Sizing of Photovoltaic Array and Battery Using Simplex Method for Stand Alone Photovoltaic System

Dissertation submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF ENGINEERING
in
POWER SYSTEMS & ELECTRIC DRIVES

Submitted By
Hardipinder Singh
(Roll No. 801141014)

Under the guidance of:
Ms. Suman Bhullar
Assistant Professor, EIED

ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT
Thapar University
Patiala-147004
JULY-2013

CERTIFICATE

I hereby declare that the dissertation entitled "Sizing of Photovoltaic Array and Battery Using Simplex Method for Stand Alone Photovoltaic System" is an authentic record of my own work carried out as the requirement for the award of the degree of M.E.(Power System & Electric Drives) at Thapar University, Patiala, under the guidance of **Ms. Suman Bhullar,** Assistant Professor, (EIED) Thapar University, Patiala

The matter presented in this dissertation has not been submitted for the award of any other degree to any other university

Hardipinder Singh

Date: 08/07/2013

HARDIPINDER SINGH
Reg. no. 801141014

This is certified that the above statement made by the candidate is correct and true to the best of my knowledge.

SBhullar 8/7/13

Ms. SUMAN BHULLAR
Asst. Prof. (EIED)
Thapar University
Patiala

Countersigned by:

S. Ghosh

Dr. SMARAJIT GHOSH
Prof. & Head, EIED
Thapar University
Patiala

Dr. S.K. MOHAPATRA
Dean, Academic Affairs
Thapar University
Patiala

ACKNOWLEDGEMENT

I would like to express my sincere gratitude **Dr. Smarajit Ghosh, Professor & Head,** Electrical & Instrumentation Engg. Department for providing the opportunity to carry out this work.

I would like to express my gratitude to my supervisor, **Ms. Suman Bhullar, Assistant Professor (EIED),** for all her guidance and invaluable advises throughout the progress. I would also like to thank **Mrs. Manbir Kaur, Associate Professor & P.G. Coordinator (PSED)** for providing all the needed help to carryout this work.

I also express my gratitude to other faculty members of the department for their intellectual support throughout the course of work.

HARDIPINDER SINGH

ABSTRACT

Photovoltaic system is emerging as a major power resource, steadily becoming more affordable and proving to be more reliable than utilities and promises a brighter, cleaner future. Photovoltaic system can be grid connected or standalone, both have their advantages and disadvantages. As most of the Photovoltaic systems are standalone, so to avoid the problem of islanding a proper size of the Photovoltaic system should be adopted to give a reliable system. Sizing of photovoltaic system is the process of designing, selecting and calculating the ratings of the equipments employed in the system. This process depends on a variety of factors such as geographical location, solar irradiation, and load requirements. In this dissertation, sizing of standalone photo voltaic system is done using linear programming problem (LPP) approach. LPP provides upper bound reliability for application and rich information for many extreme events. A method of sizing stand-alone photovoltaic systems regarding the reliability to satisfy the load demand is presented in this work.

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Chapter 1

1.1 Introduction

With the depletion of traditional energy sources and the increase in pollution and greenhouse gases emissions, the usage of renewable energy is increasing more to the world's energy consumption. Due to environmentally friendly, the power generation technologies using renewable energy will play an important role in future power supply due to increased global public awareness of the need for environmental protection and desire for less dependence on fossil fuels for energy production.

The main sources of renewable energy are hydro energy, solar energy, wind energy, geothermal energy, biogas energy, fuel cell, tidal energy etc. Among these, solar energy is one of the most important parts of renewable energy systems and will be accepted by more and more people. Solar radiations which we receive from sun as heat and light can be converted to useful thermal energy or for production of electricity through solar cells. India is endowed with vast solar energy potential. About 5,000 trillion kWh per year energy is incident over India's land area with most parts receiving 4-7 kWh per sq. m per day. So, large amount of power can be generated from solar energy.

1.2 Solar energy

Solar energy is the radiant energy that comes from the sun. It is the most abundant energy source available. Solar energy can be harnessed using a range of ever-evolving technologies for further human needs. Now, Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs number of solar cells containing a photovoltaic material.

Photovoltaic systems (PV system) use solar panels to convert sunlight into electricity. A system is made up of one or more photovoltaic (PV) panels, a DC/AC power converter (also known as an inverter), a racking system that holds the solar panels, electrical interconnections, and mounting for other components.

1.3 Organization of dissertation

The Chapter 1 outlines introduction to renewable energy, solar energy and photovoltaic systems and also discusses organization of dissertation, the objective of dissertation, methodology used and literature review.

The Chapter 2 outlines the basic components of photovoltaic system, working and characteristics of solar cell. Classification and applications of photovoltaic system are also discussed.

The Chapter 3 outlines the sizing of photovoltaic array and battery for stand-alone system. In this chapter the procedure and methodology used is discussed, followed by the data being used.

The Chapter 4 outlines the result obtained using linear programming which determines the number of photovoltaic module and number of batteries needed to meet the load demand.

The Chapter 5 outlines the conclusion and future scope of the dissertation.

1.4 Objective of dissertation

The objective of the dissertation is using C programming to find out the optimum number of batteries and PV modules for a stand-alone system, which would satisfy the specified constraints and enable the operation of a stand-alone photovoltaic system without any risk of not satisfying the load demand. The loss of power supply probability (LPSP) is used to connote the risk of not satisfying the load demand.

1.5 Methodology used

The computational scheme involves the linear programming technique in which the simplex method is used. The technique used has one objective function followed by the constraints which helps in finding the desired result. The upper bound restrictions help the simplex method not to fetch the boundaries with either of the decision variables (i.e., N_{module} and $N_{battery}$) having unexpectedly high value and the other unexpectedly low value. By solving the linear programming, the optimal combination of the number of modules in the array and the number of batteries in the battery bank to satisfy the load demand for time interval can be obtained.

1.6 Literature review

Borowy et.al.(1996) [3] presented a methodology for calculation of the optimum size of a battery bank and the PV array for a standalone hybrid Wind PV system was developed. For a given load and a desired Loss of Power Supply Probability, an optimum number of batteries and PV modules was calculated based on the minimum cost of the system.

Marwali et.al.(1997) [19] presented a methodology for calculating the production costing of an integrated photovoltaic-utility system with battery storage. The methodology used long term historical data on solar radiation to calculate the probability density function (pdf) of the photovoltaic (PV) power generation. The proposed method was simple and easy to implement, and numerical examples demonstrate the potential applications of the proposed method in a utility system.

Kellogg et.al.(1998) [17] presented the results of investigations on the application of wind, photovoltaic (PV), and hybrid wind/PV power generating systems for utilization as stand- alone systems. A simple numerical algorithm was developed for generation unit sizing. It was used to determine the optimum generation capacity and storage needed for a stand-alone, wind, PV, and hybrid wind PV system for an experimental site in a remote area in Montana with a typical residential load.

Duryea et.al. (2001) [9] estimated that about 80% of all photovoltaic (PV) modules were used in stand-alone applications and power obtained from PV systems by using a storage buffer, typically in the form of a lead acid battery. The life of a lead acid battery could be extended by avoiding critical operating conditions such as overcharge and deep discharge.

Kaushika et.al. (2005) [15] presented a simulation model for the sizing of stand-alone solar PV systems with interconnected arrays. It considered the electricity generation in the array and its storage in the battery bank served the fluctuating load demand. The loss of power supply probability (LPSP) was used to connote the risk of not satisfying the load demand.

Kaushika et.al. (2006) [16] developed a design aid expert system for solar photovoltaic (PV) power supplies corresponding to Indian region. The knowledge base was evolved from the climatological data of 14 stations in Indian region. The approach involved combining both the site and array characteristics. The resultant expert system was envisioned to provide general users the power of an expert, in the matter of design considerations.

Weixiang (2008) [24] presented a new approach to design the SPV systems in order to reduce the system cost as much as possible In this approach, the technical and non-technical factors including the selection of the optimal tilt angle of solar array and the maximum battery depth of discharge, life cycle of system, inflation rate and interest rate were taken into account in the system design.

Rong-Jong et.al. (2008) [22] developed a high-performance stand-alone photovoltaic (PV) generation system to make the PV generation system more flexible and expandable; the backstage power circuit was composed of a high step-up converter and a (PWM) inverter. In the dc–dc power conversion, the high step-up converter was introduced to improve the conversion efficiency in conventional boost converters to allow the parallel operation of low-voltage PV arrays, and decoupled and simplified the control design of the PWM inverter.

Jiyong et.al. (2009) [14] presented a novel stand-alone PV generation system based on a variable step size INC MPPT method and SVPWM control scheme for three-phase voltage source PWM inverter was build in Matlab/Simulink software. Maximum power point tracking (MPPT) techniques were used in PV systems to make full utilization of PV array output power which depended on solar irradiation and ambient temperature.

Rizzo et.al. (2009) [21] deals with the sizing a PV based source capable of working stand alone. In the paper, authors proposed a method to size, in one step, the source and the storage systems. In that way it was possible to achieve an optimal sizing with a consequent reduction of plant costs. The resulted system was capable of satisfying the load demand in all the weather conditions.

Abu-Jasser Assad (2010) [1] introduced the procedures employed in building and selecting the equipments of a stand-alone photovoltaic system based on the Watt-Hour demand. That process depended on a variety of factors such as geographical location, solar irradiation, and load requirements.

Campoccia et.al. (2010) [4] presented a reliability analysis of a stand-alone photovoltaic system for the supply of electric loads located in remote areas not easily reachable by the low voltage distribution network. The analysis was performed by characterizing the electric load behavior by means of a Monte Carlo approach for taking into account the stochastic variability of the electrical energy demand.

Khatib et.al. (2011) [18] presented a new method for determining the optimal sizing of standalone photovoltaic (PV) system in terms of optimal sizing of PV array and battery storage. A standalone PV system energy flow was first analyzed, and the MATLAB fitting tool was used to fit the resultant sizing curves in order to derive general formulas for optimal sizing of PV array and battery.

Delavaripour et.al. (2011) [7] presented the optimum calculation of battery size when used as energy storage in standalone systems with renewable energy resources. The focus in this analysis was on the effect of battery charging/discharging characteristics on system reliability and cost. This paper used the Loss of Load Expectation (LOLE) index to evaluate the reliability of a standalone system consisting of wind turbines and battery storage system.

Dursun et.al. (2011) [8] presented different power management strategies of a stand-alone hybrid power system. The system consisted of three power generation systems, photovoltaic (PV) panels, a wind turbine and a proton exchange membrane fuel cell (PEMFC). In this study, the battery energy efficiency was evaluated with three different power management strategies. The control algorithm used was Matlab Simulink.

Hong et.al. (2012) [22] proposed a simple PV constrained production control strategy, which leads to control the PV power at any level within the MPPT production ability. If the solar irradiation decreased and PV MPPT power was not able to output the desired constrained power, the control strategy continued to operate PV system with MPPT algorithm.

Chapter 2

2.1 Photovoltaic system

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. The PV system is made up of one or more photovoltaic (PV) panels, a DC/AC power converter, a racking system that holds the solar panels, electrical interconnections, and mounting for other components. Optionally, it may include a maximum power point tracker (MPPT), battery system and charger, solar tracker, energy management software, solar concentrators or other equipment.

A small PV system may provide energy to a single consumer, or to an isolated device like a lamp or a weather instrument. Large grid-connected PV systems can provide the energy to customers. The electricity generated can be either stored, used directly (island/standalone system), or fed into a large electricity grid powered by central generation plants (grid-connected/grid-tied system), or combined with one or many domestic electricity generators to feed into a small grid (hybrid system). Systems are generally designed in order to ensure the highest energy yield for a given investment.

2.2 Basic building blocks of PV Array

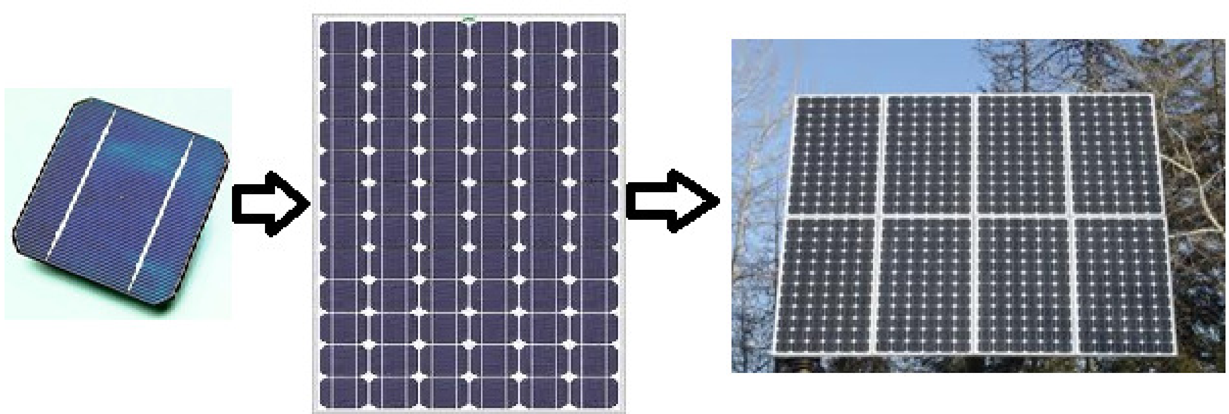


Fig. 2.1 shows: Building blocks of PV Array

2.2.1 Photovoltaic Cell

A PV cell is a thin semiconductor wafer made of two layers, generally made of highly purified silicon (PV cells can be made of many different semiconductors but crystalline silicon is the most widely used). The layers have been doped with boron on one side and phosphorous on the other side, producing surplus of electrons on one side and a deficit of electrons on the other side.

Fig. 2.2 shows: Photovoltaic Cell

2.2.2 Photovoltaic Module

A PV module consists of many PV cells wired in parallel to increase current and in series to produce a higher voltage. 36 cell modules are the industry standard for large power production

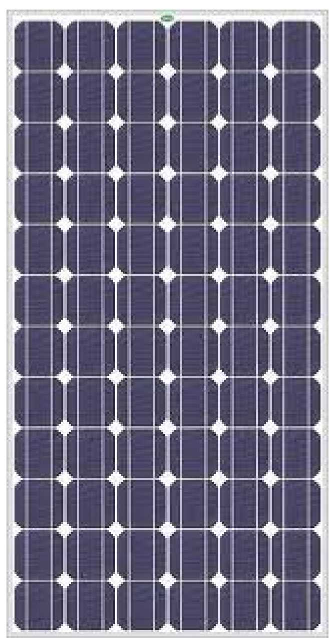


Fig. 2.3 shows: Photovoltaic Module

2.2.3 Photovoltaic Array

A PV Array consists of a number of individual PV modules or panels that have been wired together in a series and/or parallel to deliver the voltage and ampere a particular system requires. An array can be as small as a single pair of modules, or large enough to cover acres.

Fig. 2.4 shows: Photovoltaic Array

2.3 How photovoltaic cell works

A solar cell or photovoltaic cell is a junction of N-Type Silicon Phosphorous doped and P-Type Boron doped. When a photon (particle of light) strikes a solar photovoltaic cell, some of the energy it bring is captured by the semiconductor material(photons have no rest energy and no mass, so all its energy is purely kinetic and can be transferred to the semiconductor material). That energy knocks electrons loose, allowing them to flow freely. Electric fields created by photovoltaic cell, force the loose electrons to go in a certain direction, creating a current that can be led for use elsewhere.

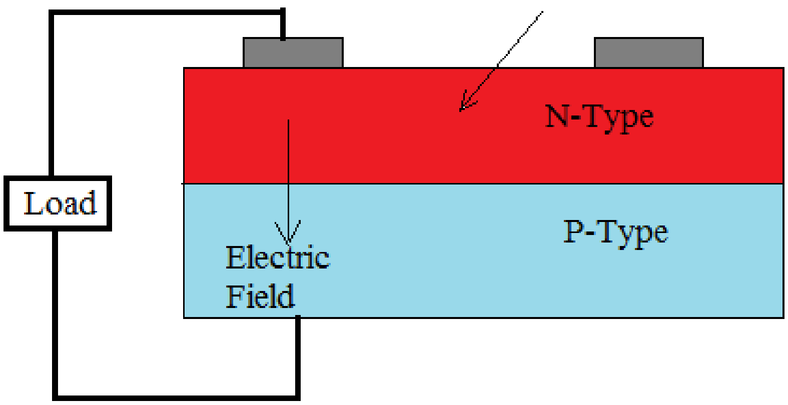


Fig. 2.5 shows: Functioning of PV cell

2.3.1 Simplified single-diode model of a solar cell.

A photovoltaic cell model consists of a current source in parallel with a diode and the output is in parallel with both of them through a series resistor. Figure 2.6 demonstrates a simplified circuit equivalent to a photovoltaic cell which is considered in the current study. A parallel resistor called R_P can be added right before R_S as it is considered in some cases.

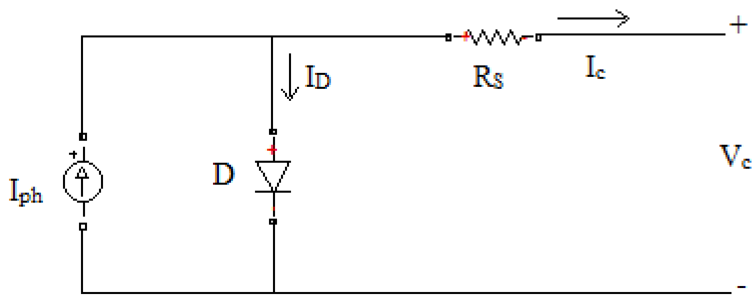


Fig. 2.6 shows: Simplified single-diode model of a solar cell.

The model contains a current source I_{ph}, one diode and a series resistance R_S, which represents the resistance inside each cell and in the connection between the cells. The net current is the difference between the photocurrent I_{ph} and the normal diode current I_D:

$$I = I_{ph} - I_D = I_{ph} - I_0\left(\exp^{\frac{e(V+IR_S)}{mkT_c}} - 1\right) \qquad (2.1)$$

Where m is idealising factor, k is Boltzmann's gas constant, Tc the absolute temperature of the cell, e electronic charge and V is the voltage imposed across the cell. $I_0$is the dark saturation current and it is strongly depending on temperature.

2.3.2 Characteristic of a solar cell

Figure 2.7 shows the I-V characteristic of the solar cell for a certain ambient irradiation G_a and a certain fixed cell temperature T_c.

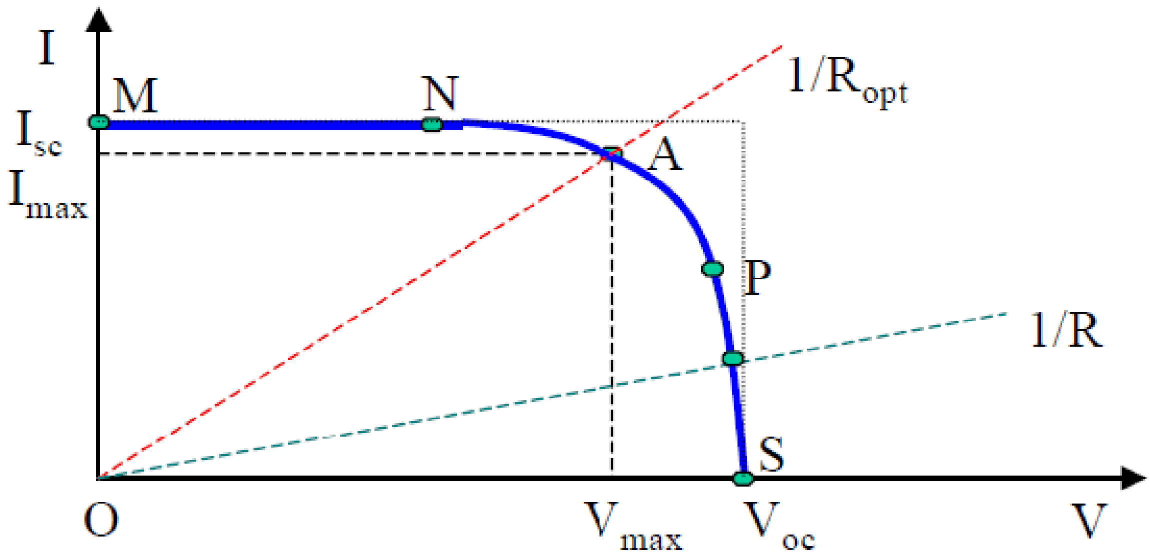


Fig. 2.7 shows: I-V Characteristic of a solar cell

If the cell's terminals are connected to a variable resistance R, the operating point is determined by the intersection of the I-V characteristic of the solar cell with the load I-V characteristic. For a resistive load, the load characteristic is a straight line with a slope I/V=1/R. It should be pointed out that the power delivered to the load depends on the value of the resistance only. However, if the load R is small, the cell operates in the region MN of the curve, where the cell behaves as a constant current source, almost equal to the short circuit current. On the other hand, if the load R is large, the cell operates on the region PS of the curve, where the cell behaves more as a constant voltage-source, almost equal to the open-circuit voltage.

A real solar cell can be characterised by the following fundamental parameters, which are also sketched in Figure 2.7:

(a) Short circuit current: $I_{sc}=I_{ph}$. It is the greatest value of the current generated by a cell. It is produced under short circuit conditions: V=0.

(b) 0pen circuit voltage corresponds to the voltage drop across the diode (p-n junction), when it is traversed by the photocurrent I_{ph} (namely $I_D=I_{ph}$), namely when the generated current is I=0. It reflects the voltage of the cell in the night and it can be mathematically expressed as:

$$V_{OC} = \frac{mkT_C}{e} \ln\left(\frac{I_{ph}}{I_0}\right) = V_t \ln\left(\frac{I_{ph}}{I_0}\right) \tag{2.2}$$

(c) Maximum power point is the operating point A(V_{max}, I_{max}) in Figure 2.7, at which the power dissipated in the resistive load is maximum:

$$P_{max}=I_{max}V_{max} \tag{2.3}$$

(d) Maximum efficiency is the ratio between the maximum power and the incident light power:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max}V_{max}}{AG_a} \tag{2.4}$$

where Ga is the ambient irradiation and A is the cell area.

(e) Fill factor is the ratio of the maximum power that can be delivered to the load and the product of Isc and Voc:

$$FF = \frac{P_{max}}{V_{oc}I_{sc}} = \frac{V_{max}I_{max}}{V_{oc}I_{sc}} \tag{2.5}$$

The fill factor is a measure of the real I-V characteristic. Its value is higher than 0.7 for good cells. The fill factor diminishes as the cell temperature is increased.

In Figure 2.8(a), an I-V characteristic of a solar cell for only a certain ambient irradiation Ga and only a certain cell temperature Tc is illustrated. The influence of the ambient irradiation Ga and the cell temperature Tc on the cell characteristics is presented in Figure 2.8(b).

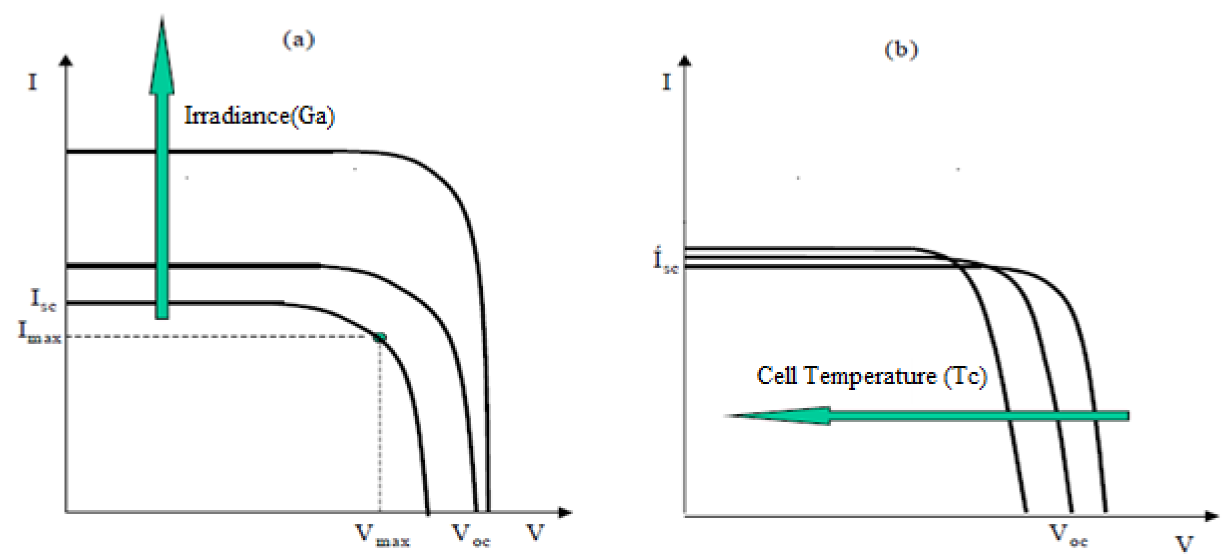


Fig. 2.8 shows: Influence of the ambient irradiation (a) and of the cell temperature (b) on the cell characteristics.

Figure 2.8(a) shows that the open circuit voltage increases logarithmically with the ambient irradiation, while the short circuit current is a linear function of the ambient irradiation. The arrow shows in which sense the irradiation and the cell temperature, respectively, increase. The influence of the cell temperature on the I-V characteristics is illustrated in Figure 2.8(b). The dominant effect with increasing cell's temperature is the linear decrease of the open circuit voltage, the cell being thus less efficient. The short circuit current slightly increases with cell temperature.

For practical use, solar cells can be electrical connected in different ways: series or parallel. Figure 2.9 presents how the I-V curve is modified in the case when two identical cells are connected in series and in parallel.

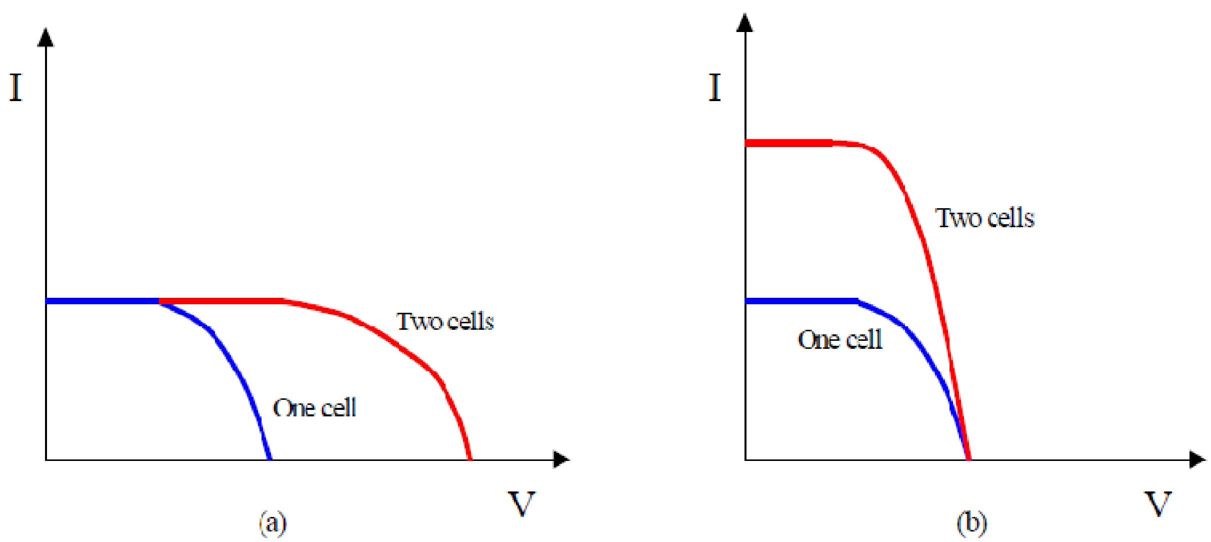


Fig. 2.9 shows: (a) Series and (b) parallel connection of identical cells.

It is seen that I-V characteristics of series interconnected cells can be found by adding, for each current, the different voltages of the individual cells. On the other hand, for parallel cells the currents of the individual cells must be added at each voltage in order to find the overall I-V curve.

2.4 Classification of PV systems

The photovoltaic systems are classified according to how the system components are connected to the power sources such as standalone (SA) and utility interactive (UI) systems. In a standalone system, the system is designed to operate independent of the electric utility grid, and is generally designed and sized to supply certain dc and/or ac electrical loads. A bank of batteries is used to store the energy in a form of dc power that is produced by the photovoltaic modules to be used at night or in the no sun days. The dc output of the batteries can be used immediately to run certain low dc voltage loads such as lighting bulbs or refrigerators or it can be converted by an inverter to ac voltage to run ac loads that constitute most appliances.

However, in utility grid connection or sometimes called utility interactive systems, power is brought in from the grid to supplement the system output when needed, and sold back to the utility when the photovoltaic modules' output exceeds the power demand. The capital cost of a SA system is still high due to the high price of the equipment used. For these reasons the SA applications have been limited to remote locations that are beyond the utility grid reach.

PV systems can be classified into two basic categories:

1. Grid or utility-interconnected PV systems.
2. Stand-alone PV systems.

2.4.1 Grid or utility-interconnected PV systems

Grid-connected PV systems are connected to the electrical grid by means of suitable power electronics inverter which converts the DC power produced by the PV cells into alternating current (AC), which is synchronized with the utility grid. This allows the generated energy to use for other users connected to the grid.

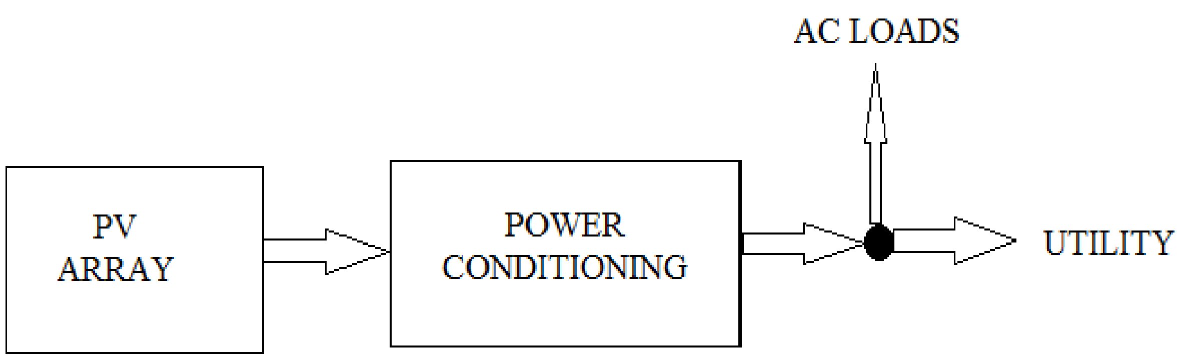


Fig.2.10 shows: Grid-connected PV system

2.4.2 Stand-alone PV systems

Stand-alone PV systems have no connection to the electrical grid and are used to supply local loads. Such a connection is mainly used when the cost of connecting particular localization to the grid is larger than the cost of the PV power system. The IEEE Standard 1374-98 divides stand-alone systems into three other sub-categories, not always easily distinguishable.

2.4.2.1 Direct-connected PV systems

Direct-connected PV systems are PV-based generating systems directly connected to the load without interposed storage systems.

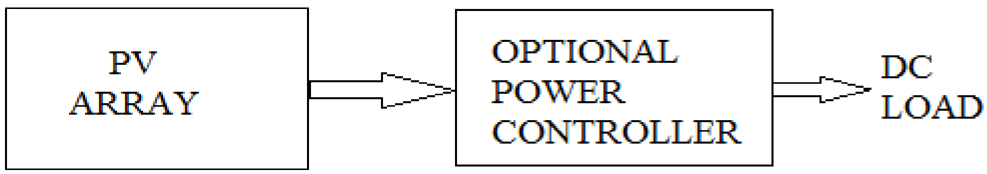


Fig.2.11 shows: Direct-connected PV system

2.4.2.2 Hybrid PV systems

Hybrid PV systems are PV systems connected to an electric load and integrated with a non renewable backup generator.

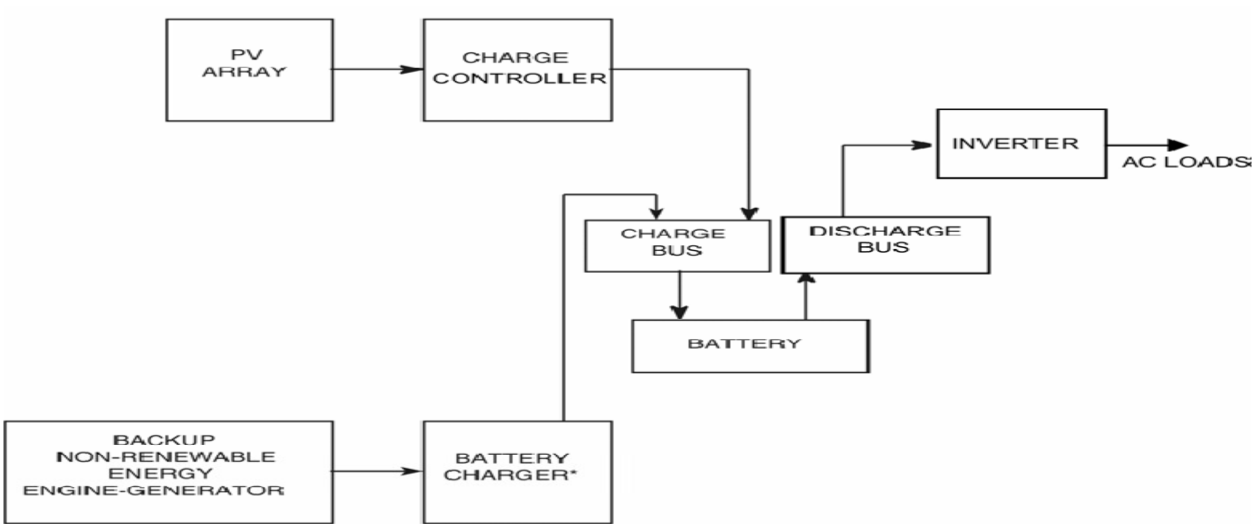


Fig. 2.12 shows: Hybrid PV System

2.4.2.3 Properly-named Stand-alone

A properly-named stand-alone PV system (only "stand-alone PV system" in the following) is a PV-based generating systems connected to a load with the interposition of a storage system.

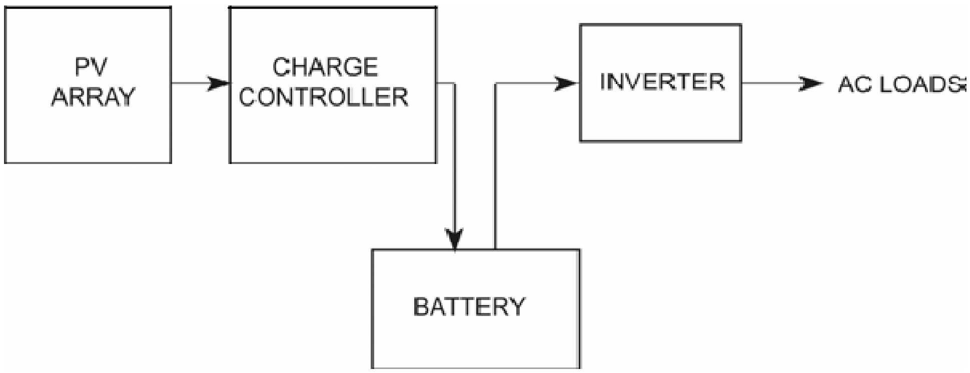


Fig.2.13 shows: Stand-alone PV system

Stand-alone PV systems are largely used for supplying electric loads not easily reachable by the distribution network (rural house, cathodic protection of buried tank, radio-base stations, etc.). They are designed considering the most critical conditions in terms of energy production (low irradiation), making it possible to supply the connected load in every period of the year. Nevertheless, in particular situations, due to the need of maintenance, exceptional load requests and momentary fault of the conversion system or low solar irradiation, the load can stay unsupplied for a certain period.

2.5 Photovoltaic Applications

2.5.1 Solar photovoltaic (PV) options for rural electrification

Simple effective solutions, including solar lanterns, solar heater and along with solar-based micro grids. Prevailing financial, policy and institutional mechanisms and barriers to wide-scale adoption are also taken up. The techno economics of a solar based micro grid is compared with grid extension. The current capital subsidy is compared with a generation-based tariff structure. Based on the analysis, a generation-based tariff is recommended for rural micro grids, solely consisting of solar energy or hybridized with other renewable energy sources, in order to ensure sustainable operation.

2.5.2 Solar-PV-based irrigation pump sets

These pumps are found to be competitive at today's cost relative to diesel-based pumps based on cost per unit of electricity or work done. Economic analysis is provided for pumps of two sizes – 1 HP and 2 HP – needed to draw water from up to 230 ft (70.1 m) and up to 530 ft (161.5 m) respectively.

2.5.3 Rooftop PV systems for diesel use abatement

In the case of solar PV systems for diesel consumption abatement, techno-economics is accompanied with a sensitivity analysis that incorporates varying diesel and PV system prices. It is demonstrated that the solar PV system could prove to be viable if diesel prices were to increase or PV systems prices were to come down. The total potential commercial rooftop available and a conservative market size for solar PV for reduction in diesel use is estimated. In addition to the economics, grid-connected rooftop PV systems could face technical challenges given India's transmission and distribution (T&D) woes.

2.5.4 Solar PV for Telecom Towers

India has more than 250,000 cell phone towers, each equipped with a diesel generator of 3 to 5 kW capacity depending on the number of operators housed on the tower. The towers are energy intensive since they operate non-stop. Given that a substantial number of these towers are in rural areas and any new additions are likely to be there as well, diesel consumption will be inevitable given the grid challenges. Roughly about 2 billion liters of diesel is consumed annually, amounting to around 4.5 million tons of CO_2 emissions. The Ministry of New and Renewable Energy (MNRE) is incentivizing the replacement of diesel for telecom towers with solar PV. This dissertation, however, does not evaluate the economics of solar PV for use in telecom towers.

Chapter 3

3.1 Sizing of PV System

Storage of the electric energy produced is not 100% efficient, and tends to be quite onerous as well. Therefore in order to maximize the economic feasibility of PV installations, it is necessary to optimize their size. System sizing is the process of evaluating the adequate voltage and current ratings for each component of the photovoltaic system to meet the electric demand at the facility and at the same time calculating the total price of the entire system from the design phase to the fully functional system including shipment and labor. The sizing methods for PV systems are classified into two categories: simulative methods and analytical methods. The simulation could be applicable when no sizing procedure is established. But it cannot avoid many trials and errors to make the sizing properly. In the preliminary design, it is important to offer easily an appropriate system. Therefore, the analytical methods are more popular. The analytical sizing methods could be categorized into three types. They are based on as follows:

1. Loads and irradiation.
2. Available areas.
3. LOLP (loss of load probability).

The sizing method based on loads and irradiation is usually used in stand-alone systems including hybrid systems and it can size appropriate PV systems evaluating loads, irradiation and all of the system losses. The sizing method based on available areas is usually applied to utility-connected systems with bidirectional power flow and it gives a PV array capacity under the available areas, such as roofs. On the contrary, the sizing method based on LOLP is a method that presents combinations of a PV array capacity and a battery capacity which makes LOLP at the desired level analytically. But it is applicable to the PV systems which consist of only PV arrays and batteries.

The sizing procedure of sources and storage systems for standalone power plants requires a preliminary analysis of the energy generated by photovoltaic arrays. This is mainly dependent on the orientation and tilt angle of the arrays respect the horizontal plane and the local solar radiation. The orientation and tilt angles of arrays are usually known, whereas the solar radiation incident on a PV module is stochastic, because it is strongly dependent on weather conditions.

3.1.1 Factors Affecting System Sizing

a) The average power demand in Watt-hour per day that can be obtained by itemizing all appliances and their hours of use each day which is referred to as the load profile.

b) Geographical location that dictates the tilt angel, panel orientation, and the average sun hours per day.

c) Home design, which plays a major rule in maximizing the amount of the generated power by considering the following points: keeping the southern area free from any barrier that prevents the sun-ray from reaching the panels, windows should be designed to face the south to keep the house as warm as possible, and insulation can be used to minimize the amount of heat losses.

d) Using energy-efficient equipment such as compact fluorescent lamps (CFL) for illumination to reduce energy requirements. Moreover, hot water and cooking should not be parts of the residence photovoltaic system. Natural gas for instance can be used for cooking and a separate thermal solar energy system can be employed to obtain the hot water directly to avoid the need for changing a part of the solar energy into electricity via the photovoltaic system and then using it to obtain hot water.

e) The use of low-voltage DC powered electric appliances, nowadays available in the market, are also an important factor in minimizing the photovoltaic system cost. This will reduce significantly the power rating of the inverter that is used to change the DC power of the batteries into AC power adequate for the ordinary appliances.

f) Frequency of switching which determines how often major rotationary loads are switched on and off such as refrigerators and water pumps. Such loads draw high currents every time they start and these loads must be accounted for.

3.2 Sizing of the Photovoltaic Array and Battery

Sizing of the PV array and battery bank for a stand-alone PV system is an important part of system design, which in turn requires the data on solar radiation and load demand. The methods based on the concept of number of autonomous days are simple and assure the required reliability of the PV system; however, the resultant sizing of the combination of PV array and battery bank for a solar PV system is not necessarily optimal. Yet another design parameter for stand-alone PV system is based on the concept of reliability of the power supply to the load, which is usually quantified by the loss of power supply probability (LPSP). It is the probability, which indicates that the combination of number of modules in the PV array and the number of batteries in the system has not been able to meet the load requirement for a certain period.

A linear programming approach is used to evaluate the optimal sizing of a stand-alone PV system with array made of interconnected modules. The assurance of reliable power supply to the load is quantified by LPSP. Solar photovoltaic systems based on non-tracking apertures are considered.

3.2.1 Linear programming approach to evaluate optimal array and battery sizing

A linear programming problem (lpp) with the objective to minimize the loss of power supply is, therefore, constructed. The number of modules in the PV array N_{module} and the number of batteries in the battery bank $N_{battery}$ during the time interval [(t-1),t] are considered as decision variables. So we have the lpp.

Min LPS(t)

subject to the following constraints:

(i) the energy obtained from the PV array during the interval [(t-1),t] is insufficient to satisfy the load demand for that interval,

(ii) the energy stored in batteries at the beginning of the time interval [(t-1),t] is discharged to the minimum allowable level,

(iii) the number of modules in the PV array at any time must be greater than some predetermined minimum value of the number of modules (i.e., $N_{mod\ min}$) in the PV array, and

(iv) the number of batteries in the system at any time must be greater than some predetermined minimum value of the number of batteries (i.e., $N_{batt\ min}$) in the system

or

$$\text{Min } LPS(t) = Load(t) - ((E_{module}(t)N_{module} + (E_{battery}(t-1)N_{battery} - E_{Bmin}))\eta_{inverter}) \quad (3.1)$$

subject to

$$E_{module}(t)N_{module}\eta_{inverter} \leq Load(t);$$

$$E_{battery}(t-1) - Load(t)/\eta_{inverter} + E_{module}(t)N_{module} \geq E_{Bmin};$$

$$N_{module} \geq N_{mod\ min};$$

$$N_{battery} \geq N_{batt\ min};$$

$N_{module} \leq N_{mod\ max}$;

$N_{battery} \leq N_{batt\ max}$

where:

$E_{Bmin} = ((1-l)C_{battery}N_{battery})$

LPS(t) = Loss of power supply for the time interval [(t-1),t]

Load(t) = Load demand during the time interval [(t-1),t] (kWh)

$E_{module}(t)$=Energy generated by a PV module during the time interval [t] (kWh)

$E_{battery}(t-1)$=Energy stored in a single battery at the beginning of time interval [(t-1),t] (kWh)

E_{Bmin} =Minimum allowable energy level for batteries at the end of each hour (kWh)

$N_{battery}$ = Number of batteries in the battery bank

$N_{batt\ max}$ = Upper bound on the number of batteries in the battery bank

$N_{batt\ min}$ = Lower bound on the number of batteries in the battery bank

N_{module} = Number of PV modules in the PV array

$N_{mod\ max}$ = Upper bound on the number of PV modules in the PV array

$C_{battery}$ = Capacity of a battery (kWh)

l = Depth of discharge of a battery (%)

$\eta_{inverter}$ = Efficiency of inverter (%)

This linear programming problem is time dependent and stochastic in nature. The coefficients Load(t), $E_{module}(t)$, and $E_{battery}(t-1)$ are time dependent and random. N_{module} and $N_{battery}$ are the decision variables. Above equation is an upper bound restricted linear programming problem in which $N_{mod\ max}$ and $N_{batt\ max}$ provide upper bounds on the number of modules N_{module} and number of batteries $N_{battery}$, respectively. The upper bound restrictions on N_{module} and $N_{battery}$ help the simplex method not to fetch minimum value of LPS(t) with either of the decision variables (i.e., N_{module} and $N_{battery}$) having unexpectedly high value and the other unexpectedly low value. Solving this lpp, we can obtain the optimal combination of the number of modules in the array and the number of batteries in the battery bank to satisfy the load demand for time interval [(t-1),t].

The loss of power supply probability, LPSP for any day can be defined as the ratio of all LPS(t) values for 24 h to the sum of load demanded for 24 h, i.e.,

$$\mathrm{LPSP} = \frac{\sum_{t=1}^{t=24} \mathrm{LPS}(t)}{\sum_{t=1}^{t=24} \mathrm{Load}(t)} \qquad (3.2)$$

If the loss of power supply probability for any day is 0.0, it means that the load demand for that day is satisfied. On the other hand, if the LPSP for any day is 1.0, it means that the demand of load during that day is not at all satisfied.

The power output of the photovoltaic module is based on current and voltage as follows,

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha \left(T_C - T_{C,STC} \right) \right] \tag{3.3}$$

where P_{PV} is the output power of the PV array (kW),

Y_{PV} the rated capacity of the PV array,

f_{PV} the PV derating factor (%),

G_T the solar radiation incident on the PV array (kW/m^2),

$G_{T,STC}$ incident radiation at standard test conditions (1 kW/m^2),

α_p the temperature coefficient,

T_C the PV cell operation temperature (^{0}C),

$T_{C,STC}$ PV cell temperature under standard test conditions (25 ^{0}C).

The energy generated by PV array for hour t , *EG(t)* can be expressed as follows:

$$E_{G(t)} = N_{PV} * E_{PV(t)} \tag{3.4}$$

where $E_{PV(t)}$- energy generated by a PV module,

N_{PV} - number of PV modules in a PV Array.

If the generated energy from the PV array exceeds that of the load demand, the batteries will be charged with the round-trip efficiency:

$$E_{B(t)} = E_{B(t-1)} + (E_{G(t)} - E_{L(t)} / \eta_{inv}) * \eta_{batt,in} \tag{3.5}$$

where:

η_{inv} - efficiency of the inverter,
$\eta_{batt,in}$ - round-trip efficiency of the batteries,
$E_{B(t)}$ - energy stored in batteries in hour t,
$E_{B(t-1)}$ - energy stored in batteries in previous hour,
$E_{L(t)}$ - load demand in hour t.

3.3 Tables for average value of data collected

The data had taken from "Continuous Ambient Air Quality Monitoring Center" located at Thapar University and main sub-station of Thapar University. The data represented in the following tables are the daily average values

Table 1: Data collected on daily average basis of various parameters

Date/Time	AT(°C)	SR(w/m^2)	Load(kw)
1/1/2013	14.8	129.3	43.93
1/2/2013	14.9	97.6	39.23
1/3/2013	14.7	122.1	53.98
1/4/2013	14.1	103.8	48.15
1/5/2013	13.5	128.3	44.45
1/6/2013	13.4	77.4	45.59
1/7/2013	13.5	164.5	74.47
1/8/2013	12.8	147.7	78.69
1/9/2013	14.7	214.4	81.6
1/10/2013	16.4	192.5	77.7
1/11/2013	17.3	202.1	43.98
1/13/2013	19.3	180.7	54.65
1/14/2013	20.2	188.1	86.04
1/15/2013	18.6	180.2	99.19
1/16/2013	19.7	229.3	91.74
1/17/2013	19.6	161.2	85.74
1/18/2013	19.1	86.5	65.98
1/19/2013	18.1	98.4	51.72
1/25/2013	19.4	611.7	64.97

Table 2: Data collected on daily average basis of various parameters

Date/Time	AT(°C)	SR(w/m^2)	Load(kw)
1/26/2013	20.3	323.6	56.83
1/27/2013	18.3	226.7	63.59
1/28/2013	18.3	203.8	86.47
1/29/2013	19.5	220.1	70.36
1/30/2013	19.1	218.2	72.33
1/31/2013	19.1	185.9	80.91
2/1/2013	19	179.5	52.7
2/2/2013	19.7	204.8	70.89
2/5/2013	20.5	141.7	76.67
2/6/2013	20.1	263.6	66.18
2/13/2013	19.7	276.7	64.09
2/15/2013	21.2	300.9	63.38
3/8/2013	24	300.9	71.4
3/11/2013	26	288.3	67.29
3/12/2013	26	268.5	70.23
3/13/2013	25.2	234	73.4
3/18/2013	23.7	318	65.89
3/20/2013	24.6	262.7	79.54
3/23/2013	25.2	285.3	60.34
3/24/2013	26.8	279.5	54.716

Table 3: Data collected on daily average basis of various parameters

Date/Time	AT(°C)	SR(w/m^2)	Load(kw)
3/25/2013	24.8	257.9	68.15
3/26/2013	24	321.5	64.08
3/30/2013	22.8	249.5	47.02
3/31/2013	26.8	345.6	58.58
4/2/2013	27.2	351.9	85.35
4/3/2013	27	296.1	72.59
4/6/2013	25.7	350.6	67.3
4/8/2013	27.8	330.1	90.49
4/9/2013	28.6	342.7	104.51
4/10/2013	29.1	319.9	113.9
4/13/2013	28.8	343.2	85.48
4/14/2013	29	340.5	75.13
4/15/2013	29.2	389.5	113.39
4/16/2013	29	290.2	125.06
4/18/2013	28.2	372.7	113.19
4/19/2013	29.4	378.1	80.39
4/21/2013	29.9	342.8	65.4
4/22/2013	28.3	280.3	117.3
4/23/2013	27.9	329.8	119.89
4/24/2013	29.3	309.1	116.59

Table 4: Data collected on daily average basis of various parameters

Date/Time	AT(°C)	SR(w/m^2)	Load(kw)
4/25/2013	29.9	289.4	120.62
5/1/2013	33.1	440.7	125.68
5/6/2013	31.9	304.4	137.44
5/9/2013	32	324.1	137.38
5/14/2013	28.5	355.1	108.99
5/15/2013	28.7	243.6	139.06
5/17/2013	33.6	381.1	134.64
5/19/2013	32.5	392.6	108.71
5/20/2013	33.5	339.1	128.47
5/21/2013	34.5	306	143.75
5/22/2013	34	319.7	142.72
5/23/2013	34.6	354.5	147.87
5/24/2013	34.9	370.8	145.14
5/25/2013	34.5	339.9	119.67
5/27/2013	34.6	325.3	140.13
5/28/2013	33.4	305.6	151.27
5/29/2013	33.2	323	140.08
5/30/2013	33.2	370.7	135.09
5/31/2013	31.8	365.2	135.19

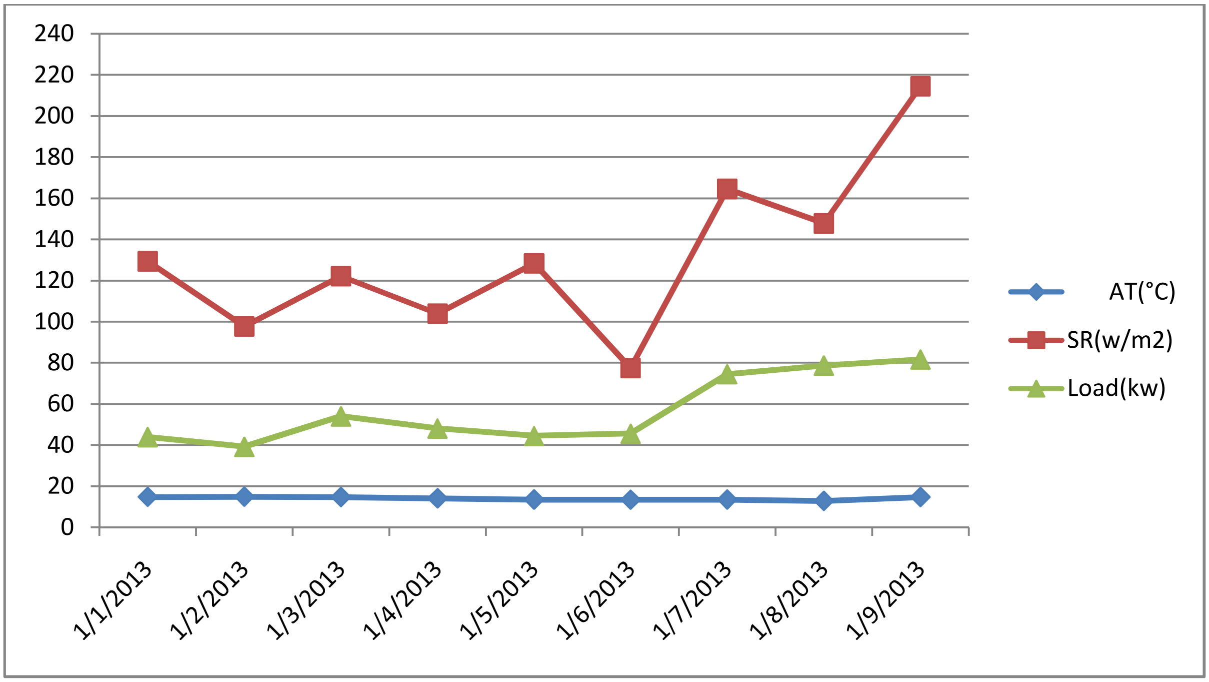
Chapter 4

4.1 Input

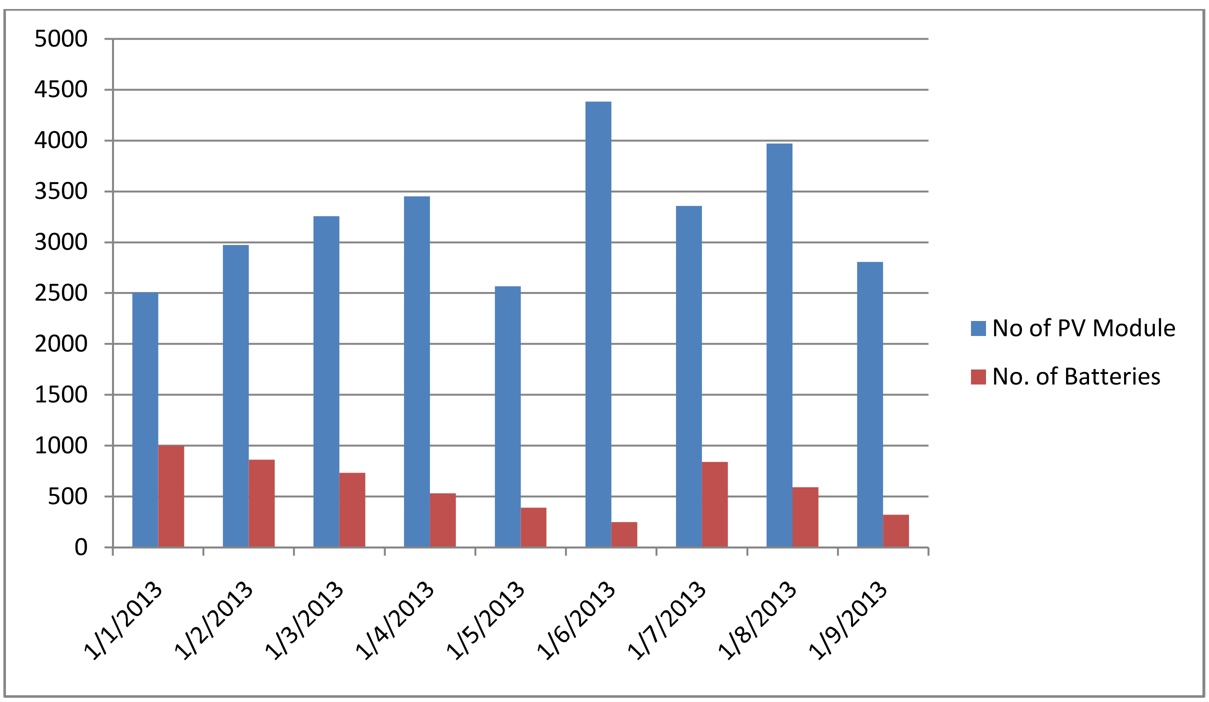
In finding out the optimum number of Photovoltaic modules and number of batteries , a 175W, 4.9A, 72 cells, 6x12, Monocrystalline PV module is chosen, the PV derating factor is taken as 0.9, G_T is the solar radiation incident on the PV array (kW/m^2), $G_{T,STC}$ incident radiation at standard test conditions and is taken as 1 kW/m^2, α_p the temperature coefficient = 0.004^0C^{-1}, T_C the PV cell operation temperature (^0C), $T_{C,STC}$ PV cell temperature under standard test conditions (25 ^0C). Initially the minimum no. of modules ($N_{mod\ min}$) chosen are 500 and minimum number of batteries ($N_{batt\ min}$) are 200. The maximum numbers of modules are 5000 and maximum numbers of batteries are 2000. The capacity of a 12V battery in the battery bank has been taken as 100 Ah. The round-trip efficiency of each battery has been considered as 85% and its allowable depth of discharge as 80%. Therefore, the number of such 12V batteries in a series string, required for the dc bus voltage of 240 V, would be 20. The energy storage capacity of each series string of 20 batteries = (240 x100)/1000=24kWh. Hence the capacity of a single battery = 24/20 = 1:2 kWh. The efficiency of inverter has been taken as 90%.

4.2 Result

Based on the available data mentioned in chapter 3, above mentioned input data and assumptions the calculations are done using simplex method to find out the optimum number of Photovoltaic modules and number of batteries for stand-alone system, to meet the load demand. First the power output from the single PV module is calculated using equation (3.3) and the energy stored in batteries is calculated by taking into account the minimum no. of modules and batteries using equation (3.5). Now by knowing the energy output from batteries at time interval (t-1) and energy output from modules at time interval (t), all the values are put in equation (3.1). Now with the help of linear programming approach using simplex method the equation (3.1) has been solved and corresponding to values available at different interval the number of PV modules and number of batteries for stand-alone system, to meet the load demand has been calculated whose values are shown below in respective graphs.

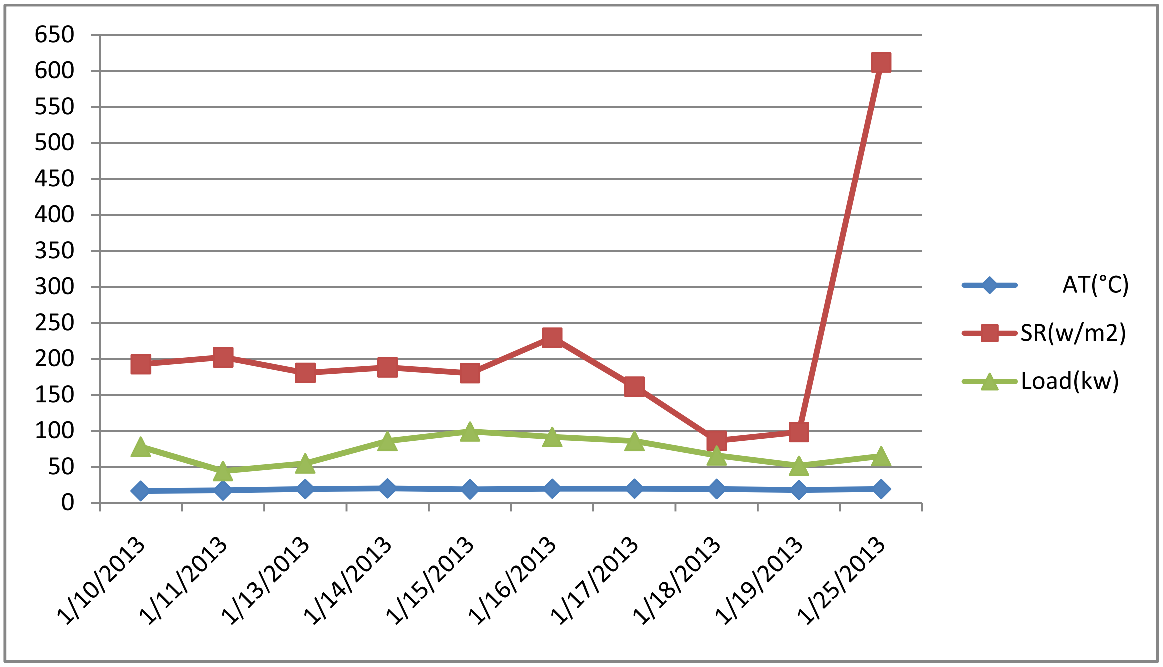


Graph: 1 shows: Variation of load, solar radiation and temperature

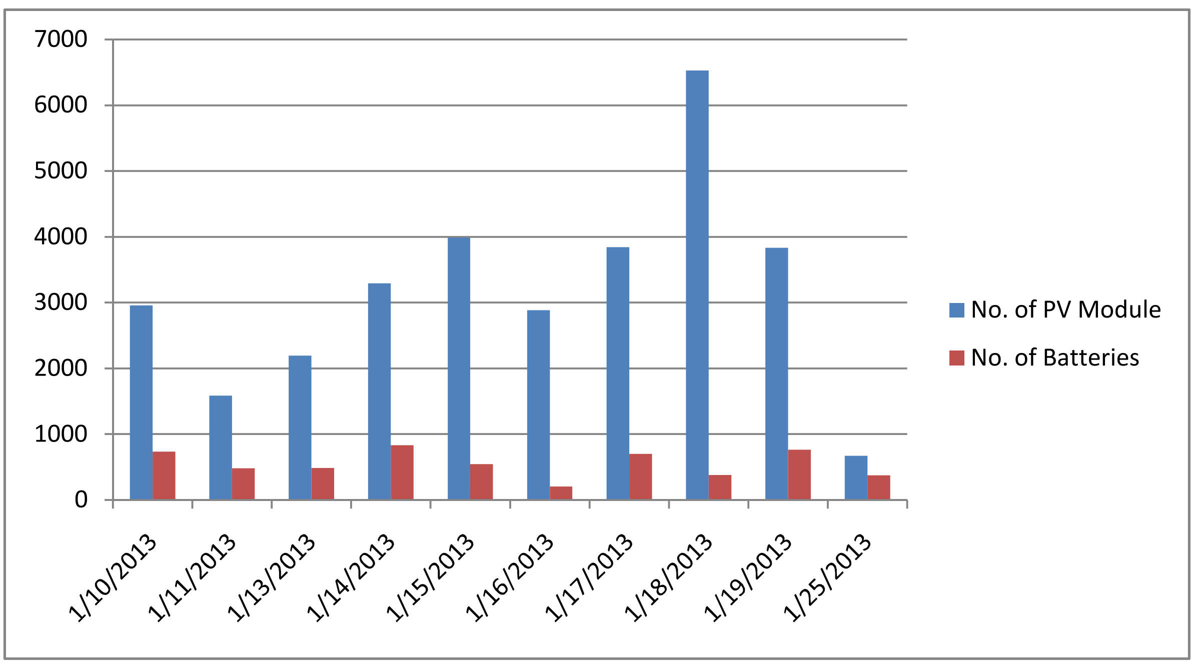


Graph: 1(a) shows: Required number of PV modules and batteries

In graph 1 the minimum radiation is on 1/6/2013 correspondingly the maximum number of PV modules required shown on same day in graph 1(a)

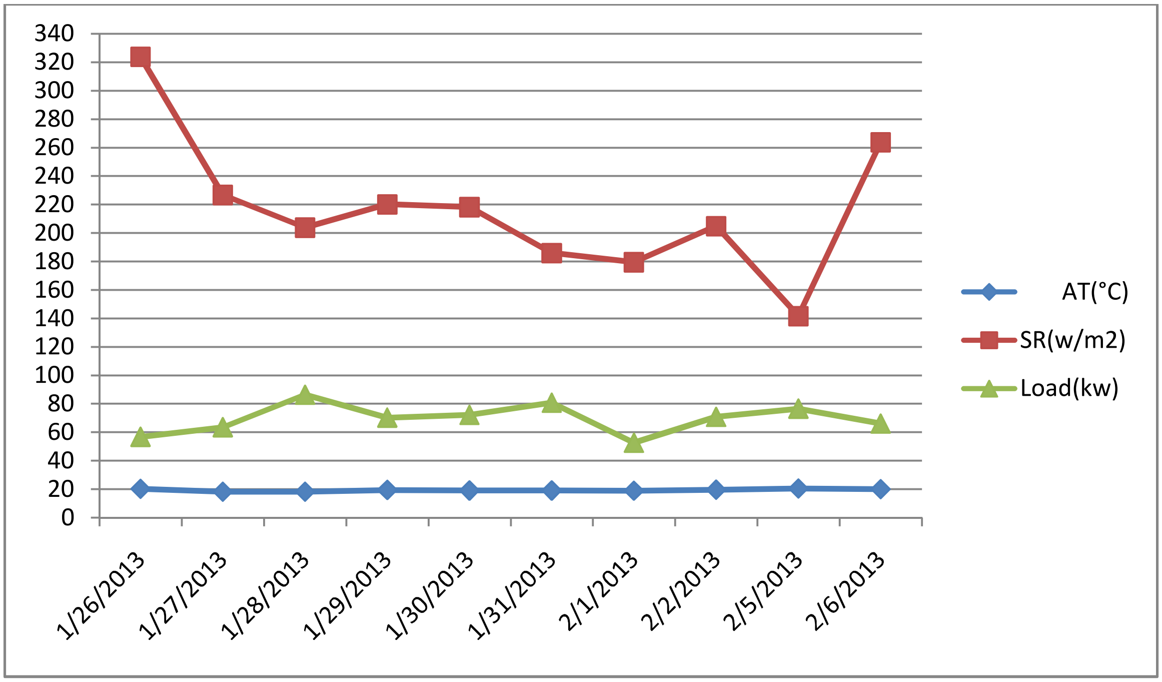


Graph: 1.1 shows: Variation of load, solar radiation and temperature on respective dates

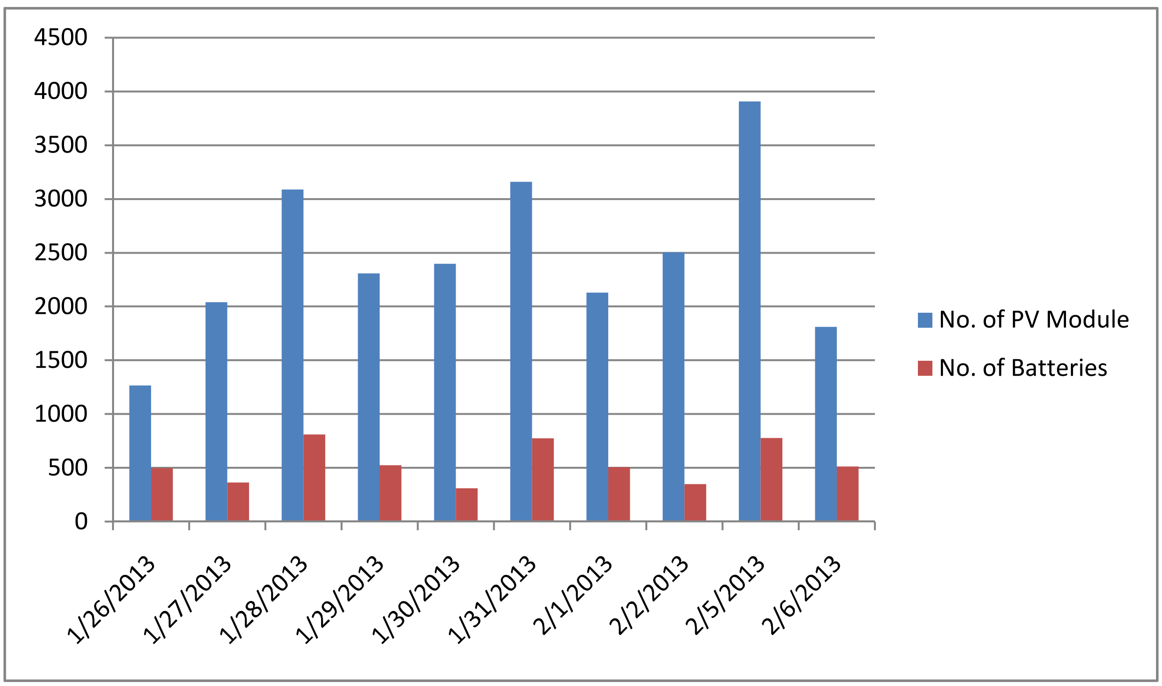


Graph: 1.1(a) shows: Required number of PV modules and batteries on respective dates

In graph 1.1 the minimum radiation is on 1/18/2013 correspondingly the maximum number of PV modules required shown on same day in graph 1.1(a) and maximum radiation is on 1/25/2013 correspondingly the minimum number of PV modules required shown on same day in graph 1.1(a)

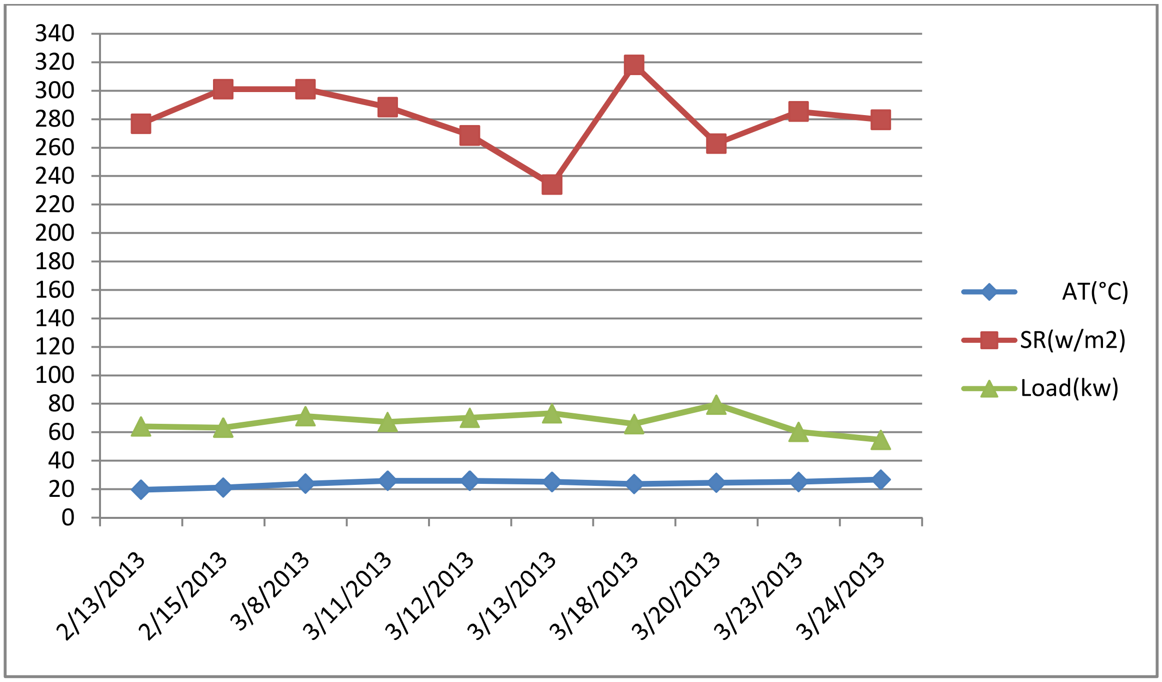


Graph: 2 shows: Variation of load, solar radiation and temperature on respective dates

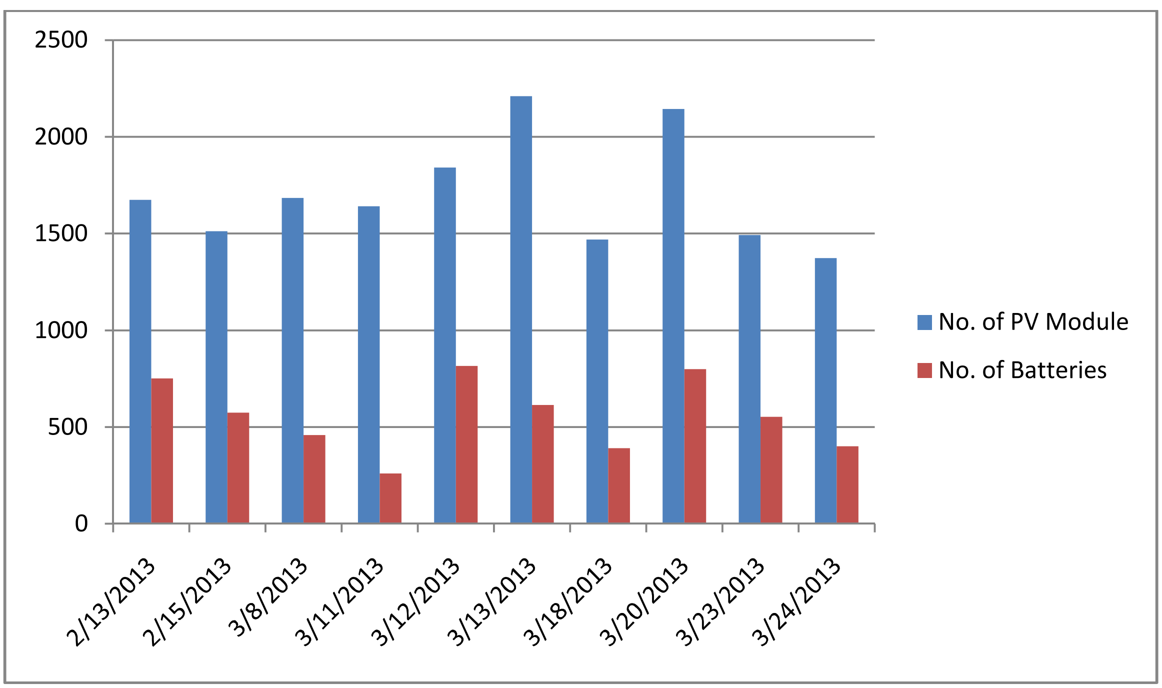


Graph: 2(a) shows: Required number of PV modules and batteries on respective dates

In graph 2 the minimum radiation is on 2/5/2013 correspondingly the maximum number of PV modules required shown on same day in graph 2(a) and maximum radiation is on 1/26/2013 correspondingly the minimum number of PV modules required shown on same day in graph 2(a)

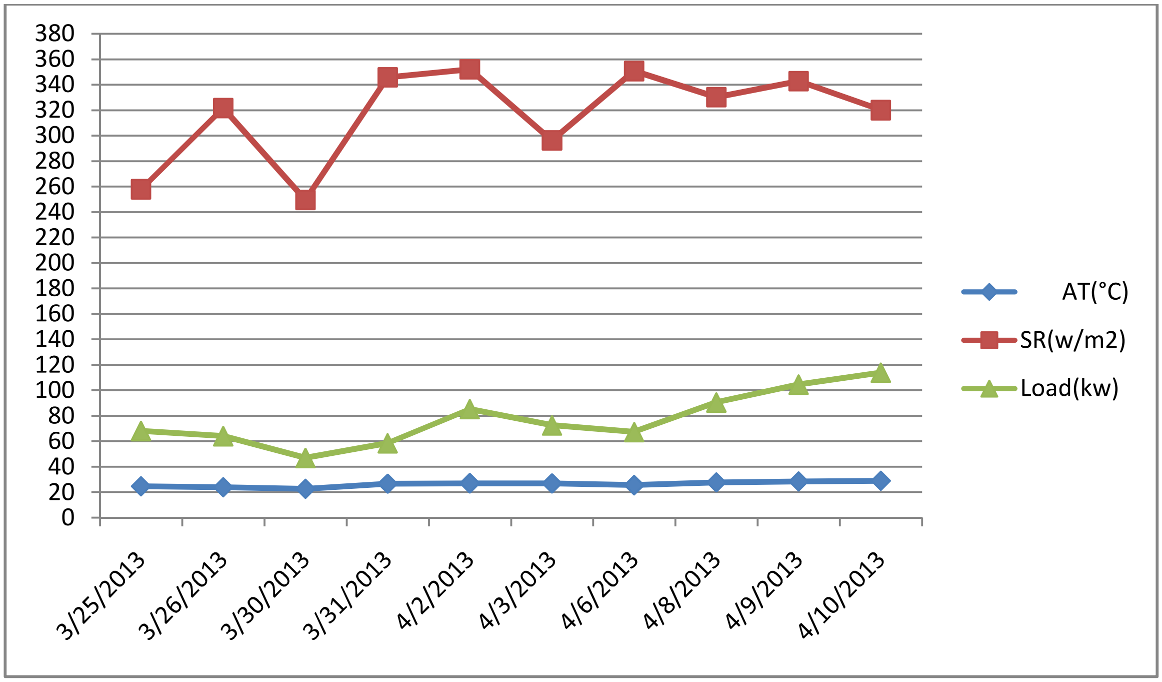


Graph: 2.1 shows: Variation of load, solar radiation and temperature on respective dates

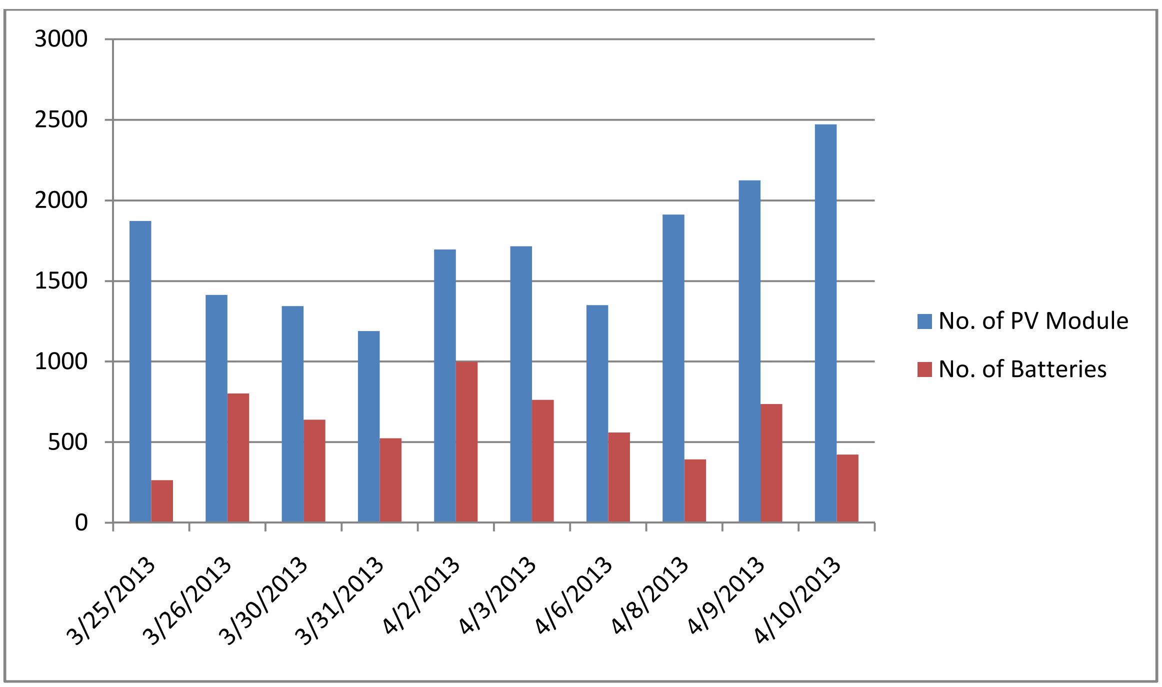


Graph: 2.1(a) shows: Required number of PV modules and batteries on respective dates

In graph 2.1 the minimum radiation is on 3/13/2013 correspondingly the maximum number of PV modules required shown on same day in graph 2.1(a) and minimum load is on 3/24/2013 correspondingly the minimum number of PV modules required shown on same day in graph 2.1(a)

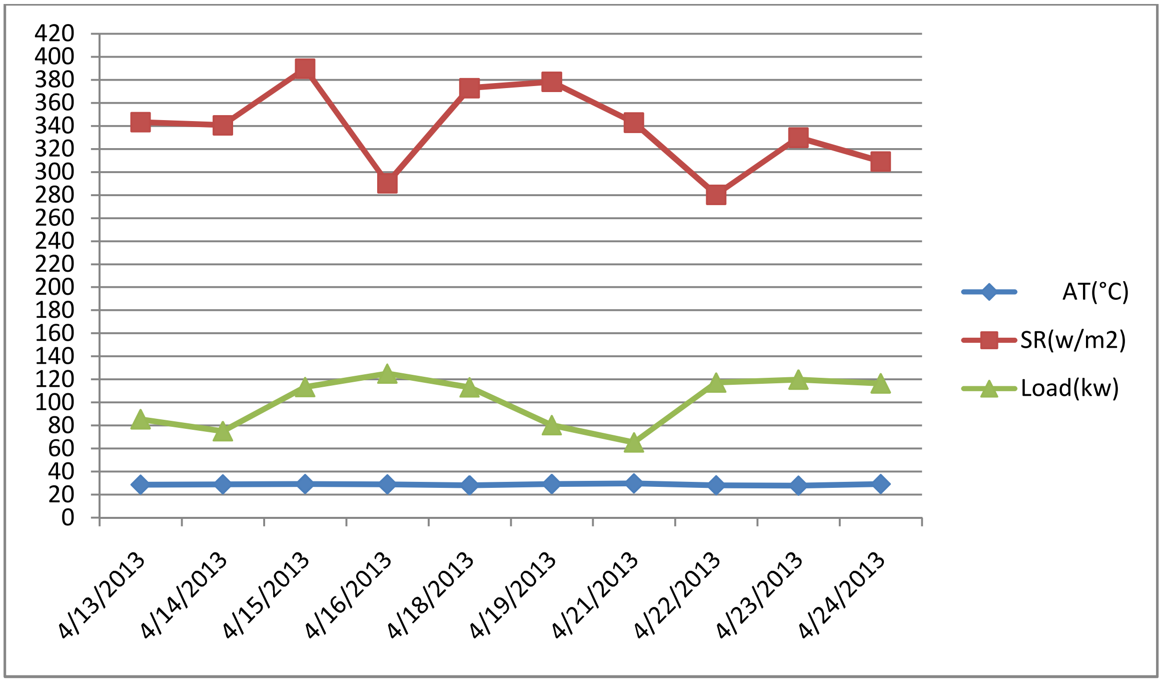


Graph: 3 shows: Variation of load, solar radiation and temperature on respective dates

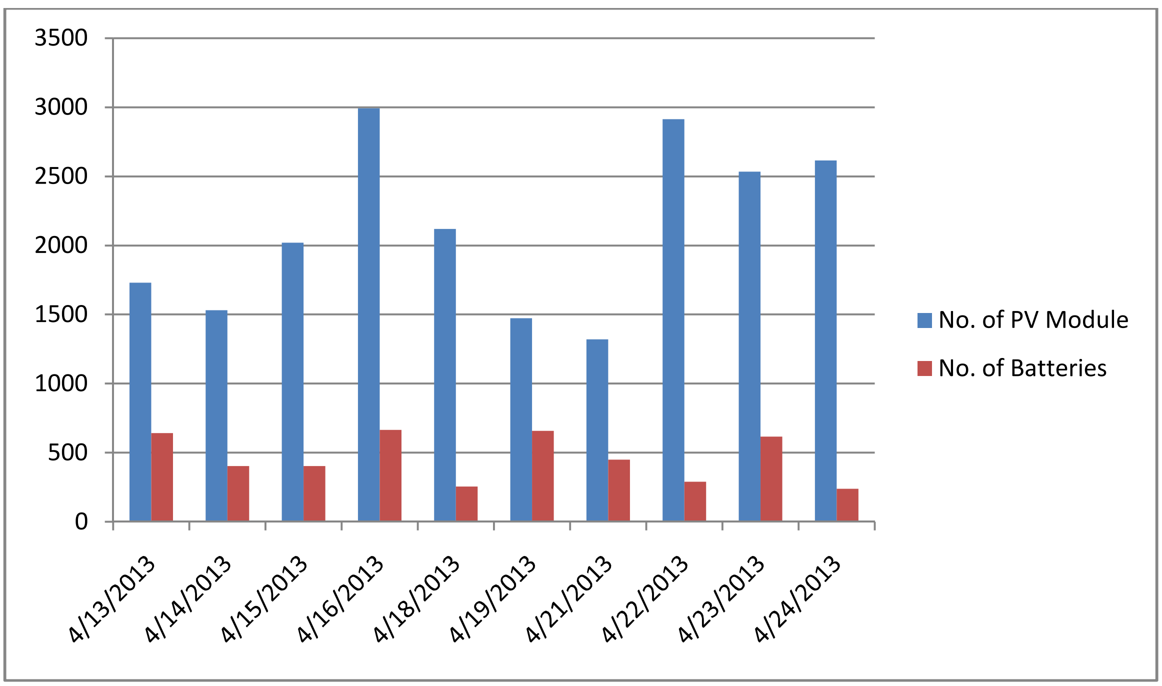


Graph: 3(a) shows: Required number of PV modules and batteries on respective dates

In graph 3 the maximum load is on 4/10/2013 correspondingly the maximum number of PV modules required shown on same day in graph 3(a)

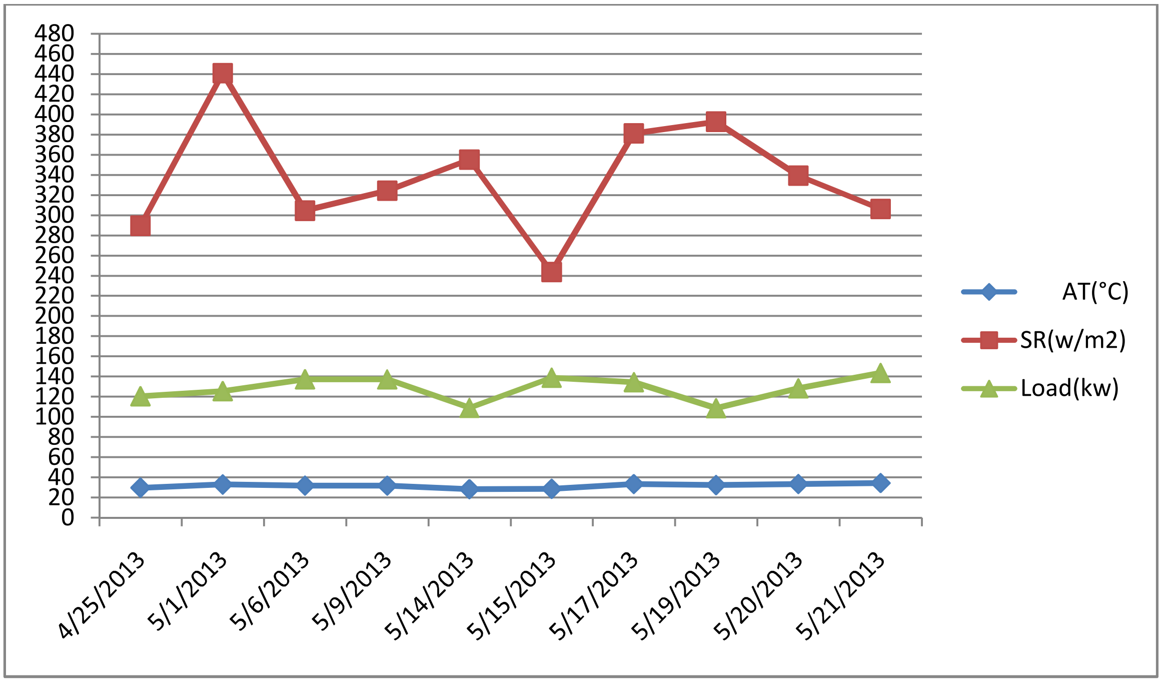


Graph: 3.1 shows: Variation of load, solar radiation and temperature on respective dates

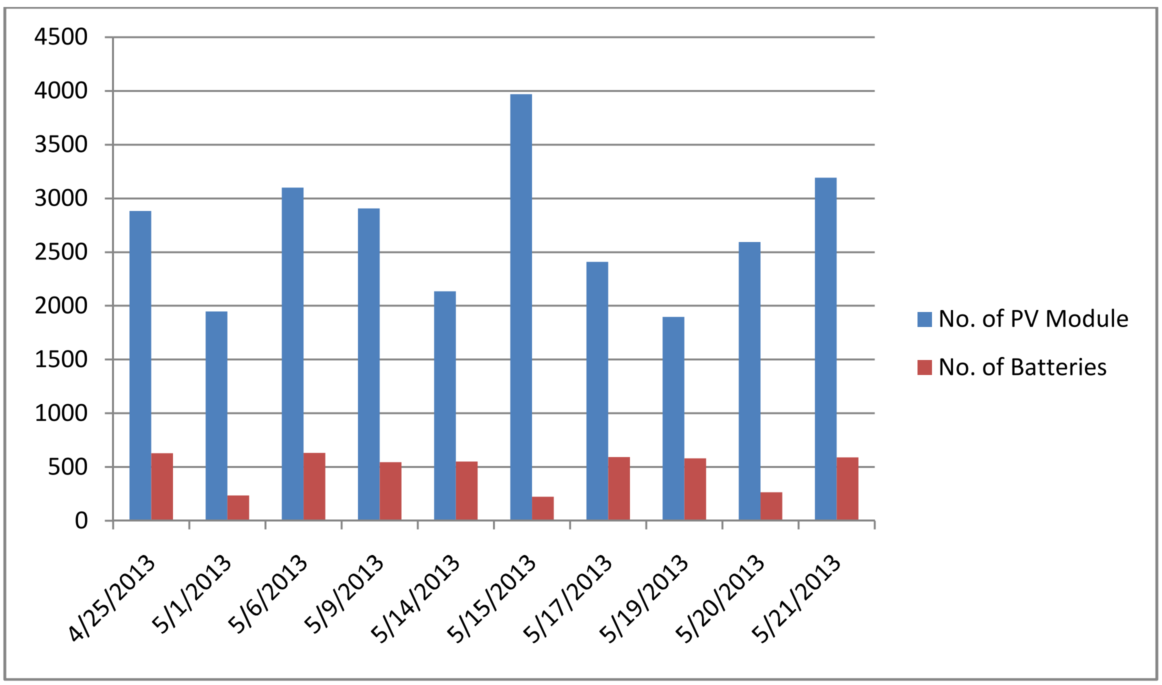


Graph: 3.1(a) shows: Required number of PV modules and batteries on respective dates

In graph 3.1 the maximum load is on 4/16/2013 correspondingly the maximum number of PV modules required shown on same day in graph 3.1(a)

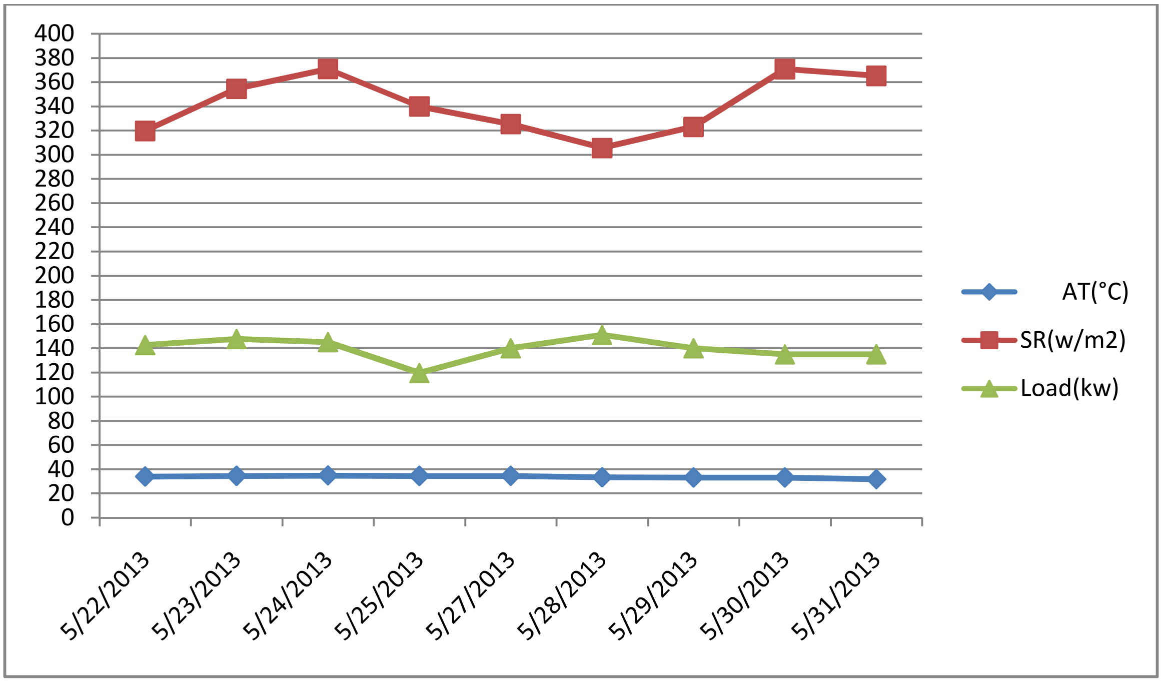


Graph: 4 shows: Variation of load, solar radiation and temperature on respective dates

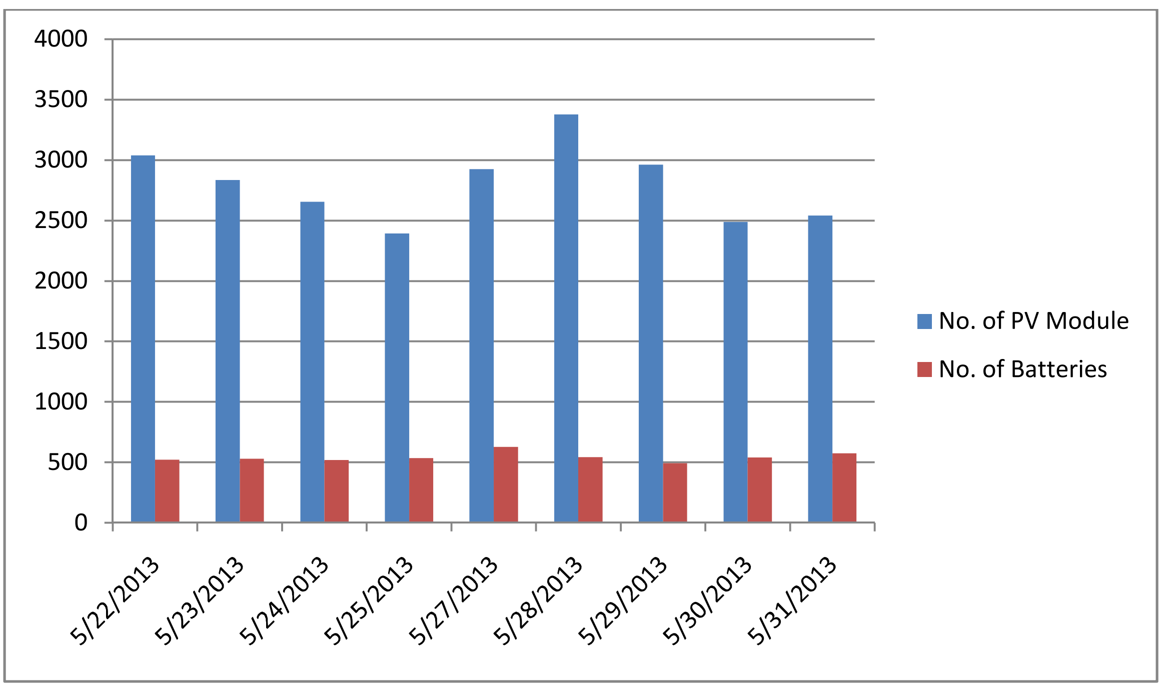


Graph: 4(a) shows: Required number of PV modules and batteries on respective dates

In graph 4 the minimum radiation is on 5/15/2013 correspondingly the maximum number of PV modules required shown on same day in graph 4(a)



Graph: 4.1 shows: Variation of load, solar radiation and temperature on respective dates



Graph: 4.1(a) shows: Required number of PV modules and batteries on respective dates

In graph 4 the minimum radiation is on 5/28/2013 correspondingly the maximum number of PV modules required shown on same day in graph 4.1(a)

Chapter 5

5.1 Conclusion

In this dissertation the sizing of photovoltaic system was done using linear programming. The Stand-alone solar PV systems with interconnected arrays have been investigated for optimal sizing of the array and battery bank. The loss of power supply probability (LPSP) is used to connote the risk of not satisfying the load demand. The computational scheme involves the linear programming techniques using simplex method and bears an objective to find out that optimum combination of the number of batteries and PV modules.

5.2 Future work

In the present work computation done only for non-tracking apertures are considered. For more reliable system single-axis tracking or multi-axis tracking system can be designed and it increases the output of the system. In case of battery as a back up or storage device, any other device like fuel cell can be used as storage device, diesel generator can be used as backup in case of autonomy days.

References:

1. Abu-Jasser Assad, " A Stand-Alone Photovoltaic System, Case study: A Residence in Gaza", Journal of Applied Sciences in Environmental Sanitation, Volume 5, January-March 2010, pp 81-92

2. Baochao Wang, Houssamo Issam, Sechilariu Manuela, Locment Fabrice, "A simple PV constrained production control strategy" Industrial Electronics (ISIE), 2012 IEEE International Symposium on Digital Object Identifier, May 28-31, 2012 , Page(s): 969 – 974

3. Borowy Bogdan S., Salameh Ziyad M., **"**Methodology for Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System" IEEE Transactions on Energy Conversion, Vol. 11, No. 2, June 1996, pp 367-375

4. Campoccia A., Favuzza S., Sanseverino E. Riva, Zizzo G. "Reliability Analysis of a Stand-Alone PV System for the Supply of a Remote Electric Load" SPEEDAM 2010 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, June 14-16,2010, Pisa, pp 158-163

5. Cano A., Jurado F., Sanchez H., Castañeda M., Fernández L. M., "Sizing and Energy Management of a Stand-Alone PV/Hydrogen/Battery-Based Hybrid System" International Symposium on Power Electronics, Electrical Drives, Automation and Motion(SPEEDAM),June 20-22, 2012 ,Sorrento, pp 969-973

6. Costello Frederick A., Macomber H. L., Ruzek John B. "Photovoltaic Stand-Alone Systems: Preliminary Engineering Design Handbook" U.S. Department of Energy Conservation and Renewable Energy Division of Solar Thermal Energy Systems, published by: National Technical Inst. Services August 1981

7. Delavaripour Hossein, Karshenas Hamid R., Bakhshai Alireza, Jain Praveen, "Optimum Battery Size Selection in Standalone Renewable Energy Systems", IEEE Telecommunication Energy Conference(INTELEC) , 2011, Amsterdam, pp 1-7

8. Dursun Erkan , Kilic Osman, “Comparative evaluation of different power management strategies of a stand-alone PV/Wind/PEMFC hybrid power system” International journal of Electrical Power and Energy Systems; Elsevier, vol 34, January 2012, pp 81-89

9. Duryea Shane, Islam Syed and Lawrance William “Battery Management System for Stand-alone PV Energy System” IEEE Industry Applications Magazine, May/June 2001, vol.7 pp 67-72

10. El Mohamed Badawe, Iqbal Tariq , Mann George K. I., “Optimization and Modeling of a stand-alone Wind/PV Hybrid Energy System” 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE),April 29, 2012, pp 1-6

11. Hansen Anca D., Sørensen Poul, Hansen Lars H., Bindner Henrik, “Models for a Stand-Alone PV System” Risø National Laboratory, Roskilde, Denmark, December 2000

12. Hong Wang, Donglai Zhang, “The Stand-alone PV Generation System with Parallel Battery Charger” International Conference on Electrical and Control Engineering, June 25-27, 2010, Wuhan, pp 4450-4453

13. IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems, IEEE Standards Coordinating Committee 21, IEEE Std 1562-2007

14. Jiyong Li, Honghua. Wang, “A Novel Stand-alone PV Generation System Based on Variable Step Size INC MPPT and SVPWM Control” IEEE 6th International conference on Power Electronics and Motion Control , 2009. (IPEMC '09), Wuhan, pp 2155 – 2160

15. Kaushika N.D., Gautam Nalin K., Kaushik Kshitiz, “Simulation Model for Sizing of Stand-alone Solar PV System with Interconnected Array” Solar Energy Materials & Solar Cells 85, 2005, pp 499–519

16. Kaushika N.D., Rai A.K., “Solar PV design aid expert system” Solar Energy Materials & Solar Cells 90, June 2006, pp 2829–2845

17. Kellogg W.D. , Nehrir M.H, Venkataramanan G., Gerez V., "Generation Unit Sizing and Cost Analysis for Stand-alone Wind, Photovoltaic, and Hybrid Wind -PV Systems" IEEE Transactions on Energy Conversion, Vol. 13, No. 1, March 1998, pp 70-75

18. Khatib Tamer, Mohamed Azah, Mahmoud M., Sopian K. "A New Approach for Optimal Sizing of Standalone Photovoltaic Systems" Hindawi Publishing Corporation International Journal of Photoenergy Volume 2012, Article ID 3912130, pp 1-7

19. Marwali M.K.C., Shahidehpour S.M., Daneshdoost M., "Probabilistic Production Costing for Photovoltaics Utility Systems with Battery Storage", IEEE Transactions on Energy Conversion, Vol. 12, No. 2, June 1997, pp 175-180

20. Rahmani R., Fard M., Shojaei A. A., Othman M. F., Yusof R., "A Complete Model of Stand-alone Photovoltaic Array in MATLAB-Simulink Environment" IEEE Student Conference on Research and Development, 2011 Malaysia, pp 46-51

21. Rizzo R., Munteanu C., Piegari L., Tricoli P., Topa V., " Sizing of Photovoltaic Sources and Storage Devices for Stand-alone Power Plants" 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania, pp 1-6

22. Rong-Jong Wai, Wen-Hung Wang, Chung-You Lin, "High-Performance Stand-Alone Photovoltaic Generation System", IEEE Transactions on Industrial Electronics, VOL. 55, JANUARY 2008 pp 240-250

23. Saengthong S., Premrudeepreechacham S., "A Simple Method In Sizing Related To The Reliability Supply Of Small Stand-alone Photovoltaic Systems" Conference on Photovoltaic Energy Conversion May 11-18, 2003 Osaka, Japan, pp 1630-1633

24. Weixiang Shen, "Design of standalone photovoltaic system at minimum cost in Malaysia" Industrial Electronics and Applications, 2008. ICIEA 2008. 3rd IEEE Conference on 3-5 June 2008, Singapore, pp 702 – 707

25. Xiong Liu, Peng Wang, Poh Chiang Loh, "Optimal Coordination Control for Stand-alone PV System with Nonlinear Load" International Power and Energy Conference, Oct 27-29, 2010, Singapore, pp 104-109

26. Yu Ru, Kleissl Jan, Martinez Sonia, "Storage Size Determination for Grid-ConnectedPhotovoltaic Systems", IEEE Transactions on Sustainable Energy, January 2012, pp 68-81