constant output voltage. To produce a constant output voltage feedback loop is used. The output voltage is compared with a reference voltage & PWM wave is generated. It has been studied that efficiency of the DC-DC converter is maximum for a buck converter & minimum for a boost converter. But here we intend to use our system either for tying to grid or to charge metro train battery bank, so we use a boost converter to step up SPV voltage.

The circuit diagram for boost converter is presented in Fig. 5.2 and converter parameters are presented in Table 5.1.

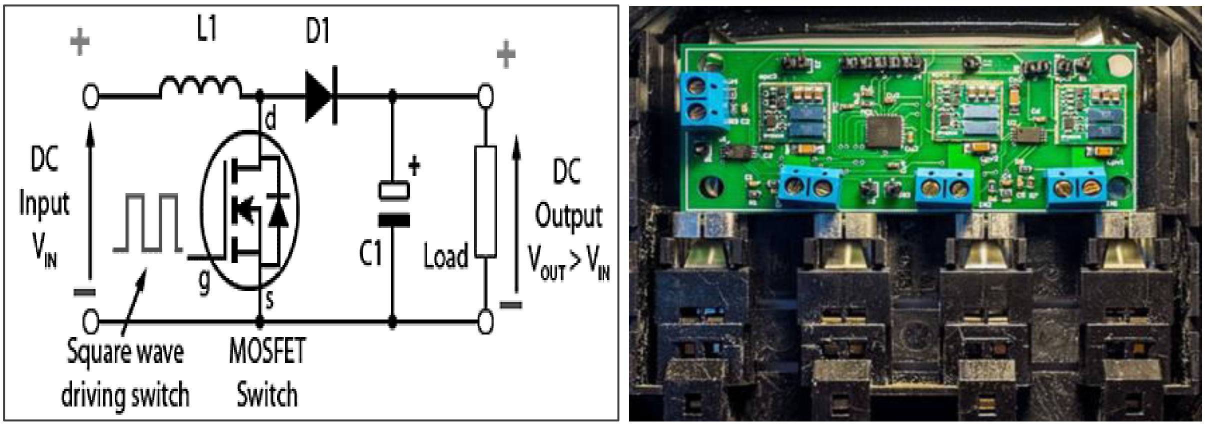

Fig. 5.2 Boost converter circuit design

Table 5.1 Boost converter parameters

S. No.	Parameter	Formula
1.	Output Voltage	$\frac{V_{PV}}{(1-\mathrm{D})}$
2.	Inductance (L)	$\frac{V_{PV}}{f_{sw}\,\Delta I_L}$ D
3.	Output Capacitance (C)	$\frac{I_{out}}{f_{sw}\,\Delta V_O}$ D

5.2 DESIGNING OF INVERTER

To cater AC load by SPV system a solar inverter is needed which comes with wide ranging efficiencies (80% to 96%). Due to inexpensive & simple construction about one third solar inverter available in industry are of transformer type as to raise voltage level of produced electricity to match main grid voltage as shown in Fig. 5.3, but due to less efficient, hefty and humming noise factor, transformer-less type are preferred having more efficiency with faster response.

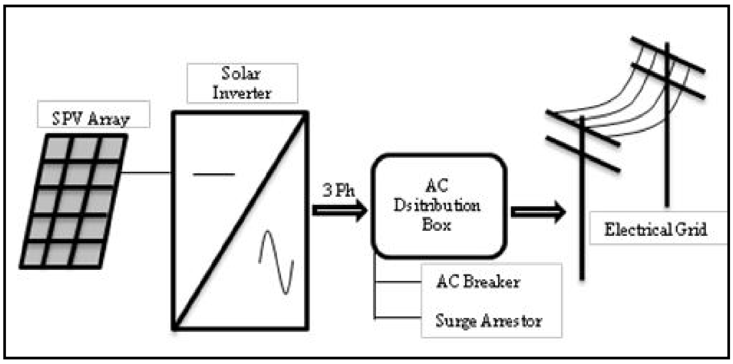

Fig. 5.3 Solar inverter operation

The prime function of an inverter is to ensure that SPV modules are operated at the maximum power point (MPP) in conjugation to DC converter and to supply sinusoidal output to the load with small harmonics. Single phase solar inverter is shown in Fig. 5.4

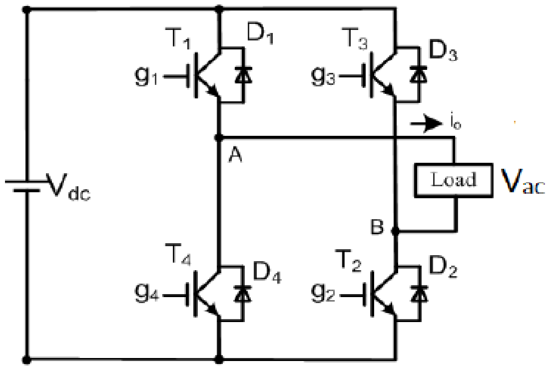

Fig. 5.4 Single phase inverter

There are different inverter configurations in accordance of connection to SPV modules and which configuration should be used depends upon the environmental and financial criterion. If the modules are not identical in construction or do not perform under same conditions, the maximum operation point is different in each panel and resulting P-V curve has multiple maxima, which constitutes a problem, because most MPPT algorithms converge to a local maximum depending on the starting point. If the operating point is not the MPP, not all the possible power generated is being fed to the grid.

5.2.1 Central Inverter

This is the simplest inverter configuration in which strings, consist of series connected SPV panels, are connected in parallel to obtain the desired output power and the resulting SPV array is connected to a single inverter, as is shown in Fig. 5.5. Here all SPV strings operate at same voltage, which may not be the MPP voltage for all. The problem with this configuration is that if panels are receiving different irradiation (shading or other problems), the true MPP is difficult to find and consequently there are power losses and SPV modules are underutilized.

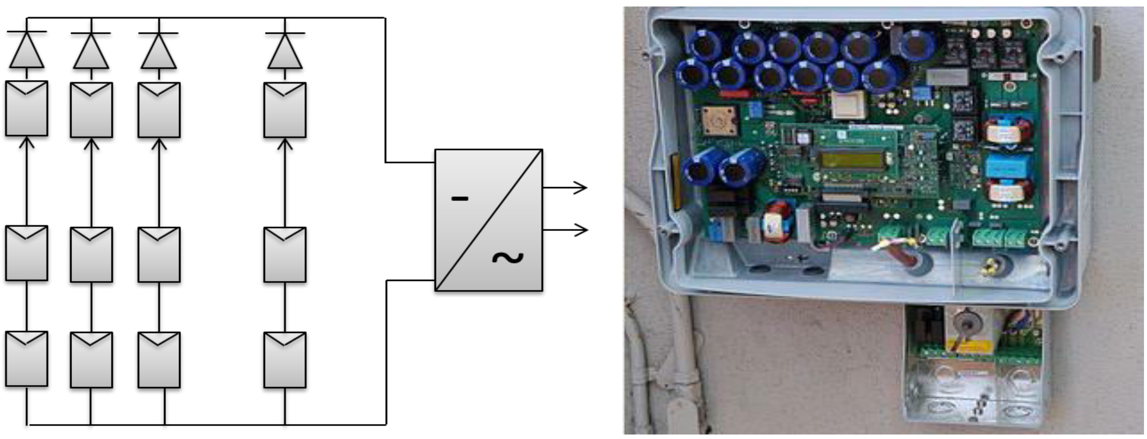

Fig. 5.5 Central inverter configuration

5.2.2 String Inverter

In string inverter configuration, each string of SPV panels connected in series to buildup voltage is connected with an individual inverter, as shown in Fig. 5.6 that can improve the MPPT in case of mismatches or shading on panel in string. Here each string might have different maximum operating point, whereas in the central inverter there is only one operating point which may not be the MPP for each string, thus induces power losses. Capital investment rises with increased number of string inverters in system.

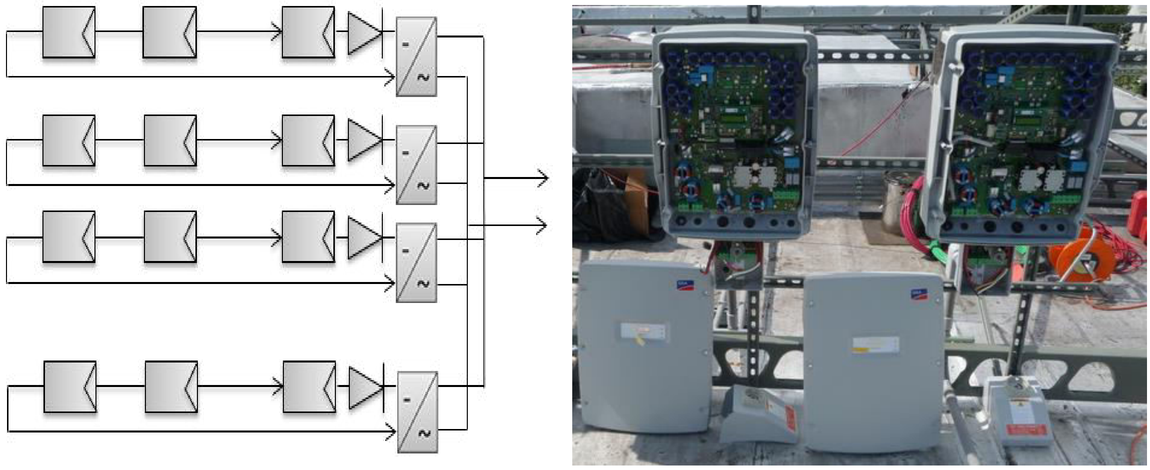

Fig. 5.6 String inverter configuration

5.2.3 Micro inverter

In Fig. 5.7 positive terminal of a panel is connected to negative terminal of other panel For AC conversion the end of solar string is connected to an inverter which is configured back into first panel for series circuit completion. Instead of being end of the line in solar string, a micro-inverter should be connected to each module which is a modular approach as shown in Fig. 5.7. By having one micro inverter per module, maximum power is optimized at module level rather than for system as a whole.

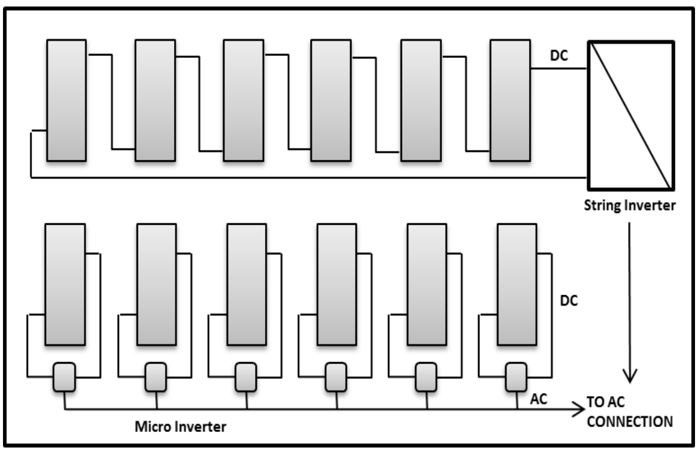

Fig. 5.7 Solar string with micro inverter

This leads to increased power output between 5 to 25% but also tends to higher installation cost. Micro inverter is advantageous in sense that if any SPV panel fails or encounter shading, it will not hinder the performance of remaining panels in that string. Micro inverters also watchdog the environmental situation of SPV cells & exercise proper load to confirm max output.

In this configuration, each SPV module is connected to a small size micro inverter that can be mounted on panel or racking structure as shown in Fig. 5.8 & consequently P_M is obtained from each panel as the individual MPP is tracked by micro inverter that communicates smart data with panels. This configuration is beneficial in terms of continuous power generation even after loss of any panel in string. However, capital investment also rises with increased number of micro inverters according to the number of SPV panels in system.

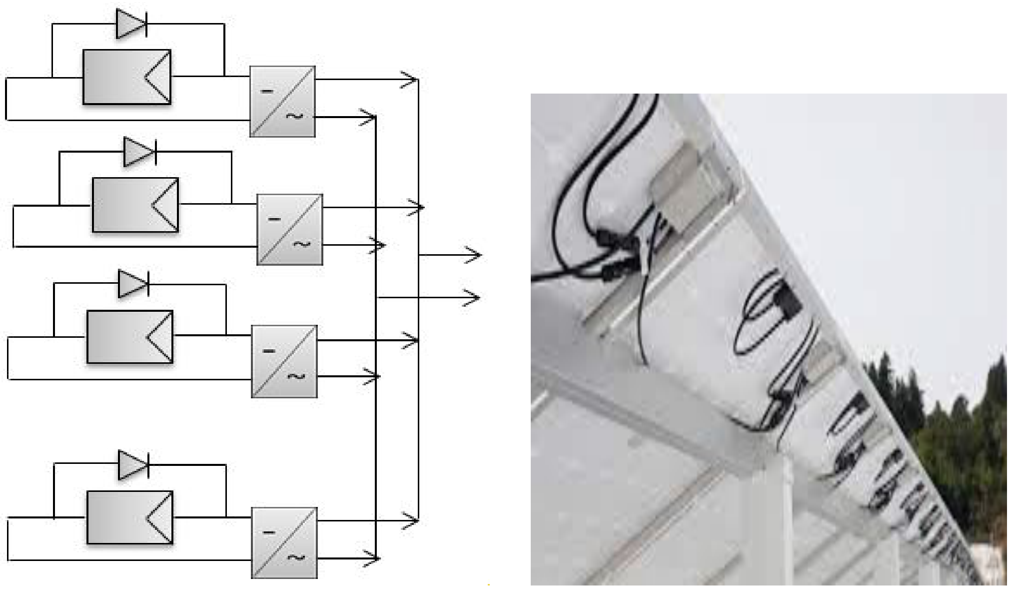

Fig. 5.8 Micro inverter configuration

5.2.4 Micro-parallel inverter

After advent study in this field, this work propose to use micro parallel inverter containing four separate channels as shown in Fig. 5.9 or micro octet inverter containing eight separate channels that each may be fastened with separate SPV panel as shown in Fig. 5.10. In this configuration, four number of SPV module can be connected to a single small size micro-parallel inverter that can be mounted on panel, roof, service box or racking structure as shown in Fig. 5.9 & consequently P_M is obtained from each panel as the individual MPP is tracked by micro parallel inverter that communicates smart data with panels & alert to the maintainer to isolate failure in panel or inverter.

This configuration is beneficial in terms of continuous power generation even after loss of any panel of four channels, no DC combiner or optimizer is required, labor & error reduction, lower cost of cabling & low losses. However, capital investment in installation of micro-parallel inverter closely competes with string inverters.

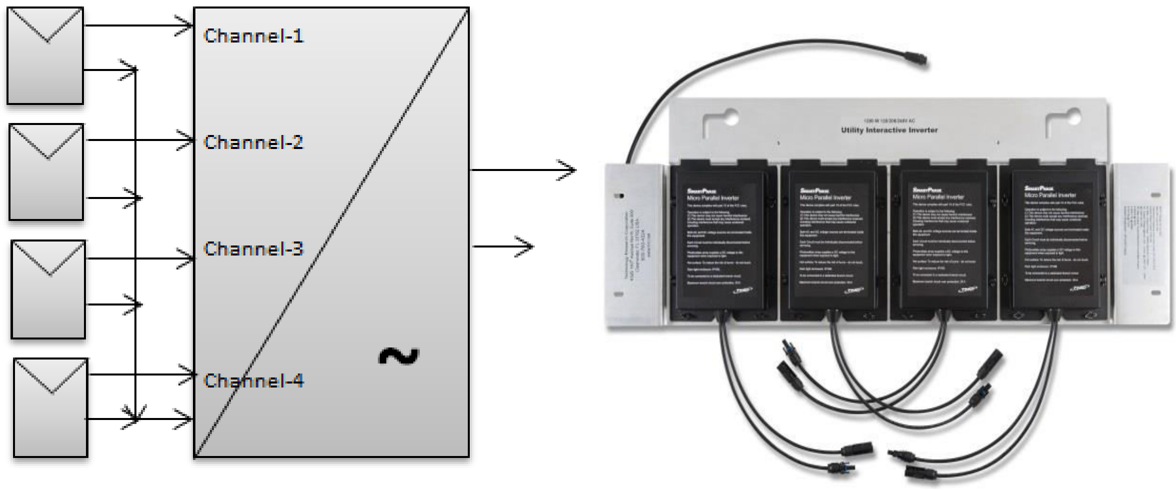

Fig. 5.9 Micro parallel inverter configuration

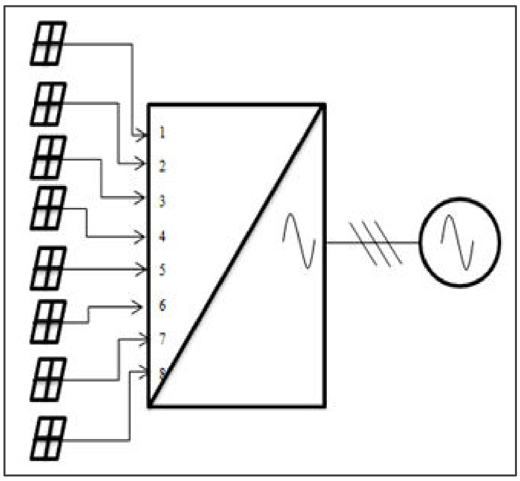

Fig. 5.10 Micro octet inverter configuration

In Fig. 5.10, each channel behaves as customized micro inverter that utilizes MPPT to optimize SPV panel output. Compared to string inverter, it also watchdogs each SPV panel performance. The micro parallel or micro octet inverter is capable to invert output of four or eight panels in parallel which saves time and cost disbursed to install four or eight different units by connecting all wires to single inverter. Such inverter employs switching connection for installation, maintenance, emergency backup and off grid applications. It is an intelligent system that can control four/eight 250W_p solar panel at a time with different channels with separate attention & MPPT application to each panel.

The intelligent circuit of micro parallel or micro octet inverter communicates about timely panel cleaning, fault acknowledgement on inverter failure, service required, power sharing and health status. SPV output decays when it is connected to a battery through charge regulator to match voltage level with battery but to deliver maximum power battery must be full charged. Here micro parallel or micro octet inverter also checks that battery level remains full charged for long. In rainy season batteries may be less than full charge which degrades panel voltage. Here MPPT Charge Controller comes into picture, shown in Fig. 5.11, which maintains maximum voltage of SPV and also feed the voltage required for battery. Simple charge controller protects batteries from over-charging, by obstructing the current flow. Besides discharging same function, MPPT controller includes DC-DC converter to convert voltage required by the batteries, with small power loss. During sunny day time after feeding load, excess SPV power used for battery charging may not be sufficient, so remaining part may be drawn from grid supply with AC–DC converter.

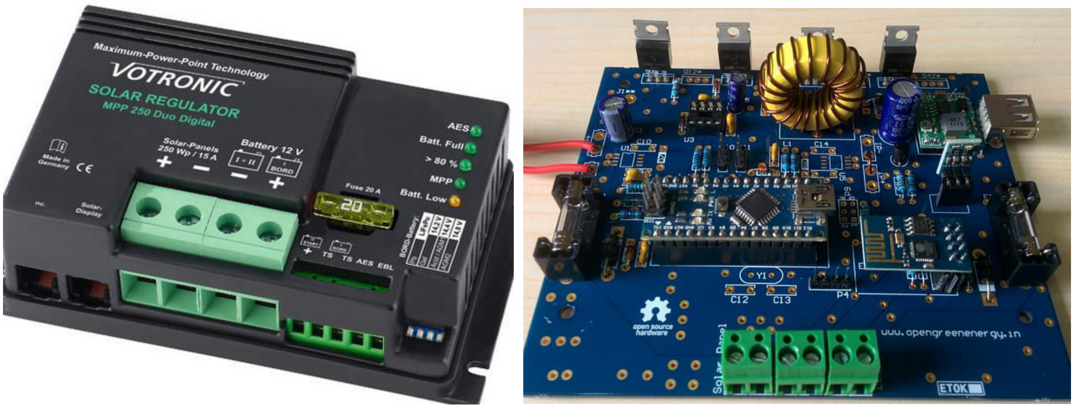

Fig. 5.11 MPPT charge controller

In absence of grid supply and fully discharged battery condition, MPPT controller modulates SPV output with pulse charging application to batteries for priority and complete utilization of SPV. When grid or solar supply is available, it provides boost charging to batteries. If batteries are fully charged, after feeding load, excess power available with SPV system can be wasted. To avoid such wastage, it ensures that even after charging through grid, batteries keep some fraction of capacity uncharged which should only be charged with excess solar power and SPV output voltage follow float voltage to avoid battery heating & overcharging. MNRE standards for charge controller are: IEC 60068, Equivalent BIS Std., IEC 61683 / IS 61683[1].

By increasing the rated AC to DC size ratio of solar inverter, energy output of system can be increased on verge of increased system cost.

As with high AC to DC size ratio when plant's DC output power exceeds the inverters rating, it limits the output power by increasing DC operating voltage which shifts plants operating point down its V-I characteristics. For solar array grounding purpose, an isolation transformer on AC side of inverter is also needed with DC inputs in parallel connection, which is must for floating SPV array as some solar inverter doesn't have galvanic isolation between DC input and AC output. An upstream circuit breaker between AC and Inverter side for over current protection and Surge protection device at both AC & DC side must be installed. The connection to grid must be far away from non-linear load to maintain grid quality regarding grid harmonics and solar inverter performance with normal utility waveform. Any device installed between SPV array & inverter must have rated voltage & rated current greater than V_{OC} & I_{SC} of SPV array. Solar Inverter must have the ability:

a) To maintain equilibrium in output power when grid frequency varies as shown in Fig. 5.12

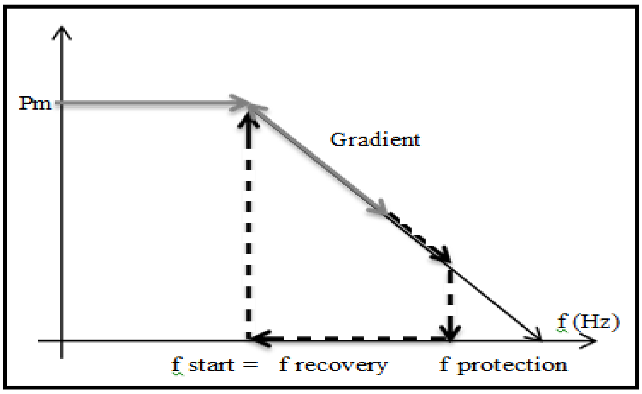

Fig. 5.12 Power vs Frequency parameter

b) To reduce output power if grid voltage rises up to Lock-in voltage and maintain constant value until grid achieves back lock-out voltage and also to feed in reactive power in grid when its output active power reached set values by following Cos φ Function that is power factor able to change by end user as shown in Fig. 5.13 & 5.14

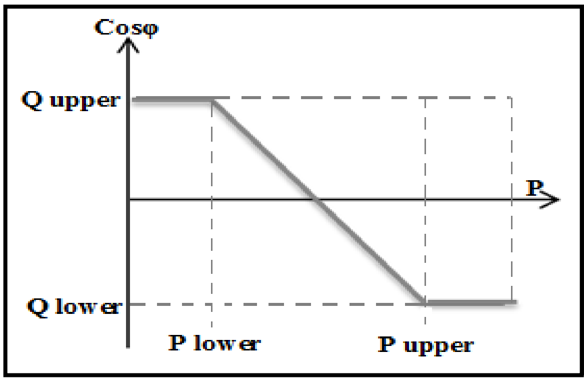

Fig. 5.13 Cos φ function

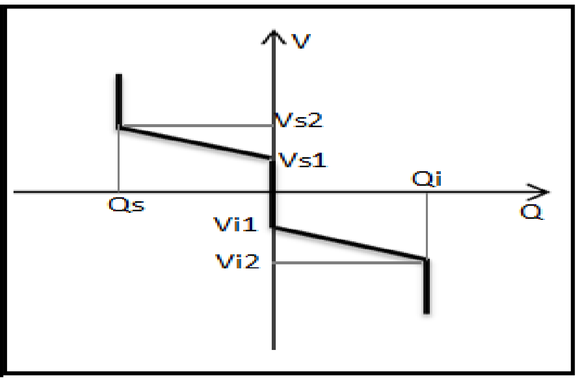

Fig. 5.14 Reactive power parameter

Solar inverter selection should be done by first calculating average part load efficiency curve shown in Fig. 5.15 and then find required solar inverter whose actual efficiency is close to average part load efficiency. The rated efficiency (η) as a function of nominal rated efficiency (η_{nom}) & reference inverter efficiency [$\eta_{ref} = 0.9637 = (P_{ac0}/P_{dc0})$] is:

$$\eta = [\eta_{nom} / \eta_{ref} - 0.162\zeta - 0.0059/\zeta + 0.9858] \quad (5.1)$$

Where $\zeta = P_{dc}/P_{dc0}$ & $P_{dc0} = P_{ac0}/\eta_{nom}$

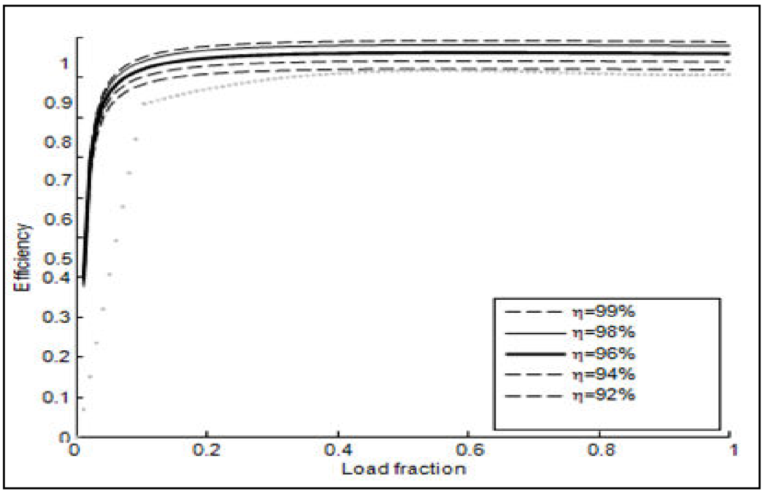

Fig. 5.15 Solar inverter average part load efficiency curve

5.3 STORAGE BATTERIES

For backup, batteries are needed as charge storage devices, but system efficiency also depends on the battery design and construction quality. Choice of battery depends on following factors:

5.3.1 Operating temperature range (-30 to +50˚C).

5.3.2 Self-discharge rate with availability and frequency of recharge.

5.3.3 Cyclic requirement (Deep or shallow discharge).

5.3.4 Nominal voltage and Ah rating.

During charging input energy in battery (E_{in}) is:

$$E_{in} = \Delta T_c \, I_c V_c \quad (5.2)$$

During discharging delivered energy by battery (E_{out}) is:

$$E_{out} = \Delta T_d \, I_d V_d \quad (5.3)$$

The energy efficiency is:

$$E_{in}/E_{out} = \Delta T_c I_c V_c \,/\, \Delta T_d I_d V_d \quad (5.4)$$

This is of two types, voltage efficiency (V_d/V_c) and& coulomb efficiency ($\Delta T_d I_d/\Delta T_c I_c$). Batteries bifurcation affirmative to SPV are enlisted in Table 5.2.

Table 5.2 Bifurcation of batteries

Battery type	Cell nominal voltage	Self-discharge (% per month)	No. of life cycle	Energy density (Wh/ Kg)
Lead-acid	2.0	5	700	30
Ni-Cd	1.2	10	1000-1500	45
Lithium-ion	3.7	3-5	500-1000	90

Having low cost, charging float voltage near 13.5V, discharging voltage near 12V, voltage efficiency near 88%, coulomb efficiency near 92% and net energy efficiency near 75-85%, lead acid battery is commonly used for solar system. Remaining 25-15% energy loss recurs as heat in battery that can also be diminished by ensuring low charging & discharging cycle. Lead acid batteries come in deep and shallow cycle where Deep cycle is designed for charging & discharging over & over, while Shallow cycle or cranking batteries are mostly used in automobile industry just to crank engine initially. Deep cycle is of two types sealed and flooded. A sealed battery doesn’t need equalization charge and water addition. It can be mounted in any position and easy to transport as it won’t cause chemical spill or leak. The downside is that it needs to be closely monitored for overcharging. However, flooded battery also requires close attention of water level check for refilling. It restores battery capacity by eliminating sulfates from battery plates, but it can also shorten the battery life by warping the plates. Alkaline batteries can be left unattended for long time and can be fully discharged without any deterioration to their life (approx 4000 cycles), last around twenty years as they utilize solution of lithium hydroxide, potassium hydroxide and distilled water, while lead acid battery cannot be reconditioned. Nickel cadmium batteries are also in race as they generally have 91% capacity for not less than five year, which is better than any other battery. With further study about batteries, this work recommends to design rechargeable battery behind the solar panel rather than using two different standalone operating systems, with which plant will achieve cost reduction up to 25% and efficiency improvement up to 20%.

CHAPTER 6
MPPT TECHNIQUE FOR SPV SYSTEM

6.1 MPPT

Maximum power point tracking is a technique to track maximum power operating point under varying environmental conditions. MPPT technique is based on the reference voltage/current signal of the SPV system adjusted to achieve maximum operating point. Different algorithms have different advantages as well limitations, like some are simple, ease of implementation with controller but suffer from response time, inaccurate, inexpensive. Some provide good accuracy, good response but very difficult to implement. So it is very important to have a thorough review of the techniques and select the optimum one as per our requirement. In this dissertation a most widely used MPPT algorithm in industrial field; Perturb and Observe has been used. There are also different techniques as discussed in Table 6.2, used to track the maximum power point. Few of the most popular techniques are:

6.1.1 Incremental Conductance method
6.1.2 Fractional open circuit voltage
6.1.3 Fractional short circuit current
6.1.4 Fuzzy logic
6.1.5 dP/dV and dP/dI feedback Control
6.1.6 Neural network

6.2 PERTURB & OBSERVE OR HILL CLIMBING MPPT

In connection of SPV array with power converter, perturbing the duty ratio of power converter perturbs the SPV array current and consequently perturbs the SPV array voltage. With voltage rise, power increases only when the operating point lies in left side of the MPP & decreases when operating point in the right side of the MPP. Therefore if power increases, perturbation should be kept same to reach the MPP & if power decreases then perturbation should be reversed. Periodical repetition of this process is required until the MPP occur and if system oscillates around MPP; the oscillations can be minimized by reducing the perturbation step size, which may results as slow MPPT process. P&O and Hill Climbing method can fail under rapidly changing environmental conditions. Two sensor are usually requires to measure the SPV array voltage & current from which power is computed.

P&O is the most commonly used MPPT algorithm in industrial field due to its simple structure & easiness to apply. It depends upon the idea that in P-V curve shown in Fig. 6.1 dP/dV approaches towards zero at the top of the curve and power variation w.r.t. voltage is positive (dP/dV > 0) on left side of MPP and negative (dP/dV < 0) on right side of MPP. The P&O operates by periodically perturbing (incrementing or decrementing) the SPV array terminal voltage/current and comparing the corresponding output power of SPV array perturbation P(n+1) with the previous perturbation P(n). If the perturbation in terminal voltage leads to an increase in power (dP/dV >0), the perturbation should be kept in the same direction otherwise the perturbation is moved to the opposite direction. The perturbation cycle as discussed in Table 6.1, is repeated until the maximum power is reached at the dP/dV=0 point. Due to hill kind of curve P&O is also known as 'hill climbing method'. This method is advantageous in sense of suitability requiring zero information about SPV array, satisfactorily accurate and also eases of implementation with digital controller. The major problems with P&O technique are that oscillations near MPP under steady state condition and poor tracking (might be in the wrong direction, away from MPP) with changing irradiance. Methods to improve the dynamic behaviour of P&O, including variable step size & perturbation frequency, have been suggested in literature.

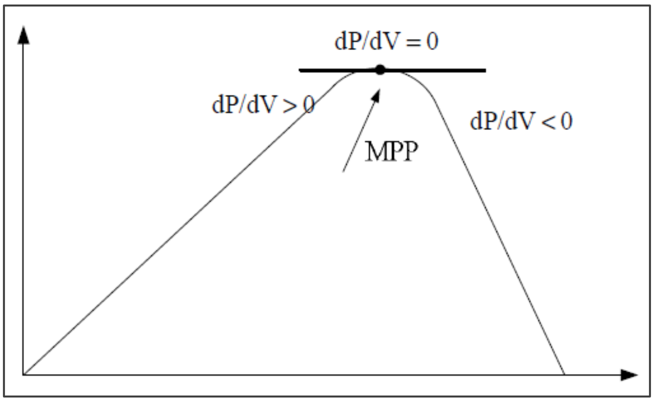

Fig. 6.1 P-V curve for P&O MPPT technique

Table 6.1 P&O MPPT technique perturbation

Perturbation	**Change in power**	**Next perturbation**
Positive	Positive	Positive
Negative	Positive	Negative
Positive	Negative	Negative
Negative	Negative	Positive

With reference to Table 6.1, perturbation changes according to change in power. If change in power is positive, next perturbation depends upon the previous perturbation. If change in power is negative then next perturbation is invert of previous perturbation i.e. negative for positive previous perturbation and positive for negative previous perturbation. A flow chart illustrating P&O MPPT technique is shown in Fig. 6.2

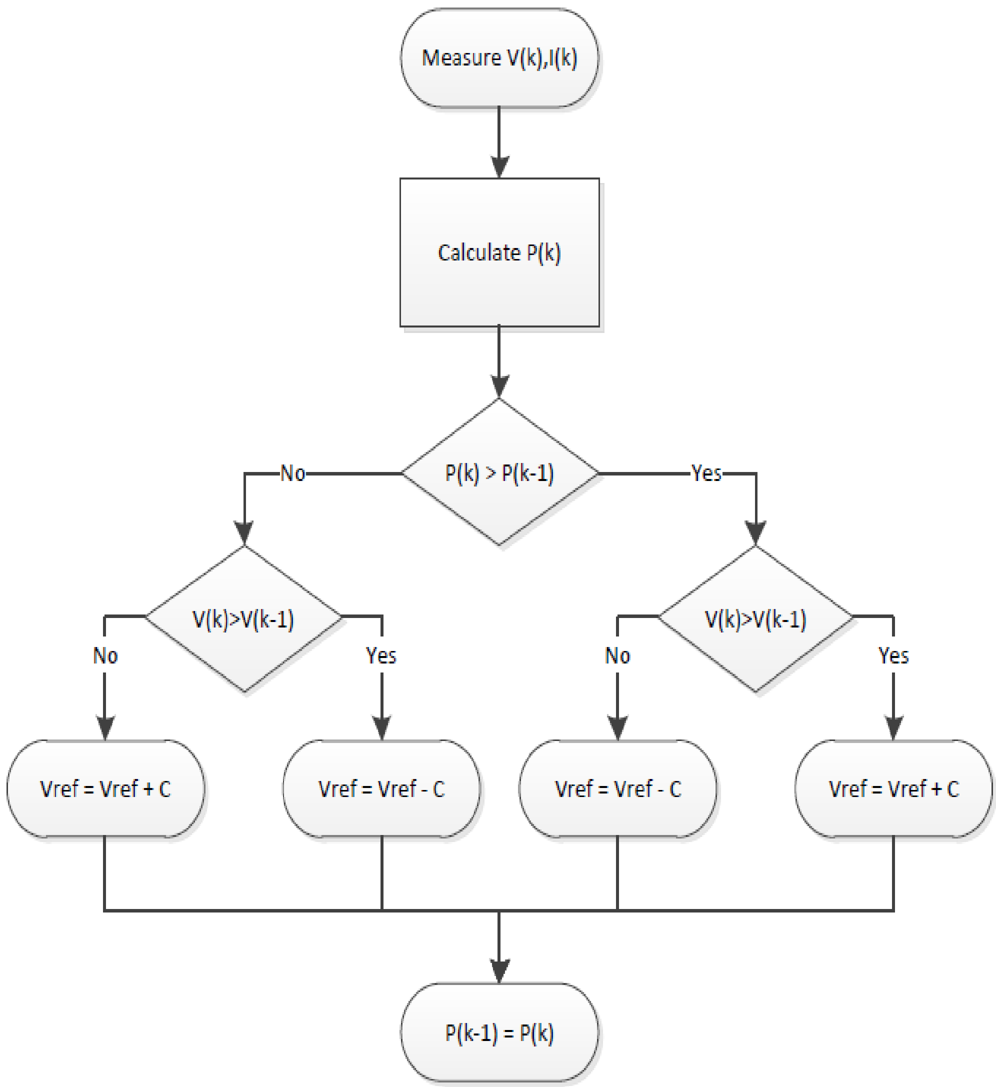

Fig. 6.2 Flowchart of P&O MPPT technique

Table 6.2 MPPT Algorithm comparison

MPPT Techniques	SPV Array Dependent	Real MPPT	Analog or Digital circuit used	Control strategy	Concurrence Speed	Complexity to implement	Parameter to sense	Periodically tuned	Cost	Efficiency
P&O/Hill Climbing	No	Yes	Both	Sampling	Varies	Low	V, I	No	High	medium
Fuzzy Logic	Yes	Yes	Digital	Probabilistic	Fast	High	Varies	Yes	high	very high
Fractional Open circuit voltage	Yes	No	Both	Indirect	Medium	Low	V	Yes	cheap	low
dP/dV and dP/dI Feedback Control	No	Yes	Digital	Indirect	Fast	Medium	V, I	No	high	medium
Current Sweep	Yes	Yes	Digital	Modulation	Slow	High	V.I	Yes	high	high
I and C	No	Yes	Digital	Sampling	Varies	Medium	V, I	No	high	medium
Load V or I maximization	No	No	Analog	Indirect	Fast	Low	V. I	Yes	high	medium
Neural Network	Yes	Yes	Digital	Probabilistic	Fast	High	Varies	Yes	high	very high
DC link capacitor droop control	No	No	Both	Modulation	Medium	Low	V	No	high	medium
Fractional Short circuit current	Yes	No	Both	Indirect	Medium	Medium	I	Yes	cheap	low

CHAPTER 7

MODELLING AND SIMULATION OF SPV SYSTEM

7.1 MATLAB/SIMULINK MODEL OF 250W SPV PANEL & 5KW SPV ARRAY

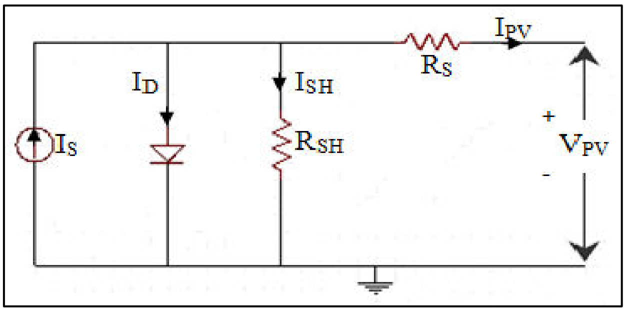

Fig. 7.1 Equivalent circuit of 250W SPV panel

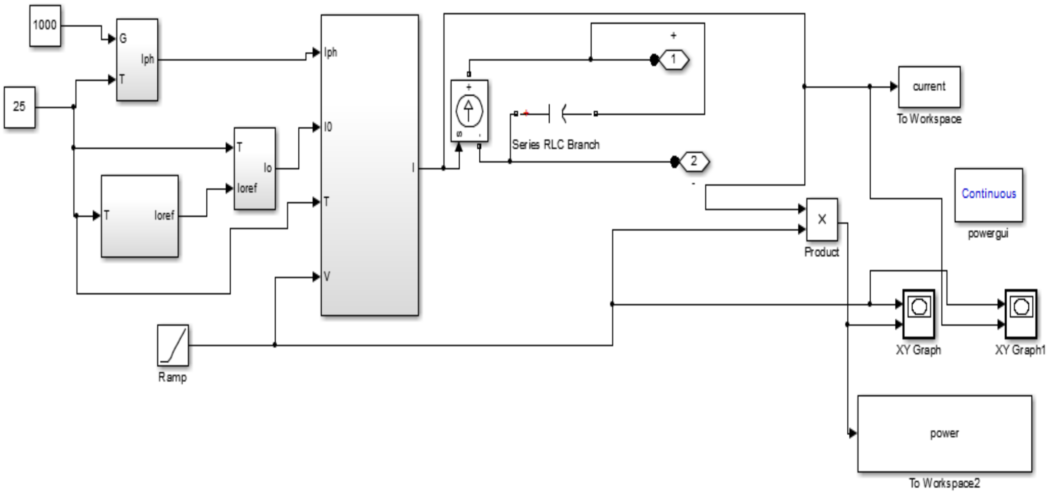

Fig. 7.2 Simulink model of 250W SPV Panel

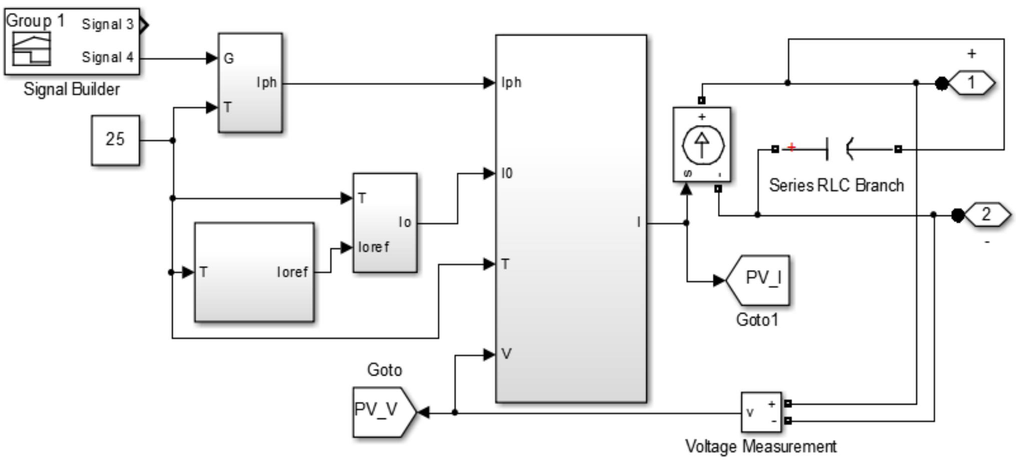

Fig. 7.3 Simulink model of 5kW SPV array

$$I = I_{Ph} - I_o\left[\exp\left\{\frac{q(V+I*ns*Rs)}{N_S AkT}\right\} - 1\right] + \frac{I*ns*.55+V}{Rp} \tag{7.1}$$

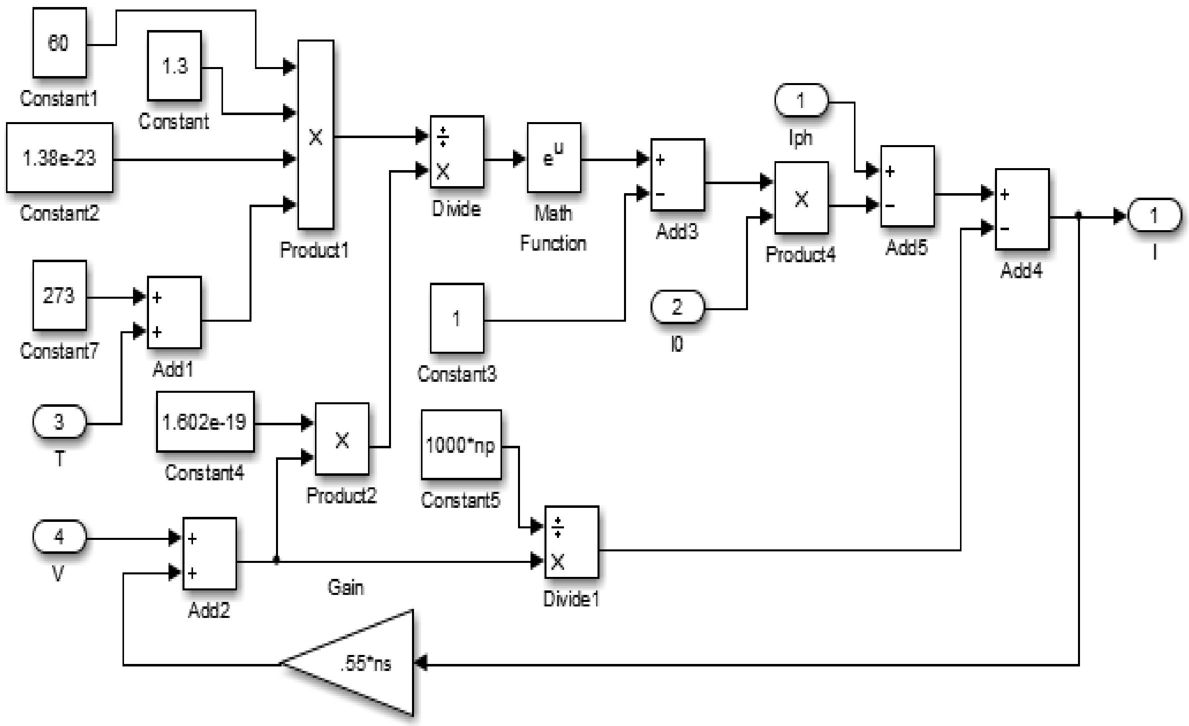

Fig. 7.4 Simulink model of I

$$I_{Ph} = \left(\frac{G*[((T+273)-298)*.0013+8.71*np]}{1000}\right) \tag{7.2}$$

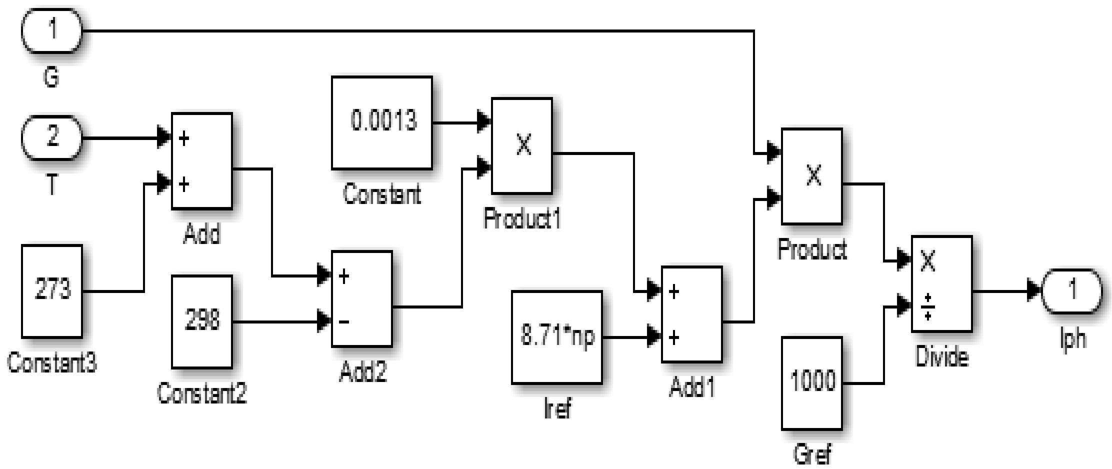

Fig. 7.5 Simulink model of I_{Ph}

$$I_{oref} = 8.71 * np/\left[\exp\left(\frac{q37.3*ns(=Voc)}{(T+273)*(1.38*10^{-23})*1.3*60}\right) - 1\right] \quad (7.3)$$

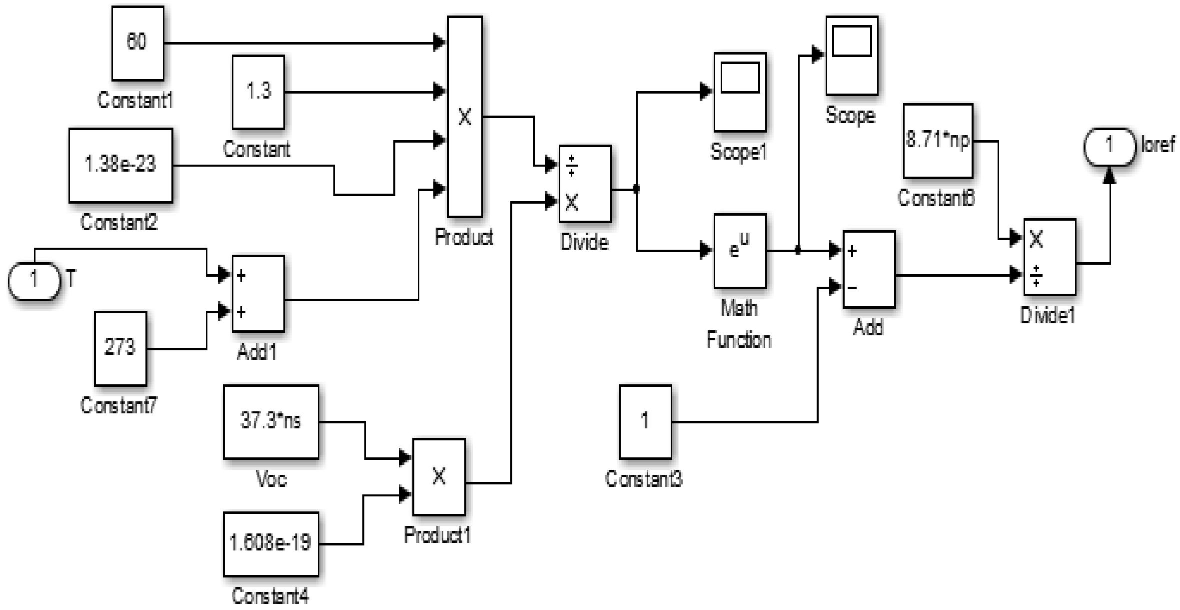

Fig. 7.6 Simulink model of I_{oref}

$$I_o = I_{oref}\left[\frac{\left(\frac{T+273}{298}\right)^3}{A(=1.3)k} * e^{\frac{(1.12*1.6*10^{-19})/}{1.3*1.38*10^{\wedge}-23}}\left(\frac{1}{298} - \frac{1}{T+273}\right)\right] \quad (7.4)$$

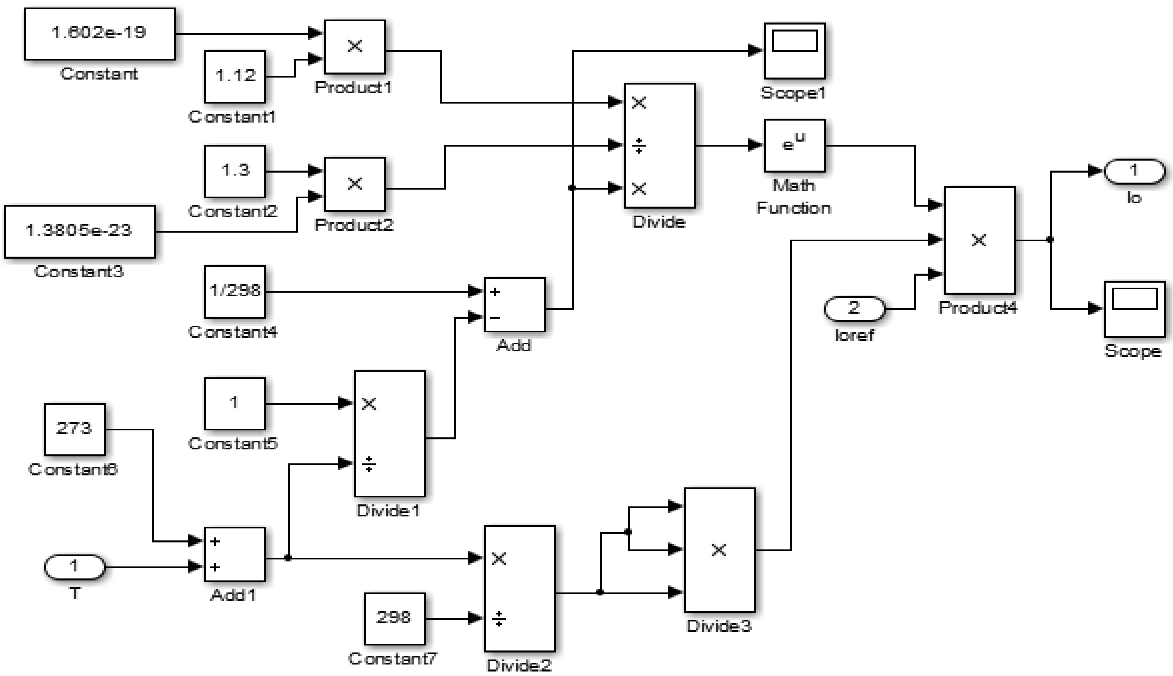

Fig. 7.7 Simulink model of I_o

7.2 MATLAB/SIMULINK MODEL OF CONVERTER

$$D = 1 - V_{in}/V_{out} \tag{7.5}$$

$$L = \left[\left(\frac{Vin*(Vout-Vin)}{dI*fs*Vout} \right) \right] \tag{7.6}$$

$$Cout = \left[\left(\frac{Iout*D}{fs*dVout} \right) \right] \tag{7.7}$$

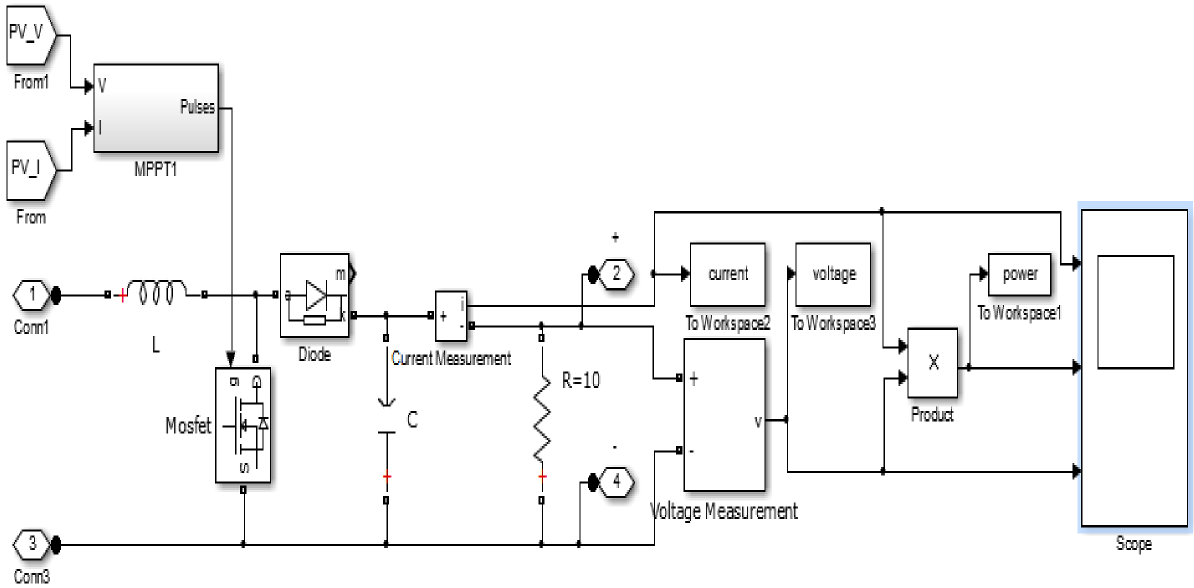

Fig. 7.8 Simulink model of boost converter with MPPT on 250W SPV panel

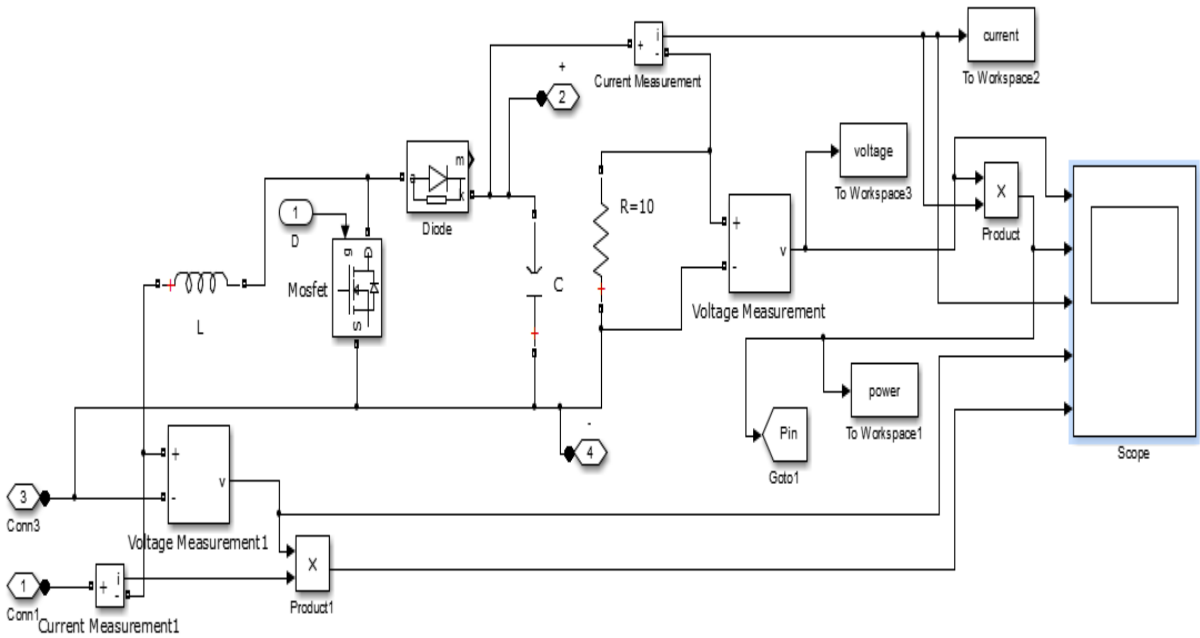

Fig. 7.9 Simulink model of boost converter on 5kW SPV array

Table 7.1 Boost converter specification

S. No.	Component	Values
1	Inductor	6.25 µH
2	Input Capacitor	1000 µF
3	Output Capacitor	5000 µF
4	Resistive Load	150 Ω

7.3 MATLAB/SIMULINK MODEL OF BATTERY BANK

Battery Bank for 5kW SPV array is obtained by connecting many batteries in series to buildup voltage & battery capacity.

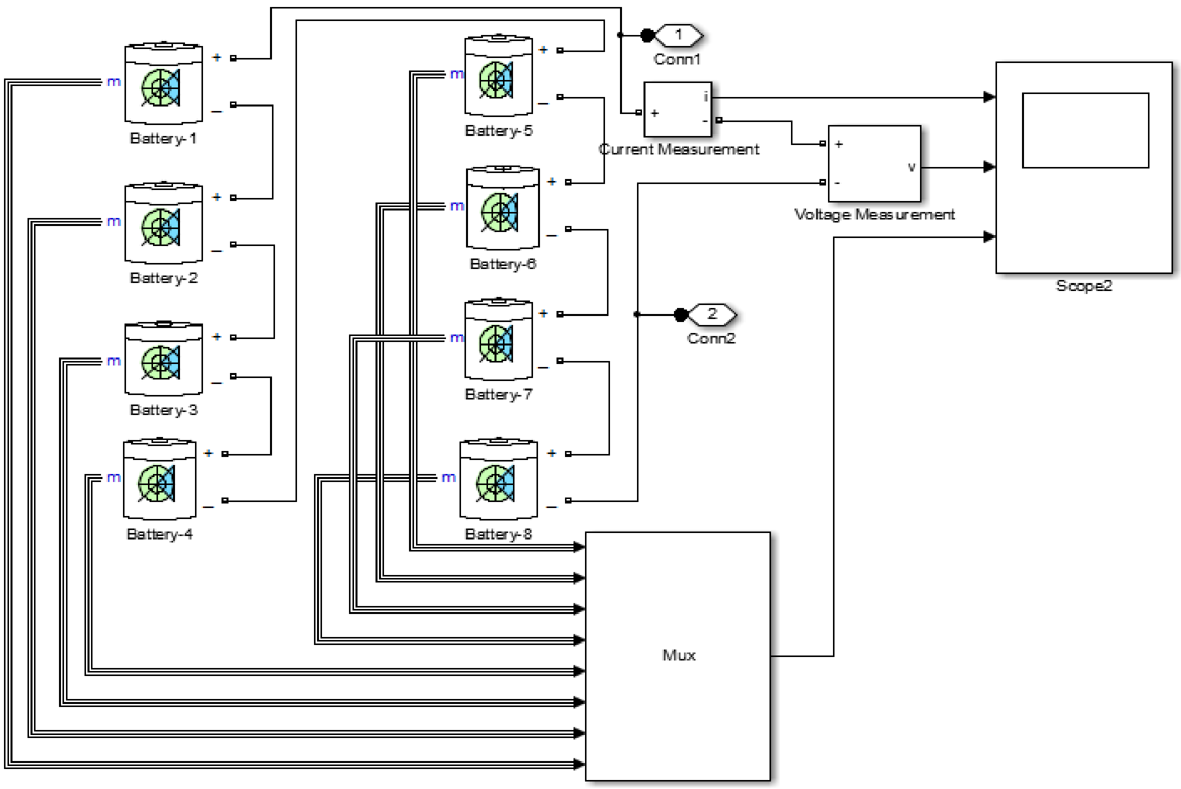

Fig. 7.10 Simulink model of battery bank

Table 7.2 Battery specification

Nominal Voltage (V)	50
Rated Capacity (Ah)	13
Initial State of Charge (%)	95
Internal Resistance (Ω)	0.038462
Maximum Capacity (Ah)	14.77
Nominal Discharge current (A)	2.6

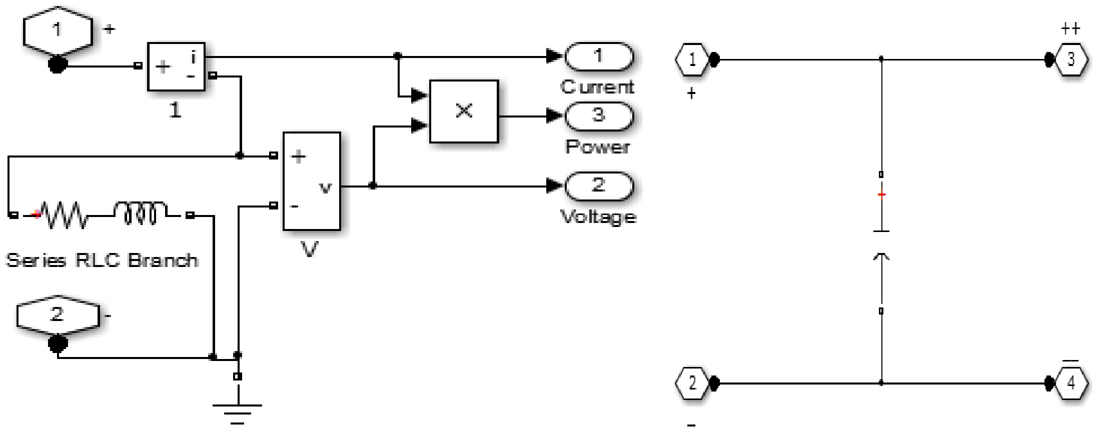

Fig. 7.11 Simulink model of DC load & DC link

7.4 MATLAB/SIMULINK MODEL OF SINGLE PHASE INVERTER

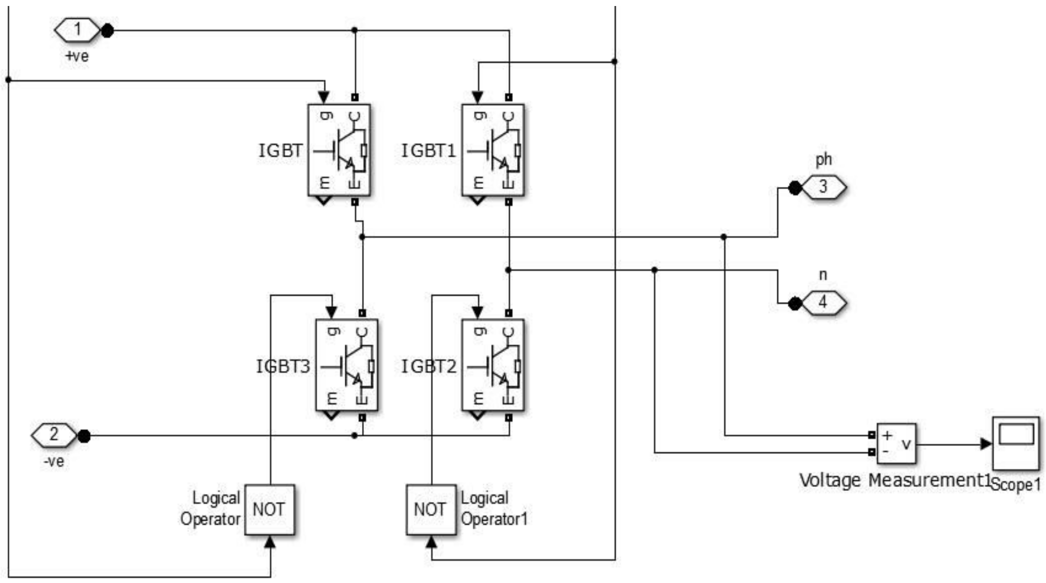

Fig. 7.12 Simulink model of single phase inverter

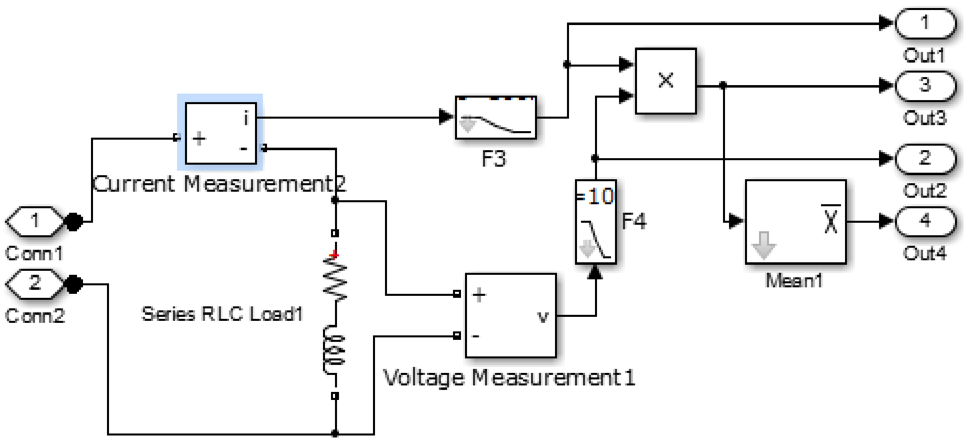

Fig. 7.13 Simulink model of inverter sub system

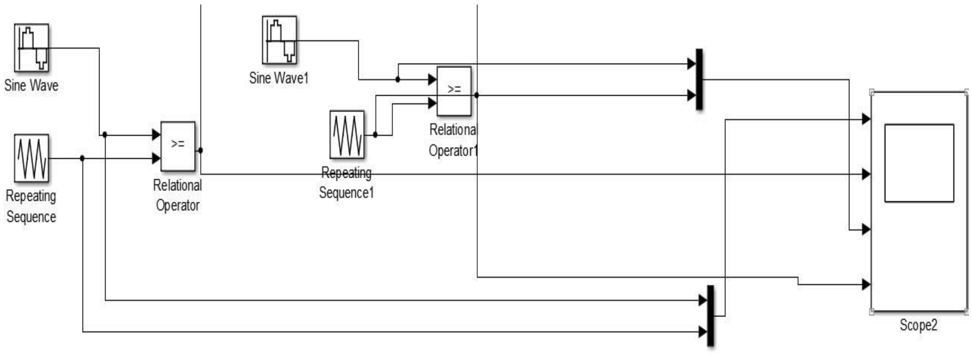

Fig. 7.14 Simulink model of control technique for single phase inverter

7.5 MATLAB/SIMULINK MODEL OF COMPLETE SPV SYSTEM

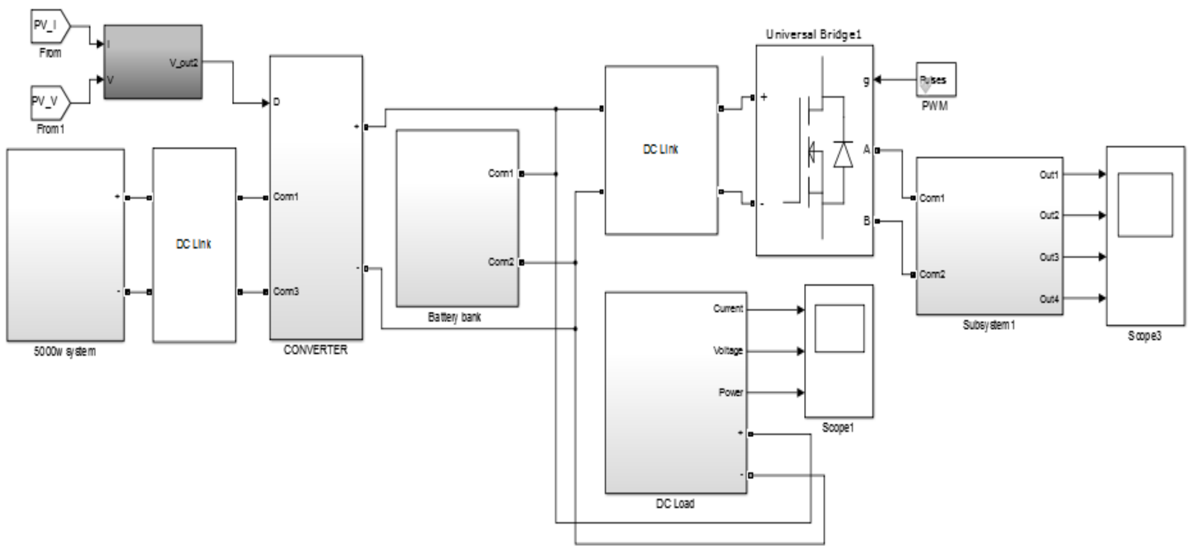

Fig.7.15 Simulink model of 5kW SPV array system with P&O technique

7.6 MATLAB/SIMULINK MODELLING OF PERTURB AND OBSERVATION

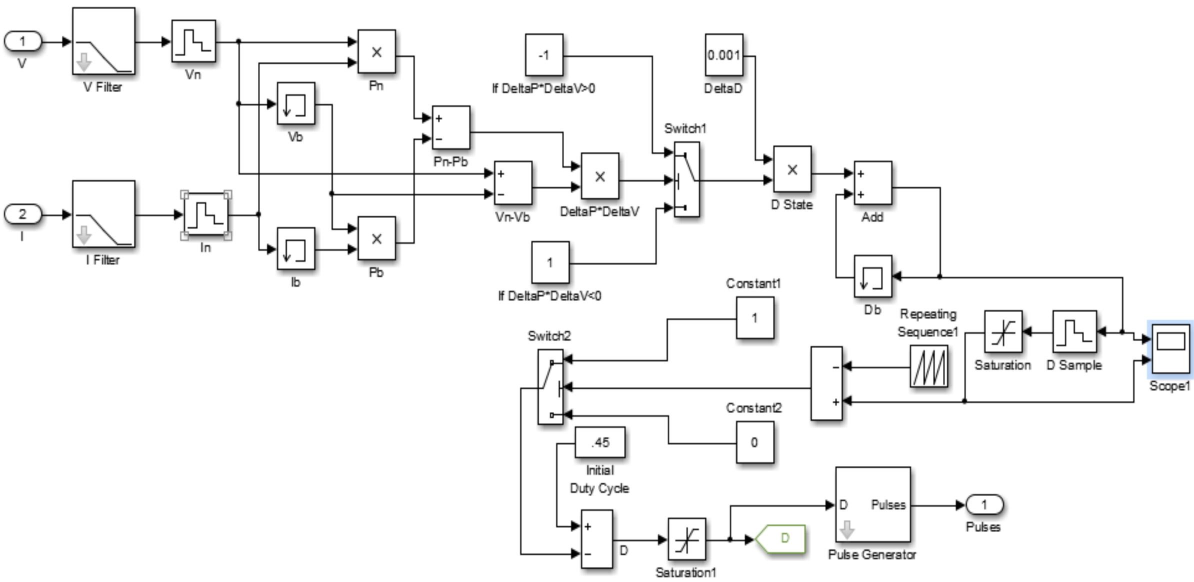

Fig. 7.16 Simulink model of P&O technique on 250W SPV panel

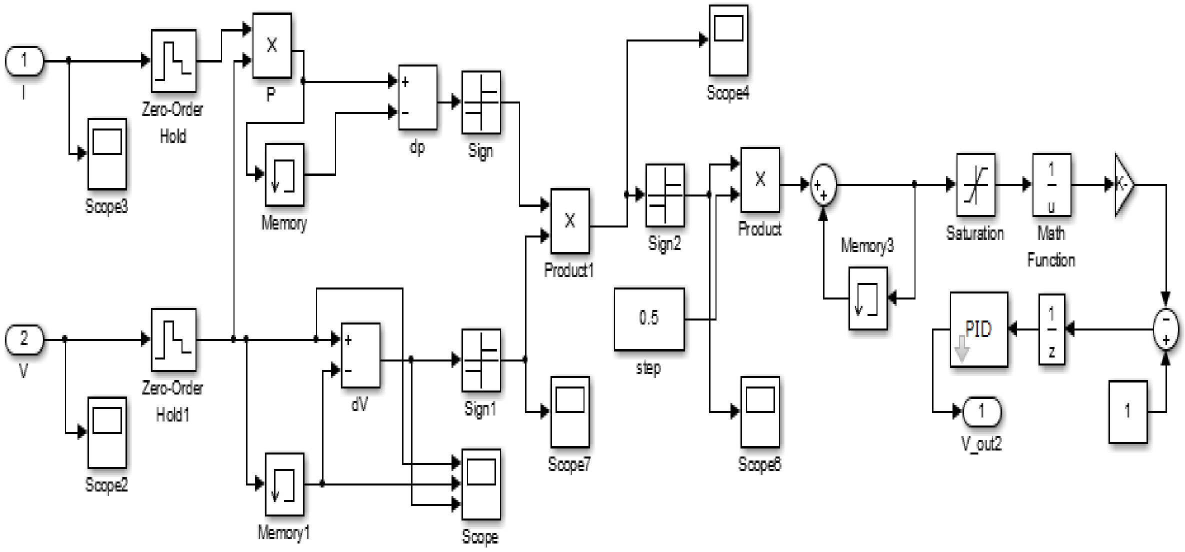

Fig. 7.17 Simulink model of P&O technique on 5kW SPV array

CHAPTER 8

OPTIMUM STRATEGY & SIMULATION RESULTS

8.1 To design an optimized SPV system following steps should be considered:

8.1.1 Estimation of load.

8.1.2 Estimation of required number of SPV panels.

8.1.3 Estimation of battery bank capacity & number of batteries required or grid tied option.

8.1.4 Estimation of complete system cost.

8.2 To calculate SPV plant's monthly electrical output following algorithm steps are used where annual electrical output is sum of the 12 months output.

8.2.1 Determine monthly POA incident radiation from available data such as solar irradiation, site latitude & longitude, SPV array type, tilt & azimuth angles.

8.2.2 Determine effective POA incident radiation with respect to reflective losses and wind speed at high solar incidence angles.

8.2.3 Determine cell temperature based on array type which expects module height of 5 meters above ground and nominal operating cell temperature of 45°C for our fixed system with consideration of effective POA incident radiation.

8.2.4 Determine total DC output of the plant w.r.t. reference POA incident radiation of 1,000 W/m^2, cell temperature, reference cell temperature of 25°C and temperature coefficient -0.45%/°C for the standard module type, -0.35%/°C for the premium type.

8.2.5 Determine total AC output of the plant from total DC output of the plant and System Losses w.r.t. nominal inverter efficiency (96%) with adjustment in part-load inverter efficiency.

Considering all factors described briefly in this dissertation work and duly performed tests with monthly simulation results for plant output over an entire year, optimized plant output data is expressed in Table 8.1 & 8.2. DC & AC output simulation results are also expressed in Fig. 8.1-8.20.

Table 8.1 5kW SPV array month wise ameliorated performance data

5kW$_P$ SPV Array Monthly Optimized Performance Data (Jan-2016 to Dec-2016)				
Module Type			Premium	
System Losses (%)			10.49	
Micro Inverter Efficiency (%)			97	
DC to AC Size Ratio			1.1	
Capacity Factor (%)			17.4	
Month	**AC system output (kWh)**	**Solar Radiation (kWh/m^2/day)**	**Plane of Array Irradiance (W/m^2)**	**DC array Output (kWh)**
Jan	522.41	4.16	129.02	546.08
Feb	601.79	5.41	151.54	627.72
Mar	766.06	6.45	200.01	798.52
Apr	767.69	6.83	204.81	800.57
May	704.45	6.06	187.83	735.21
Jun	618.34	5.44	163.06	646.18
Jul	559.07	4.62	143.18	585.11
Aug	601.11	4.92	152.40	628.50
Sep	651.79	5.58	167.45	680.25
Oct	703.51	5.86	181.80	733.49
Nov	586.97	4.93	147.85	611.82
Dec	535.37	4.29	132.96	558.83
Total	**7618.56**	**64.55**	**1961.91**	**7952.28**

Table 8.2 500kW SPV plant month wise ameliorated performance data

500kW$_P$ Solar Plant Monthly Optimized Performance Data (Jan-2016 to Dec-2016)				
Module Type			Premium	
System Losses (%)			12.3	
Capacity Factor (%)			19.3	
Micro Inverter Efficiency (%)			97	
Capacity Factor (%)			19.3	
Month	**AC System Output(kWh)**	**Solar Radiation (kWh/m^2/day)**	**Plane of Array Irradiance (W/m^2)**	**DC array Output (kWh)**
Jan	69158.61	5.56	172.29	72152.83
Feb	65508.53	5.90	165.23	68311.12
Mar	80194.91	6.65	206.11	83674.68
Apr	80103.57	7.01	210.29	83574.89
May	80344.69	6.91	214.34	83850.58
Jun	71513.27	6.34	190.28	74714.26
Jul	62269.15	5.28	163.82	65145.28
Aug	62280.28	5.25	162.84	65122.89
Sep	67448.74	5.89	176.60	70435.34
Oct	73032.58	6.17	191.25	76201.93
Nov	66757.76	5.74	172.16	69628.99
Dec	67939.48	5.56	172.33	70848.99
Total	**846551.57**	**72.26**	**2197.54**	**883661.78**

8.3 P-V & V-I CURVE OF 250W SPV PANEL

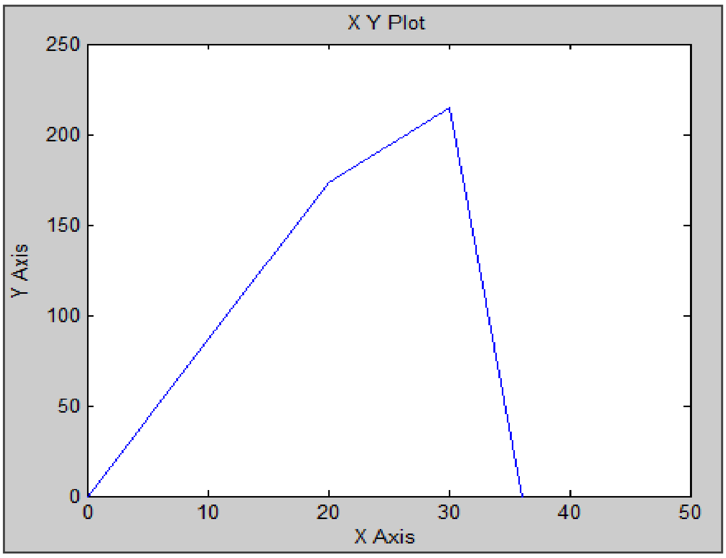

Fig. 8.1 P-V curve of 250W SPV panel

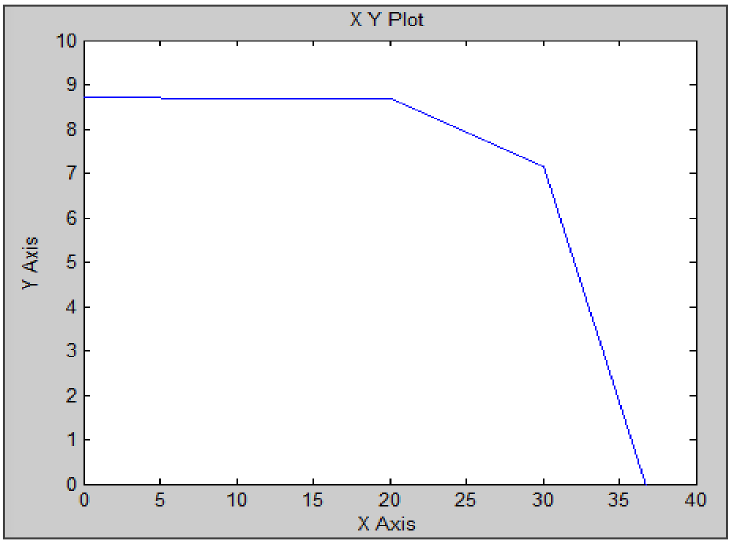

Fig. 8.2 V-I curve of 250W SPV panel

8.4 BOOST CONVERTER RESULTS WITH P&O TECHNIQUE

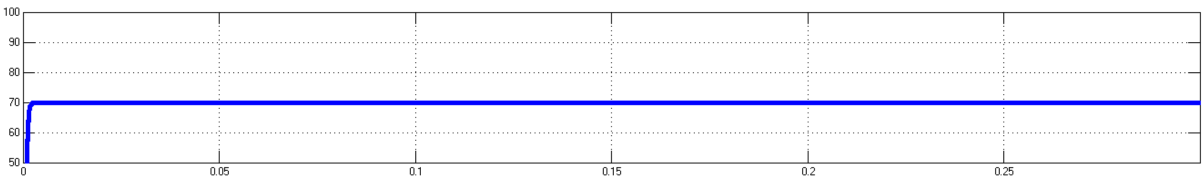

Fig. 8.3 Boost converter terminal voltage with P&O in 250W SPV panel

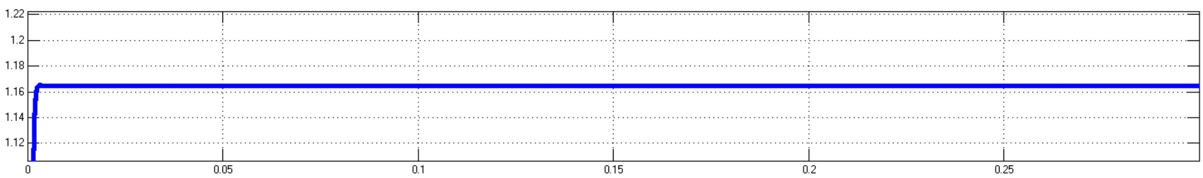

Fig. 8.4 Boost converter terminal current with P&O in 250W SPV panel

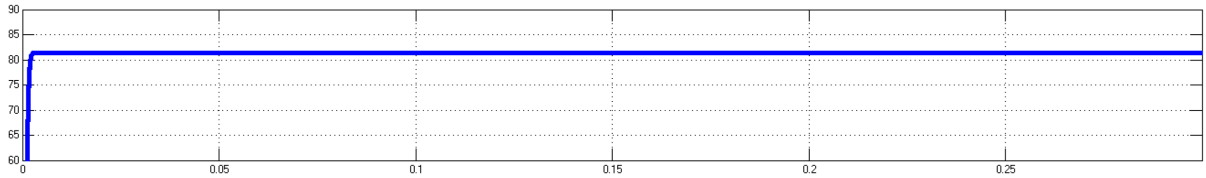

Fig. 8.5 Boost converter terminal power with P&O in 250W SPV panel

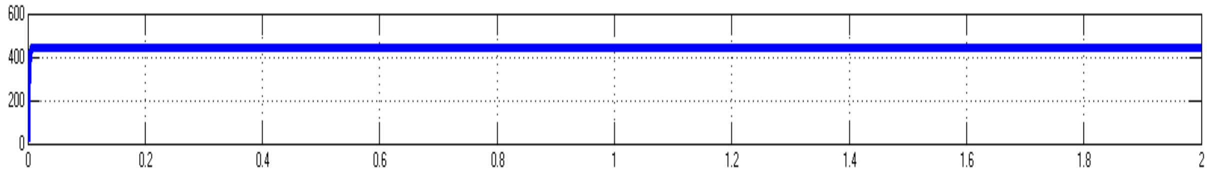

Fig. 8.6 Boost converter terminal voltage with P&O in 5kW SPV array

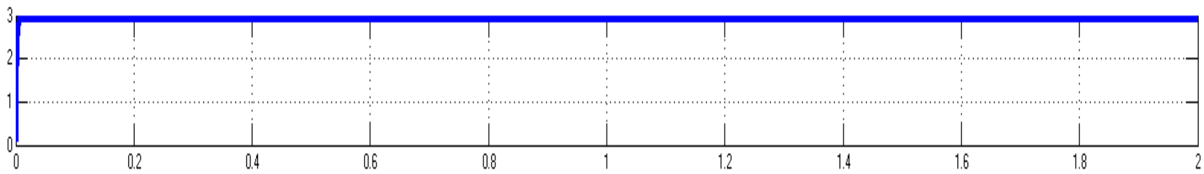

Fig. 8.7 Boost converter terminal current with P&O in 5kW SPV array

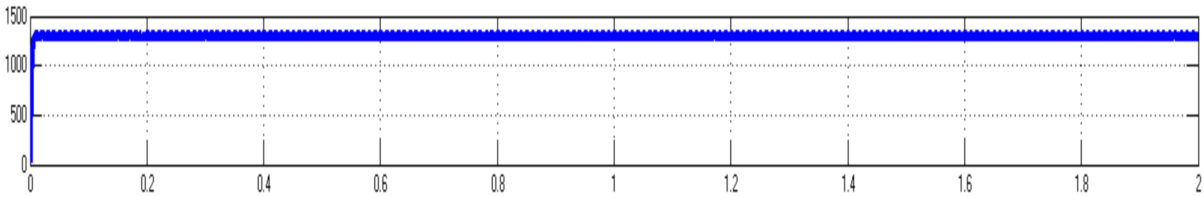

Fig. 8.8 Boost converter terminal power with P&O in 5kW SPV array

8.5 RESULTS WITH P&O TECHNIQUE

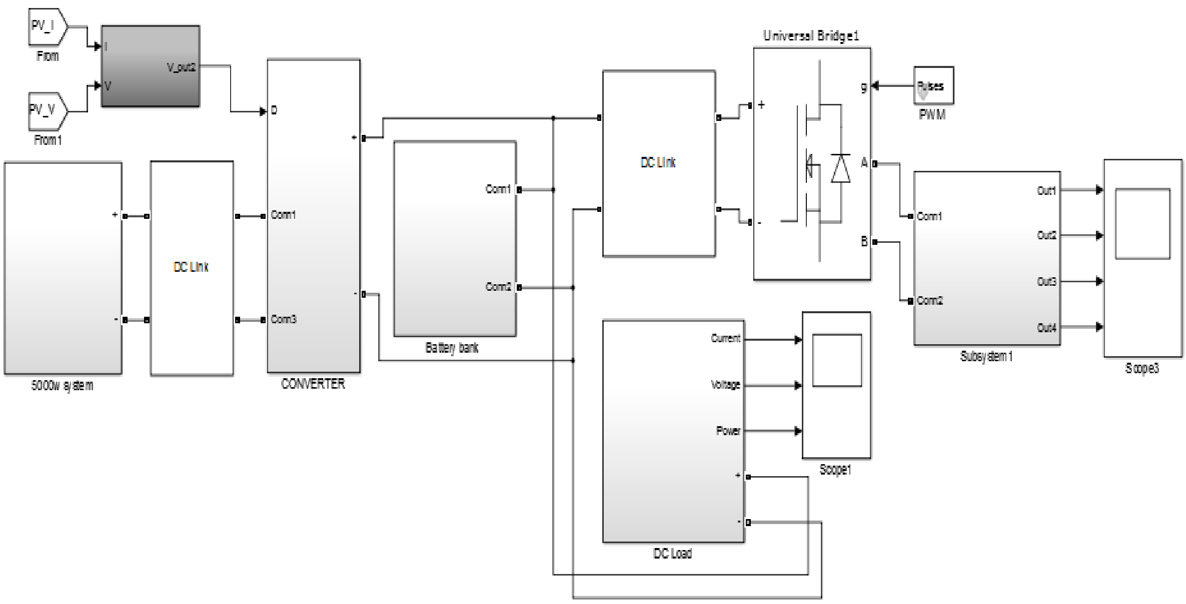

Fig.8.9 Simulated 5kW SPV system with P&O technique

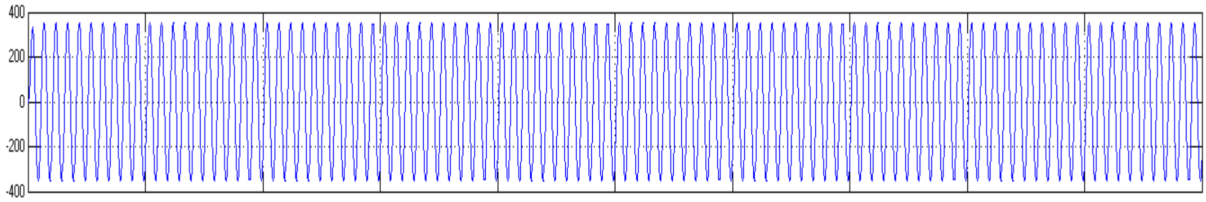

Fig. 8.10 5kW SPV array voltage result for AC load

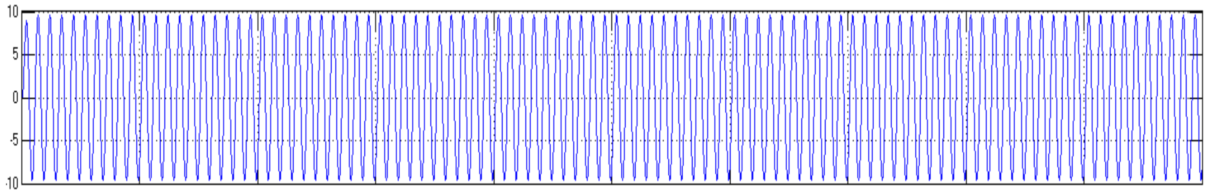

Fig. 8.11 5kW SPV array current result for AC load

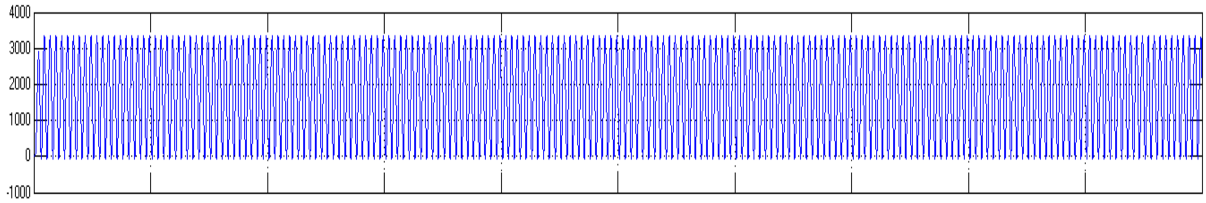

Fig. 8.12 5kW SPV array instantaneous power result for AC load

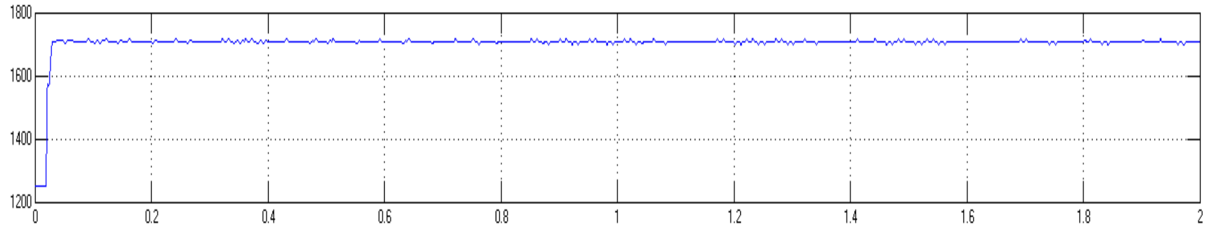

Fig. 8.13 5kW SPV array average power result for AC load

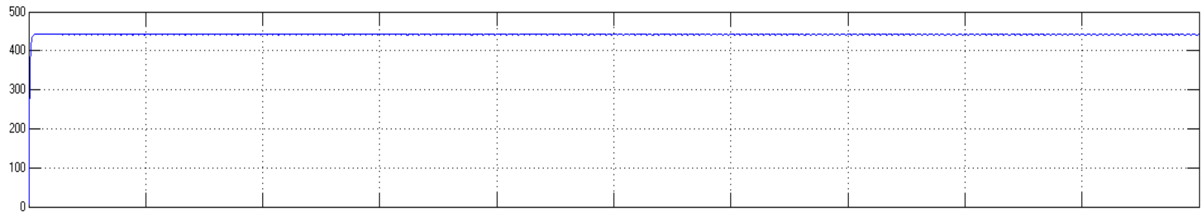

Fig. 8.14 5kW SPV array voltage result for DC load

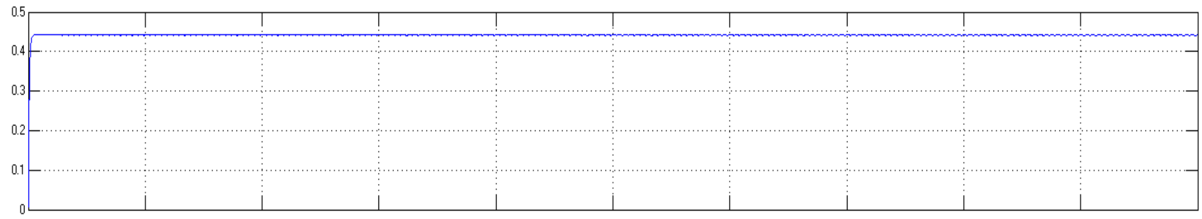

Fig. 8.15 5kW SPV array current result for DC load

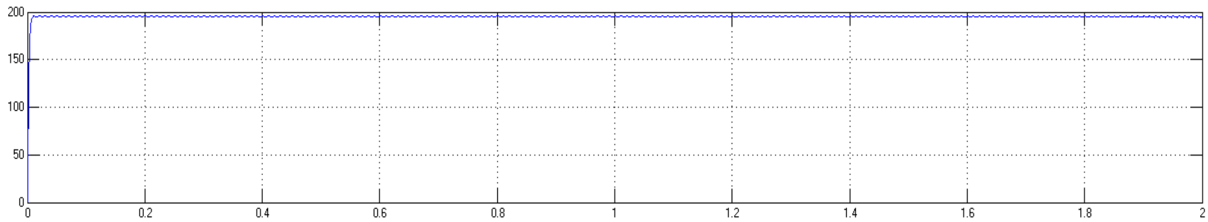

Fig. 8.16 5kW SPV array power result for DC load

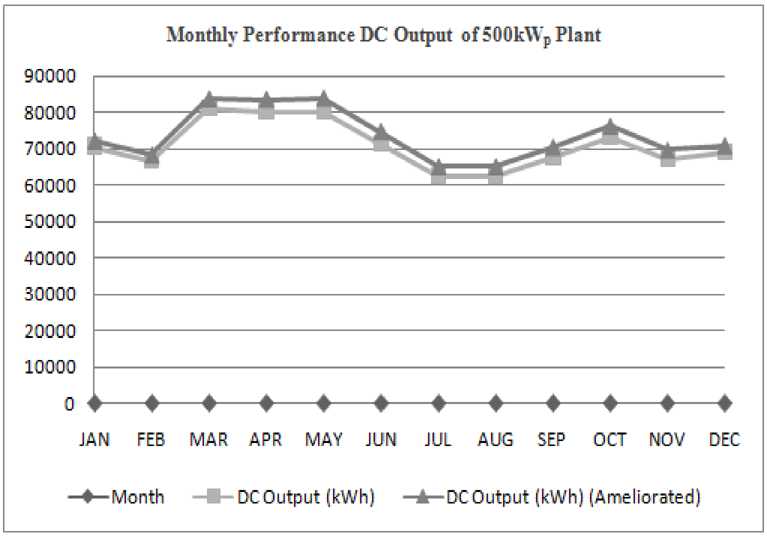

Fig. 8.17 Monthly variation in DC output power.

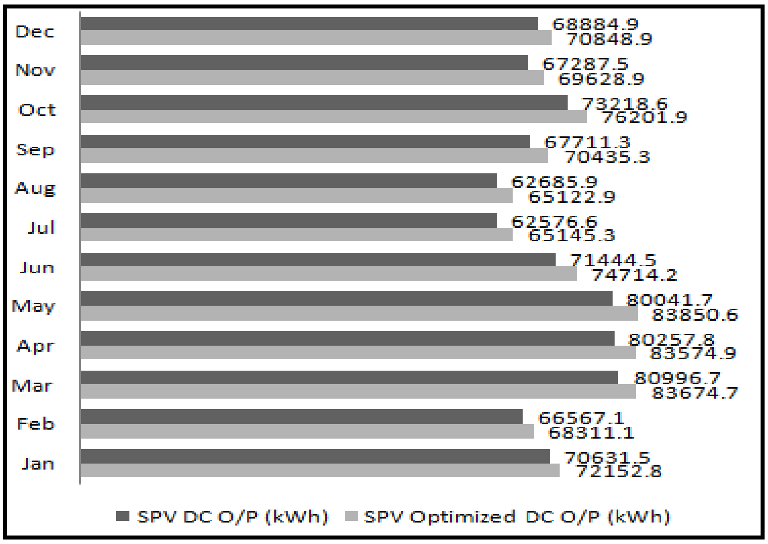

Fig. 8.18 Monthly performance of DC output

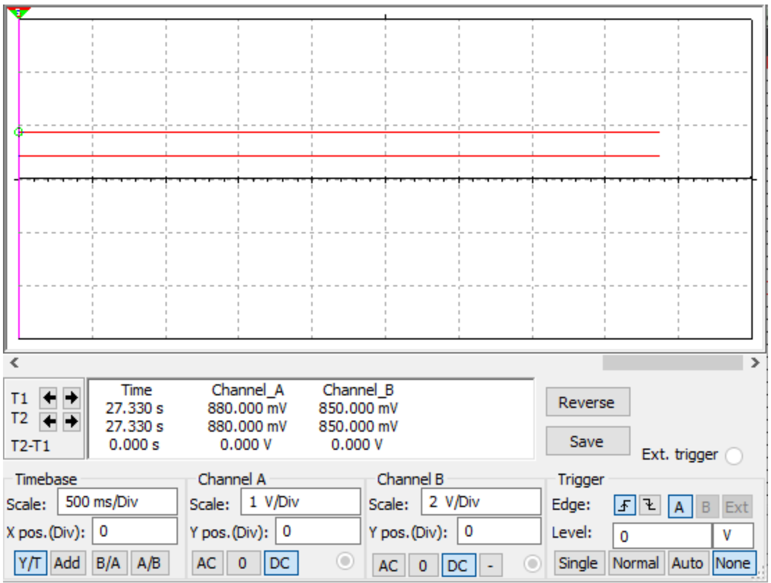

Fig. 8.19 DC output power simulation result of solar array

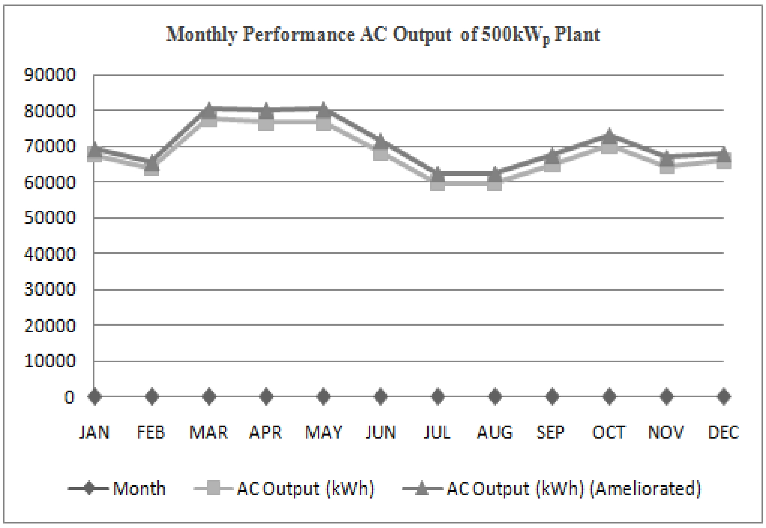

Fig. 8.20 Monthly variation in AC output power

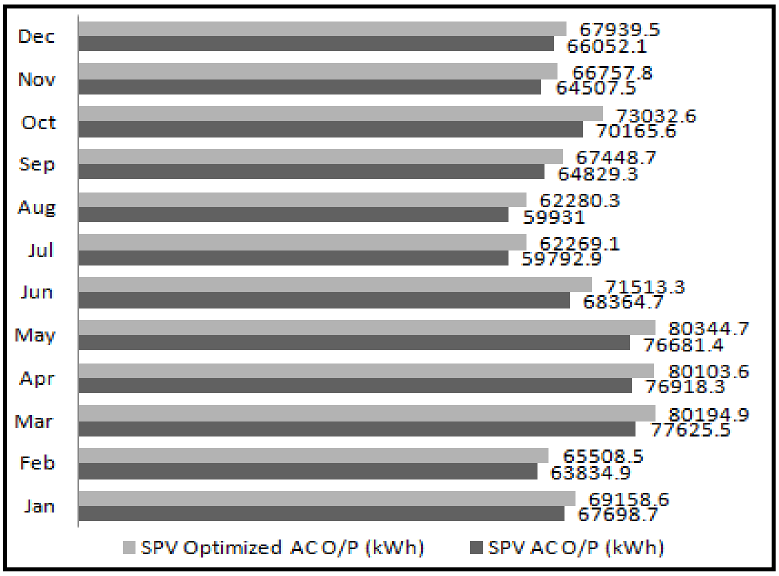

Fig. 8.21 Monthly performance of AC output

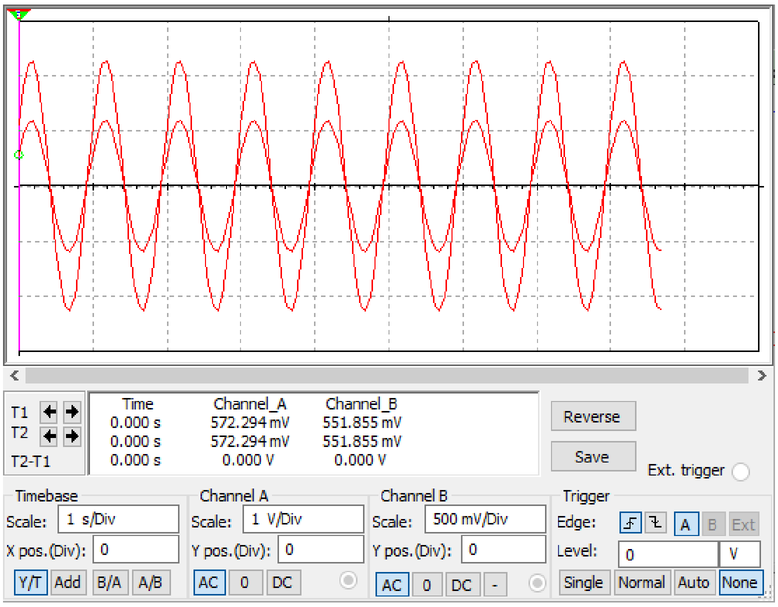

Fig. 8.22 AC output power simulation result of solar array

CHAPTER 9
CONCLUSION AND FUTURE SCOPE

9.1 CONCLUSION

Because of enormous scope of development and implementation in our country, this dissertation work of studying SPV has effectively tried to ameliorate solar plant output & efficiency. Output characteristic curve concludes that plant output (power, current and voltage) decreases when solar irradiation reduces. Output power & voltage increase marginally with increase in temperature, whereas output current almost keeps constant. This dissertation work examined SPV array operation for various physical parameters which includs shunt & series resistance, fill factor, cell surface region, battery choice, inverter choice (Micro/Micro Parallel/Micro Octet) & working conditions such as temperature, irradiation level and shadow effect. This Dissertation work presents rigid mounted SPV system with Matlab/Simulink model and simulates the performance of 5kW SPV array with P&O MPPT technique. The control algorithm executes P&O MPPT & allow module to operate at maximum power point according to solar irradiation and match load with the source impedance to provide maximum power. This MPPT model is advantageous because of less cost, easier circuit design, circuit efficiency and also saved the extra energy required in mechanical tracking. The optimal control of SPV physical parameters, SPV parallel configuration with micro inverter persuade a rise of 3.7% in overall SPV annual output achieved over conventional flat system.

Even 1% efficiency improvement in future would save tons of fuels & ores yearly. There is further huge scope of research on SPV system to harvest solar energy & ameliorating the factors to improve solar efficiency.

9.2 FUTURE SCOPE

9.2.1 DC output power is directly utilized to charge batteries of metro trains installed in driving & trailing cars.

9.2.2 Rigid mounted system with battery backup can be utilized to feed metro depot & station lightning load to save electricity bill.

9.2.3 Replacing any surface Like Metro Train roof, Train body, Inspection Bay Line roof, Workshop building roof with solar cell by thin flexible SPV sheets as future option.

9.2.4 Modification of commercial printer accepting solar ink made of metal salts suspended in a polymer fullerene blend is required, which proves to be scalable and incredibly cost effective as it can be printed at atmospheric pressure and ambient temperature in spite of conventional silicon solar cells which must be manufactured in airtight vacuum sealed chambers and dust free environment that significantly raise the cost of manufacturing.

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