POWER FLOW MANAGEMENT AND DC BUS STABILIZATION FOR SPV BASED BATTERY ENERGY STORAGE SYSTEM

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT
FOR THE AWARD OF THE DEGREE
OF
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IN
POWER SYSTEM

Submitted by:
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CANDIDATE'S DECLARATION

I, Anupam, Roll No. 2K20/PSY/05, a student of M. Tech (Power System Engineering), hereby declare that the Major project II Dissertation titled "Power Flow Management and DC bus Stabilization for SPV Based Battery Energy Storage System" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation.
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Place: New Delhi
Date: 2022

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CERTIFICATE

We hereby certify that the major project II titled "Power Flow Management and DC bus Stabilization for SPV based Battery Energy Storage System" which is submitted by ANUPAM (2K20/PSY/05) belonging to Master of Technology, Power System, Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of Master of Technology is a record of the project work carried out by the student under our supervision. To the best of our knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: New Delhi
Date: 2022

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ABSTRACT

Solar photovoltaic energy has gained a significant popularity and attention due to its capability of generating electricity by using solar cells to convert solar irradiance into electricity. Now a days photovoltaic (PV) energy generation has a great commercial and academic interest. Recent studies indicate that in longer term PV generation will become technically and commercially feasible to be implement for electricity generation. According to various data, many portions of India, particularly rural and island areas, have either little or no access to power. The fundamental reason for this situation is the large distance between the power plants and distribution hubs in these rural and remote areas. This emphasizes the significance of power generation subsidiarity using renewable energy supplies. Although electricity is mostly supplied by AC current in today's power generation scenario, a wide range of common utility items, such as cell phone chargers, computers, laptop chargers, and so on, all operate on DC power internally. By providing DC power to the listed devices, the number of intermediary energy transfer stages is greatly reduced. Other works cited in this research work demonstrate a gain in total system efficiency and cost reduction. With an abundance of solar irradiance availability and significant advancements in the field of power electronic conversion devices, DC grid can be utilised to power remote or rural place using solar PV power. With the help of an solar PV (SPV) with battery energy storage system (BESS) and appropriate power electronic conversion devices at each load point, a system for a household that is not connected to the main grid can be successfully simulated for various loads.

The main purpose of this research is to study the performance of PV arrays under various irradiance and to stabilize the DC bus at various voltage levels. The DC output of the PV array is boosted to 48 volts using DC-DC converter and MPPT perturb and observe (P&O) algorithm. The bidirectional converter is used in this model to regulate the bus voltage and for power flow balance between PV power generation and load power requirement. Battery energy storage is also used for the effectiveness of the system. During the course of this research, we have explored the application of power electronic approaches for array configuration, MPPT tracking and stabilization of DC bus.

With the increase penetration of renewables in the grid, different ways of integrating them are being researched for stabilizing the system operation. In case of DC micro grid, distributed energy resources (DERs) can be connected in parallel to a common DC bus to improve the stability of the system.

This Dissertation work “Power Flow Management and DC bus Stabilization for SPV based Battery Energy Storage System” mainly focuses to construct the DC electrification in homes. Its application mainly focuses in rural electrification and remote urban houses. Moreover, the topology can be able to develop an efficient and reliable DC powered house loads. The work mainly focuses for the stabilization of DC bus at all the three levels of voltages (i.e. 24V, 48V, and 310V). This project is simulated under Simulink platform with DC as well as AC electrification. From the results and calculation it is observed that, DC electrification with the SPV array and battery is more economically feasible compared to existing AC system.

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LIST OF ABBREVIATIONS

SOC	State of charge
BESS	Battery Energy Storage System
SPV	Solar Photovoltaic
LVDC	Low voltage DC
MVDC	Medium voltage DC
NNE	Null Net Energy
BCM	Bus converter Module
CC	Constant Current
CV	Constant Voltage
ESU	Energy Storage Unit
MPPT	Maximum Power Point tracking
P &O	Perturbation and Observation
PWM	Pulse width Modulation
DOD	Depth of Discharge
VRLA	Valve Regulated Lead Acid
SOH	State of health
EOL	End of Line
SST	Solid State Transformer
Z_L	Load impedance
Z_m	Measuring Impedance
Z_{set}	Setting Impedance
CT	Current transformer
VT	Voltage transformer

LIST OF SYMBOLS

V_L	Inductor voltage
V_o	Load voltage
V_{in}	Input voltage
V_c	Capacitor voltage
R_L	Load resistance
I_{in}	Input current
I_c	Capacitor current
L	Inductor
C	Capacitor
V_g	Output voltage of bidirectional converter
C_{i_bat}	Input capacitance of bidirectional converter
C_{o_bat}	Output capacitance of bidirectional Converter
I_{batt}	Average Battery current
V_{ref}	Reference voltage
$V_{carrier}$	Carrier voltage
P_{spv}	Power of Solar photovoltaic array
P_{load}	Load power
SOC_{batt}^{max}	SOC of battery at Maximum threshold value.
SOC_{batt}^{min}	SOC of battery at Minimum threshold value.
P_{cables}	Power of cable

CHAPTER-1

INTRODUCTION AND REVIEW OF LITERATURE

1.1 Introduction

Due to the depletion of fossil fuels and conventional sources of reserves, the concern for building an emission free environment has grown. More than half of the world is still in the requirement of electricity and there areas are far away from the grid. One of the major benefits of installing a DC off grid is that it can be coupled directly from the renewable energy sources. It is very good opportunities to begin with the application of renewable energy technologies in the area where the grid could not able to penetrate. Though almost all of the basic household appliances like led, cellphone chargers, T.V etc. Consumes DC, so it's easy to integrate these devices with renewable energy technologies like solar PV and BESS [1].

With the increasing demand of electricity, DC grid is gaining more importance these days. The research is further being continued in this area by developing countries to carry out the changes in building electrification. DC electrification is considerable for both rural as well as urban areas. The most of the electronic appliances used today in our households are electronic in nature which operates on DC. The AC voltages are drawn by these appliances and converted into low voltage DC using rectifiers. The conversion and its losses would have avoided if the electrification is DC. The renewable sources of energy is increasing in both standalone as well as grid connected modes of operation. The BESS are further interconnected via DC-DC converters for high reliability of power supply to the loads. In order to improve the efficiency and stability of renewable energy system, power flow management is the primary condition. Moreover, the enhancement of power electronic interfaces in a DC grid facilitates the control of SPV system and charging/discharging process of BESS [2], [3].

Power flow in the system and its control get balanced under varying irradiances and load conditions. The DC bus voltage is required major attention in order to improve SPV system stability. Power management of the system is improved with the help of battery energy storage device along with bidirectional converter. The reliable operation of DC grid under different operating condition is ensured with the help of power management and coordination control. The DC voltage will remain below the acceptable limits along with the maintenance of system power balance in both islanded as well as grid connected modes.

The state of charge (SOC) of an energy storage device will be used to obtain safe charging/discharging limits. The slope of SOC measures the battery charging/discharging rate. During day time, the SPV provides electricity to the load as well as charges the battery. The bidirectional converter during day-time act as buck mode while charging the battery, and in night time it acts as boost mode and discharges the battery to the DC load [4].

1.2 Objective of Research

The main purpose of designing DC house to power the houses in rural as well as not so developed urban area. With the help of DC electrification it allows unfortunate houses to improve their living style. Positive impact on rural electrification has observed with the help of power electronics equipment and DC distribution system. The feasibility of DC houses has been investigated for various level of voltages (i.e. 24V, 48V and 310V). It will be observed from the result that bus at different voltage level is maintained constant at different load with varying time and irradiances. Voltage level with different DC distribution system are explained below

A) 24V DC Voltage:

This Voltage level is one of the proposed voltage at which DC distribution is most feasible for low voltage DC appliances. The following reasons are follows:

1) Most suitable voltages for all low voltage DC appliances and electronic equipment's.
2) Losses and voltage drops across the 24V DC is lesser when compared for the LVDC appliances when connected across AC voltage.
3) Safety level of 24V DC bus is more for electronic equipment's than other high level of DC voltages.
4) 24V DC bus Short circuit current is lesser when compared with the other low voltages i.e. 12V.

One of the fact that under normal circumstances voltages below 24V DC are safer and reliable. Furthermore, the voltages below 24V DC does not required any special measures to protect against direct and indirect touch. Moreover, the conductors here are required to be protected against overcurrent's and short circuits. In addition, there is requirement that voltage losses in the conductors should not malfunction the household appliances which directly runs with AC supply.

B) 48V DC Voltage:

This voltage level is used as the main bus from where the other voltage bus is drawn, 48V DC voltage is considered to be safest voltage for human being with direct contact up to 3-5 seconds. It has made evaluation between 230V AC with 24V DC and 48V DC distribution. It has been observed that number of converter has also reduced significantly. From the researches it is observed 48V DC bus is most suitable and reliable for various home appliances. Various bus voltage level is also extracted from this standard voltage bus. Investigation has also done with existing motor that is replaced by brushless Direct current (BLDC) motors. It is observed that efficiency of BLDC appliances is much better than conventional motors and compatibility of BLDC motors with 48V is much more efficient than conventional electrification.

C) 310V DC Voltage:

This is one of the most suitable voltage level for high voltage household loads such as refrigerators, air conditioners and washing machines. The conversion steps of AC to DC is removed. The replacement cost of the DC system is less than the other system because most of the existing appliances do not requires cables and circuit. The 230V AC appliances insulation can easily withstand up to 310V DC without any rupture. 310V DC voltage is the best chosen for supply power to high level voltage. Due to the reduced number of converters and higher efficiency, battery backup is further increases the reliability in the critical conditions. DC home is the new concept of DC grid distribution system to operate as standalone system with and without grid. The choice of 310V DC is made to supply power to data centres and other high voltage telecom appliances in IT industries.

1.3 Advantages of DC Electrifications

From past few years, the data centres and telecom servers in the IT industries are increasing continuously. These applications are inherently DC and very similar to the other high rating DC appliances. For the purpose of 310V DC distribution data centres and telecom industries are greatly looking for the most energy efficient option to establish and supply their servers. 310V DC distribution is being chosen as standardized distribution and proven to show the increment of efficiency about 5 to 8%. DC distribution system is more efficient because of its less number of conversion stages when compared to AC distribution. Three conversion stages are required for AC distribution for supplying power to data centres and telecom devices. AC distribution needs rectifier circuit to charge the battery storage system which is DC in nature. Inverter is required for utilising the stored energy from the battery and finally all the electronics item requires AC-DC conversion units and buck converters. Each conversion stages add losses in the connection and also there will be lot of issues will arise such as reliability issues, harmonic imbalances etc. 310-350V DC voltages are considered to be most feasible for the electricity distribution in offices and residential premises.

Merits of DC house electrification:

1) Better safety and less prone to electric shock.
2) Energy efficient (energy will increases up to 30%).
3) Appliances life will increase significantly.
4) Manufacturing cost of consumer appliances will decreases.
5) More compatible with renewable energy sources.

1.4 Challenges of DC Electrification

Safety features is one of the major aspects of DC distribution. For the DC distribution, the safety devices are not widely available at this moment. Only the few companies manufacture these type of devices according to the consumer requirements. 310V DC is one of the most predominant voltage level in DC distribution. 310V DC level of voltage is considered to be low enough to provide safe transmission and high enough to reduce the conductors cost. The researches is still going on for this standardized level of voltage. Following safety issues are concern for the DC distribution:

a) Zero crossing are absent in DC current and voltages.
b) Occurrence of arc will take place while instant switching.

The challenges of DC distribution is in applications and its compatibility with daily appliances. The main challenge of DC distribution is that it requires bus converter module (BCM), if distribution voltage exceeds the safety limits.

Demerits of DC house electrification:

1) Application and manufacturing of DC appliances are not very common in industry.
2) The existing infrastructure need to be upgraded for DC system/DC distribution.
3) Conductor size increases due to high current.

1.5 Concept of standalone DC grid

DC grid is small scale power grids which can be used in the remote locations or rural areas to supply power for particular consumers. DC grid can easily be integrated in the smart grid applications whose concept becomes more important and familiar to various areas. One of the major benefits of DC grid is that it can be easily installed at islands, mountains and remote locations where the unavailability of grid structure [5], [6]. The DC- grid increases the economics and operational efficiency when connected to the grid or power supply. DC grid supply a reliable, efficient and secured electric power at islands, mountains and remote locations without connecting with the utility grid. The second part of research is further based upon the DC distribution system which are classified into DC and AC electrification. The AC electrification further requires two stage of conversion to provide power to the load and appliances. For AC electrification there is requirement of protection and standards, bus synchronization, stability and need for reactive power. Moreover, DC electrifications have no such requirements. In addition, DC electrification with SPV based system eliminates DC/AC or AC/DC power conversion stages which were required in AC electrification to integrate the renewable energy source, loads and battery energy storage device. The DC grid have the advantages in terms of cost, efficiency, and system size. Moreover, DC based grids need further research about operating range of DC voltage and protection equipment's for DC circuits. In this research work, a standalone DC grid consists of SPV array and battery energy storage system as the energy source. AC loads and DC loads are further considered for three level of voltages i.e. 24V, 48V and 310V which is explained in chapter IV. Hybrid electrification are explained in chapter V, where the voltage level of 230V, 48V and 24V are considered. The entire models are validated under the Simulink/MATLAB to investigate the operation of DC- grid in different situations and modes of operations. Furthermore, the PV module is controlled by using perturbation and observation method and BESS is used with bidirectional operation to charge/discharge in case of excess/ shortage of the generating power respectively. When the voltage at DC bus is maintained constant at 48V, it helps the power electronic converters and inverters operation to work more efficiently and effectively at constant duty ratios, this helps the reduction of switching losses, harmonics and fluctuations.

1.6 Organization of Dissertation

This organization of dissertation follows the six chapters which are assembled in the following manner:

CHAPTER 1: The first chapter outlined with introduction, research objective and concept of DC grids. This chapter further describes the advantages and challenges of DC electrification. Furthermore this section organised with dissertation outlining and literature review.

CHAPTER 2: The second chapter outlined with the system components and its description. The description includes solar PV array, maximum power point tracking, modelling of DC-DC converters and loads used in the household applications.

CHAPTER 3: The third chapter discusses about the battery energy storage system**,** charging algorithm and power management of DC and AC electrifications. It has discussed the safety requirements which need for electrify and design the DC house. It includes modelling and design of lead acid battery. Further, it also explained the construction details, charging algorithm and power management scheme for DC grid.

CHAPTER 4: The fourth chapter is outlined with system model integration and simulation which includes architecture, benefits and challenges of DC grid. It includes application and efficiency improvement of DC grid. This chapter also discusses protection scheme with simulation design and results with various level of voltage.

CHAPTER 5: The fifth chapter is outlined with system model integration and simulation which includes the AC electrification from the standalone PV based system. This chapter also discusses the inverters and battery used in this system. Furthermore, it gives the outlining of (CC/CV) charging algorithm. Control objectives and case studies are also explained for AC and DC loads during day time and night time both.

CHAPTER 6: This chapter summarizes the whole research work with its practical implications for future work.

1.7 Literature Review

1) H.K. Mahore and V. Dake have worked on "Modelling and analysis of grid-integrated solar system with power management scheme using battery". This research area is basically focuses on the modelling of solar system with energy management scheme using battery energy storage device. The battery connected to the system provides a constant and valid power output from solar radiation despite of its continuous variations from PV array.
2) Alias khamis and Azah Mohamed have worked on "Single phase grid connection using solar photovoltaic array and battery based power generation". This research work focuses on stability operation during the faults and network disturbances in grid. This paper further discusses the PV array connection with MPPT and step up converter to optimize the solar PV output and DC/AC inverter to convert the DC output voltage of solar module into AC electrifications. They also proposes the ideas of battery storage connection with common DC bus using charge controller for supporting the bus stability during night time.
3) 'Mayank Kumar' have worked on "Solar PV based DC micro grid under partial shading condition with battery Energy management system". This research work focusses on extraction of optimal power from Solar PV array under partial shading conditions (PSCs). Further, this work also discusses on the improvement of reliability and power quality to the end users. The analysis of bidirectional converter is also done which is used to regulate the isolated DC bus voltage and maintains the power balancing between PV power generation and load power demand for surplus and deficit power conditions by charging and discharging of battery. Different controller design aspects are also proposed here to balance the load power requirement with respect to the availability of source power and SOC of the battery.
4) 'Deepak Singh', 'Alok Agarwal' and 'Rajesh gupta' have worked on "Power Management in Solar PV fed micro grid system with battery storage support". This research work focusses on the renewable energy installation at single phase residential premises for the need of power management and coordination control of operating system. He also discusses the various components applications in the

research work which includes Solar PV (MPPT) via boost converters, bidirectional DC-DC converters for battery charging applications and bi-directional AC-DC converters for feeding AC loads. This research work further elaborates the standalone solar PV system with power management scheme. It also explained the SPWM scheme, which used to control AC side voltage operating in islanded mode. During the day time, system will work in islanded mode where excess/deficit of power exchanged with energy storage unit (ESU).

5) 'Ahmed Shaniqua Anees' have worked on "Grid Integration of Renewable Energy Source: Challenges, Issues and possible solutions." This research work focuses on various issues related to grid integration of RES. They have also discussed on the large and small scale power generations. Further they have explained the challenges encountered during integration of renewable energy sources with possible solutions.
6) 'Sangsoo Park' and 'Sang-yung Kim' have worked on "Hardware Implementation of optimization technique based sensor less MPPT". This work gives the analysis for finding maximum power point for the PV system. It also describes the method of non-linear optimization algorithm which is a powerful tool for designing the sensor less MPPT for tracking maximum power.
7) 'P.GAYATHRI' and 'Dr. B. Ashok Kumar' have worked on the "Control of DC link voltage of single phase grid connected to solar PV system" which shows the effectiveness of standalone PV system under varying atmospheric conditions. This research further explains output voltages variation and efficiency of the converter for SPV array to obtain maximum output power from the solar photovoltaic array.
8) 'Akel Fethi' and 'Berhouk El-madjid' have worked on the "power control of three phase single stage grid connected photovoltaic system". This research work focuses on the power flow control in single stage photovoltaic energy conversion system. The research work investigated the control strategy for active and reactive power with desired performances for different constraints in a single grid stage of PV grid structure. This research work also explains the control system structure which effectively tracks the maximum possible power of PV generation irrespective of solar irradiance and temperature conditions.
9) 'Lalit Mohan Satapathy' and 'Annadanapu Harshita' have worked on the "Comparative analysis of boost and buck-boost converter in photovoltaic power system under varying irradiance using MPPT". This research work further shows the modelling and simulation of standalone solar PV system to analyse the performance of boost or buck-boost converters under varying irradiance with varying load. The mppt algorithm uses to track the maximum power point and control the DC-DC converter. A pulse width modulation scheme is used for controlling the DC-DC converter. This work also give the analysis on inverter which is connected with LCL filter in order to reduce the harmonics. Further the analysis and comparison has done on the voltage fluctuation of phase voltage produced by boost converters and voltage produced by buck-boost converter.
10) 'Adel Merabet' and 'Rupak kanti Dhar' have worked on the 'Solar photovoltaic micro grid simulation platform for energy Management Testing'. This research work mainly focusses on the integration of distributed energy sources with battery storage

system with their ability to perform in islanded and grid-tied mode. It gives the analysis of Power electronic converters whose monitoring based upon the SCADA. This research work further investigates the adaptability and capability of solar photovoltaic microgrid platform with various situation.

1.8 Project Overview

The main purpose of designing DC house to power the houses in rural as well as not so developed urban area. With the help of DC electrification it allows unfortunate houses to improve their living style. Positive impact on rural electrification has observed with the help of power electronics equipment and DC distribution system. The feasibility of DC houses has been investigated for various level of voltages. It will be observed from the result that bus at voltage level 24V, 48V and 310V is maintained constant with varying loads and irradiances with switching time t= 2 ,2.5 and 3 seconds respectively.

CHAPTER 2

SOLAR PV SYSTEM

2.1 Introduction

Due to the depletion of fossil fuel reserves, the concern has increased for the creation of an emission free environment. This concern is trying to push the entire mankind towards renewable energies and new technologies. With the help of power electronic devices and their implementation we are moving towards the new world. Among all kind of renewable energy, the solar based PV distributed power is one of the fastest, cheapest to implement and efficient in operation [7]. A target of 2000Mwp has kept for off-grid solar PV applications which covers the applications of solar power plants, solar street lighting, solar home lighting, solar pumps, solar lanterns and solar study lamps. 200Mwp was kept for mission under the phase-1 from 2010-13, 253Mwp sanctioned under phase-2 from 2013-17, a target of 500Mwp achieved for phase-3 for off-grid. Under PM KUSUM scheme, a target of 118MW is to achieve excluding solar pumps. Under 'Saubhagya' scheme which comes under ministry of power, installation of solar home lights were targeted. [https://mnre.gov.in/solar/solar-offgrid]. The application wise status of solar plant installation under off-grid and decentralised PV application is mentioned in table 1.1.

TABLE 1.1
Solar System Vs No. of Units/Capacity Installed

System	No. of units/capacity installed
Solar Lamps/ Lanterns	65,18,000
Solar pumps	2,38,000
Solar street Lightings	6,72,000
Solar Home Lightings	17,16,000
Solar Power Plants	212 Mwp

One of the major advantage of using solar energy is that it can be applicable in both islanded and grid mode of operation. With the help of power electronic equipment's and devices, the DC grid integration with the DC appliances can be done easily [12], [13].

With the advent of battery storage system along with buck-boost converter, the power management for the DC grid has improved considerably. The power management with the help of coordination control assures the reliable operation of solar based standalone DC grid under various circumstances. This research work mainly focuses on DC grid voltage stability at various voltage level with changing load. DC loads have been considered for three different voltage levels-48V (representing medium voltage residential DC appliances), 24V (representing low voltage residential DC appliances) and 310V (representing high voltage residential DC appliances). The state of charge (SOC) of battery energy storage system indicates the safe charging / discharging limits. The slope of SOC indicates the rate of charging/discharging limits. Voltage of DC grid is controlled by balancing the power produced via solar PV, BESS, and load consumption [14].

This work focuses on the solar PV array, battery energy storage system, power electronic converters and control system for managing the power supply. Further analysis has been done on MPPT, DC-DC converter and loads considered for household appliances.

2.2 Solar Photovoltaic

Single cell of SPV array used to generate the power of 0.5W to 1.5W depends upon the surface area. With the help of SPV modules the output power is stepped up by interlinking the PV cells in series and parallel as shown in figure 2.1. PV cells electrically connected in series and/or parallel in order to generate high voltages, high current and power. The presence of PV cells in the solar modules to absorb sunlight. The energy absorbed from the PV cells are in the form of photons of light which is transferred to the semiconductor material. Electrons flows through semiconductor material in the form of electric current. Each PV module of solar is rated in the range of 50 to 400W. When the multiple number of PV cells are collected in a single entity is known as PV module. Integration of multiple number of PV modules is known as photovoltaic panels. Integration of required number of PV panels gives the complete power generating unit known as photovoltaic array. The accomplishment of PV module and arrays are rated according to their DC power output within standard temperature conditions (STC). STC are defined by PV module (cell), operating temperature of 25° Celsius and incident solar irradiance of (1000W/m2). While working of this PV module and arrays, the performance of STC rating will work at 85 to 90% of the actual rating.

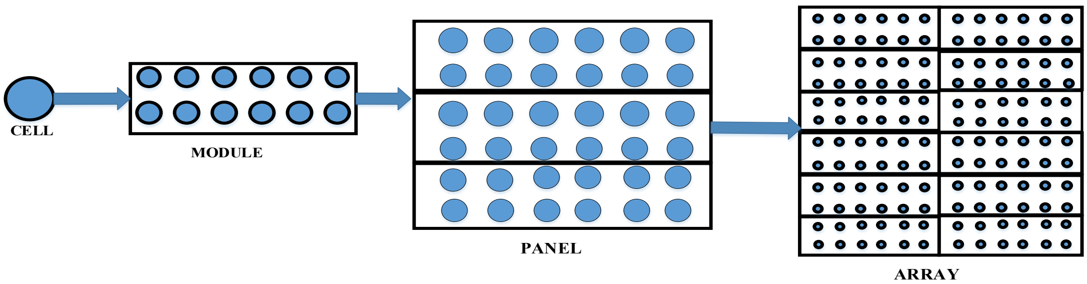

Figure 2.1 Photovoltaic cell, module, panel and array

2.2.1 Construction of Solar PV Module

Construction of Solar cell is based upon crystalline silicon which consists of n-type semiconductor. This cell is made up of three layer. The P-N junction formation takes place by these three layers, first or upper layer is known as emitter layer, second layer is p-type layers which is also called to be base layer and the third layer is the sandwiched layer where both the n-type and p-type layer are sandwiched. The anti-reflection coating is coated over the surface to avoid the loss of incident light energy due to reflection. Electron which is created on the n-type side, or created on the p-type side get collected by the junction and swept entire electron onto the n-type side, which travels through the wire and power the load. These power continues through the wire till its reaches to p-type semiconductor-metal contacts. Electrons when get recombined with the holes make electron-hole pairs on the p-type side of the solar cell, or a hole which has swept across the junction from n-type side after being created there.

Figure 2.2 shows the photovoltaic effect with energy conversion Photovoltaic module has the composition of a group of solar cells. Solar cell is a device that directly converts light energy into electrical energy .With the use of photovoltaic effect, the arrangement of solar cell is done into large groups called arrays. The arrays have the composition of large no. of individual cells which converts the sunlight into electrical energy. The converted electrical energy is further distributed into industrial, commercial and residential premises. The equivalent circuit of ideal PV cell is represented in figure 2.3. Non-ideal conditions is assumed for SPV cell modelling. The shunt and series resistances are included in the model, Rsh represents high value equivalent shunt resistance and Rs represents Small value of equivalent series resistance. The equations depicting the relationship between solar cell current and voltages are given below,

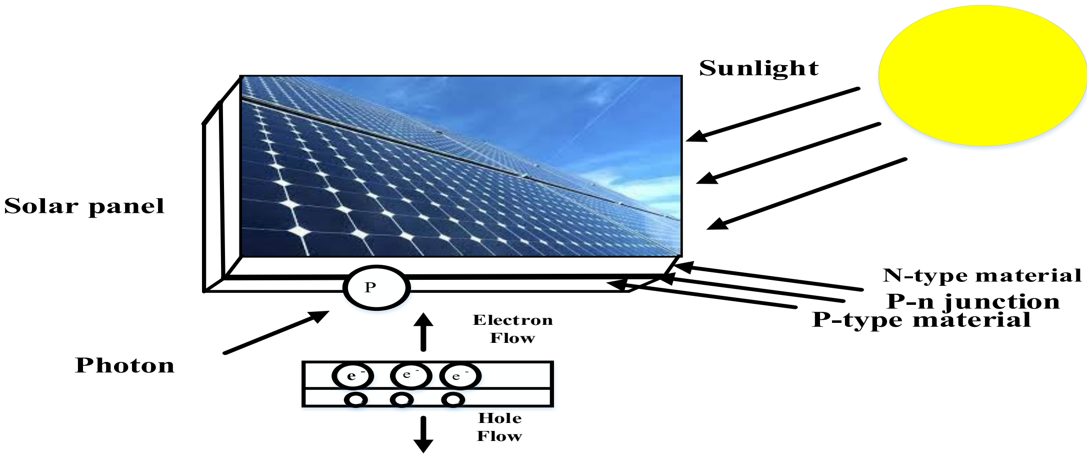

Figure 2.2: Photovoltaic effect with energy conversion

$$I_{ph} = I_d + I_{R_{sh}} + I_{pv} \tag{2.1}$$

$$I_{pv} = I_{ph} - I_d - I_{R_{sh}} \tag{2.2}$$

$$Ipv = Iph - I_o e[\frac{q(Vpv + IpvRs)}{nKT}] - \frac{Vpv + IpvRs}{Rsh} \tag{2.3}$$

Where, I_{pv} is the solar cell current; I_o is the reverse saturation current; I_{ph} is the cell photo current; V_{pv} is the solar cell voltage; K is the Boltzmann's constant; T is the temperature in Kelvin; q is the unit charge; R_S is series resistance; R_{sh} is parallel shunt resistance.

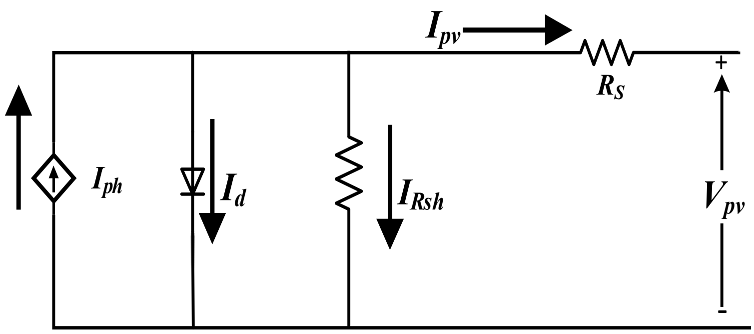

Fig 2.3: Equivalent circuit of single SPV cell

Current induced in the solar cell is determined by the irradiance and the temperature applied to the cell, and it is stated as follows:

$$I_{ph} = \frac{(I_{Sc} + K_i(T_c - T_r)I_r)Irradiance}{1000} \quad (2.4)$$

Where, I_{sc} = short-circuit current of cell; K_i = temperature coefficient; I_r = irradiance of cell; T_c = cell temperature; T_r = reference temperature.

Table I shows the details of the PV panel considered in this work.

TABLE 2.1

Electrical Characteristics of PV Panel

(SOLTECH 1STH-215-P) AT (1000 W/m^2 AND 50°C)

Parameters	Value
N_P (PV parallel strings)	2
N_S (PV series strings)	1
V_{OC} (Open circuit voltage)	36.3V
I_{SC} (Short circuit current)	7.84A
V_{MP} (Voltage at MPP)	30V
I_{MP} (Current at MPP)	7.35A
P_{MP} (Power at MPP)	213.15W

2.2.2 Solar PV Characteristics

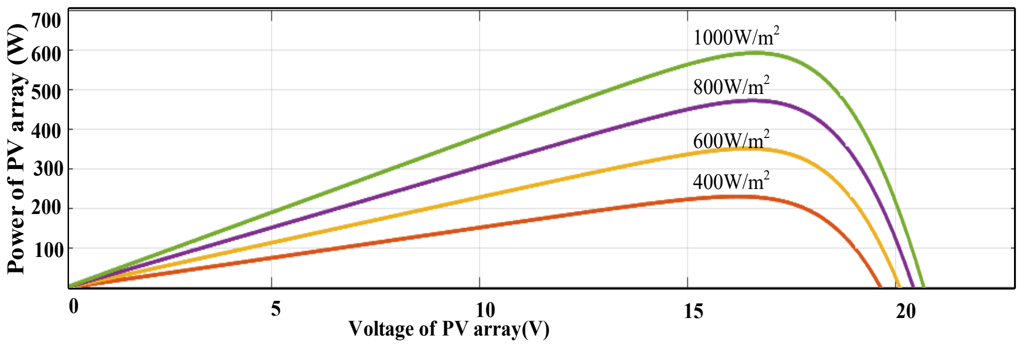

Figure 2.4: Solar PV array plot of power and voltage.

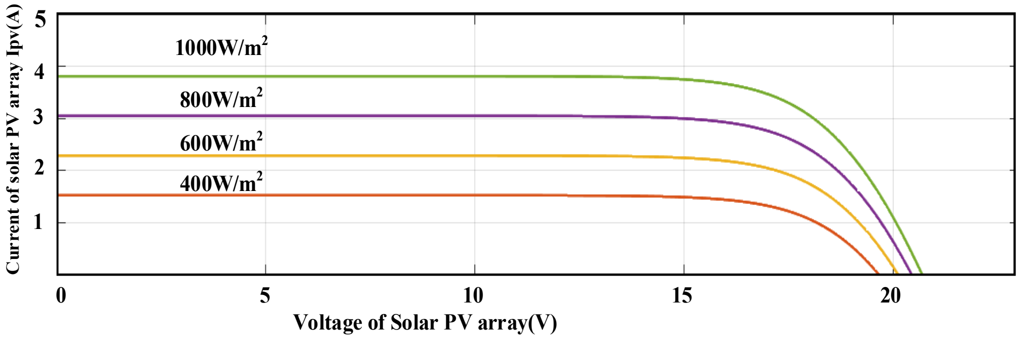

Figure 2.5: Solar PV array plot for current and voltage.

Solar cell: It is a photovoltaic cell that converts light energy into electrical energy due to photovoltaic effect. The arrangement of solar cell is done into large grouping called an arrays. These array composes thousands of individual cell. The array will work as a power station where electrical energy obtained from sunlight and distribution of power takes place in industrial, commercial and residential premises. The solar panel providing electric power in many remote terrestrial location where conventional electric power sources are either expensive or unavailable. Figure 2.4 and figure 2.5 represents the variation of P-V and V-I curve of solar PV array with varying irradiances respectively.

2.3 Maximum Power Point Tracking

Maximum power point tracking devices is use to maximize the output power of photovoltaic (PV) system. MPPT continuously tracks the maximum power (MPP) from the system. Moreover, the dependency of MPP is on irradiance conditions, panel's temperature and with connected load. MPPT extracts maximum power from the device and increases the energy that can be transferred from the array to an electrical system. Its main functioning is to adjusting panel's voltage to supply maximum energy to load.

The three primary components in the MPPT has designed to interfaced with SPV system named as switched mode dc-dc converter, control system and tracking component. Switched mode converter helps the entire supply to store in the magnetic energy which is released at different potential levels.

Voltage converters are designed basically for providing fixed input voltage or current that corresponds to maximum power point and it allows the output resistance to match the internal resistance of supply. In order to match this objective, controller has become very important component to monitor PV system continuously and it is to ensure the operations of PV panels and maximum power point tracking by this MPP [15], [16].

The aim of controller installed in MPPT is to continuously measure the current and voltage values. The values generated from the controller and PV system are compared with a threshold value and apply either with voltage controlled method, power feedback control or resistance matching in order to transfer maximum power from the PV panels to the load.

2.3.1 Perturb and Observe Algorithm

The MPPT is defined as an electronic device which draws the maximum power from the solar module/SPV array. In the Perturb and Observe (P&O) technique, minor perturbation is introduced which causes the power variation in the PV module. Fig2.6 shows the graphical representation SPV module with MPPT algorithm. It also gives the pictorial representation of SPV array with boost converter.

The SPV output power is periodically measured and compared with previous powers. The main concept of this algorithms for MPPT is to analyse and compare the output power and voltage of the array with its previous corresponding values. With the help of PV module the voltage will either be increased or decreased in order to check whether the power has increased or decreased. The power at time 'k' is compared with 'k-1' which generates the signal, from this the power is governed for the next instant towards maximum power point. Fig 2.7 represents the working steps of P&O algorithm. This procedure observes the output voltage and power of the PV array that perturbs the signal. There will be increment and decrement of the voltage signal by the constant amount which further sent to the boost converter. The signal direction further decides on the observation and comparison with the SPV power output. The obtained value is further compared with the reference value at the MPPT point, which based on the direction of the signal. The signal will be ΔV when the output power increases and it will be -ΔV when output power decreases [17], [18].

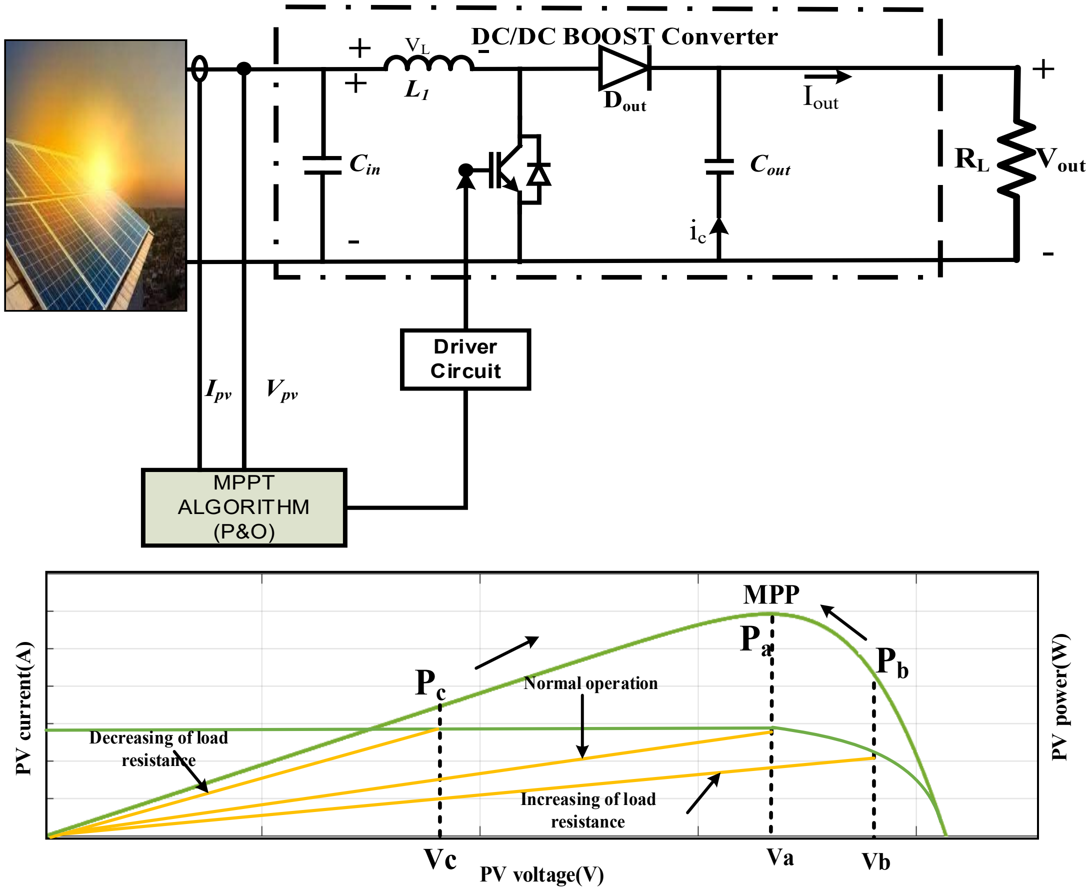

Figure 2.6 SPV module with MPPT algorithm

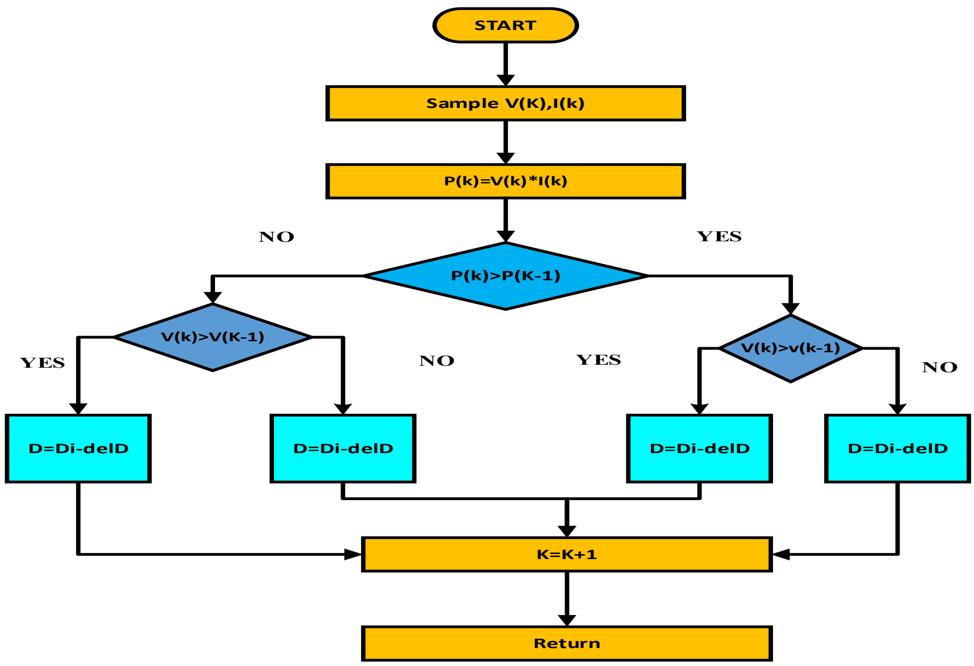

Figure 2.7: Flow diagram of P&O algorithm

2.3.2 Incremental Conductance Algorithm

Incremental conductance method is use to determine the maximum power from the solar PV array by comparing and measuring the instantaneous and incremental conductance of PV module. Maximum power is found when instantaneous conductance and incremental conductance becomes equal.

It has seen that within operating limits, power output of PV module increases with increasing terminal voltage PV module (If slope of the power curve >0, then dP/dV>0). On the other hand, Output power decreases when the terminal voltage of PV module increased (If slope of PV power curve<0, then dP/dV < 0).

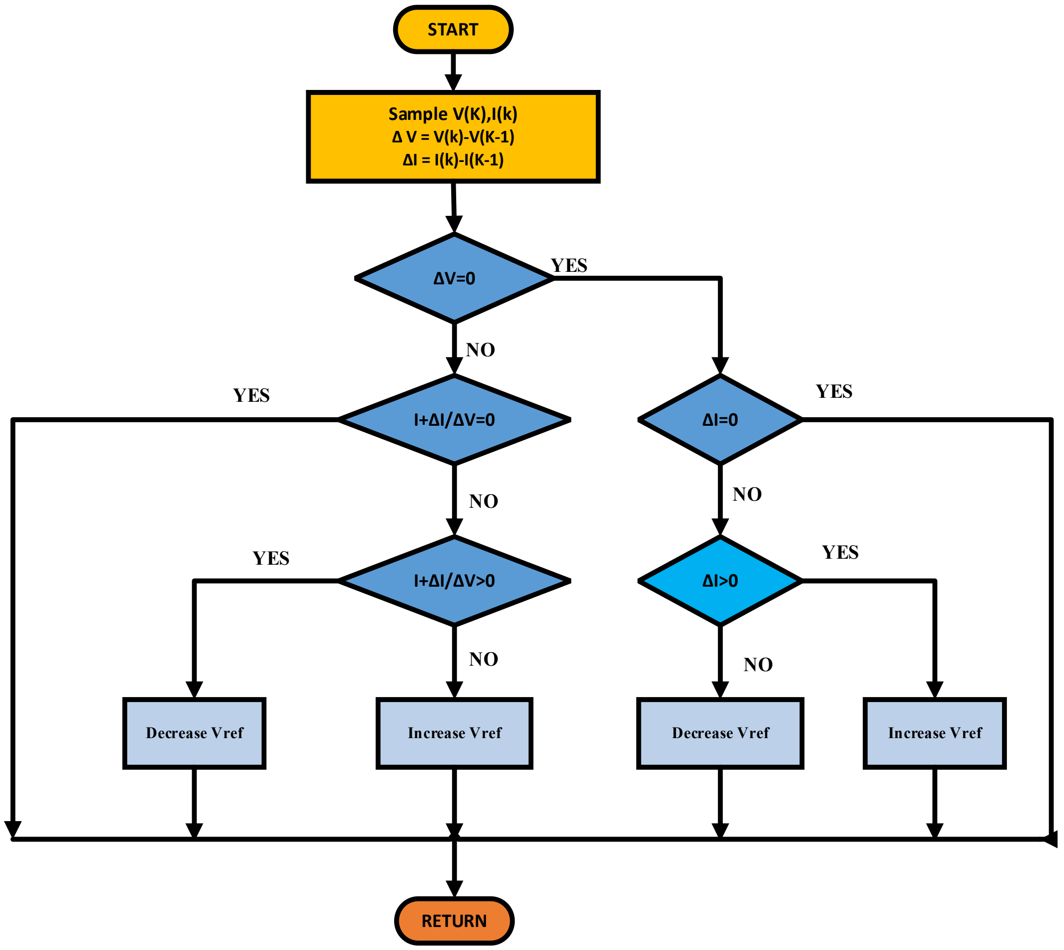

Figure 2.7: Flow diagram of incremental inductance algorithm

While comparing the incremental and instantaneous array conductance (dI/dV and I/V) it increases or decreases the voltage until maximum power point is reached.

2.4 Following conclusion are follows for the incremental conductance:

1) If (dI/dV >I/V) and dP/dV>0, the reference voltage is decreases and dP/dV approaches to zero.
2) If (dI/dV <I/V) and dP/dV<0, the reference voltage decreases and dP/dV approaches to zero.
3) If (dI/dV= I/V) and dP/dV = 0 reference voltages does not need any change.

2.5 Modelling of DC-DC Converter:

DC-DC converters plays a major role in varying the DC source voltage to higher or lower level as per requirement. In this section, the DC-DC converters named as boost, buck and buck-boost which are modelled and simulated in Matlab/Simulink. The switched mode DC-DC converters plays an important role in PV system. Since, the output voltage of PV panel is DC, so the DC-DC converters are used at the output of PV panel. Depending on the SPV panel voltage, different types of DC-DC converters are used for DC bus voltage. Buck, boost and buck-boost converters are mostly used for the PV array power flow management and DC bus stabilization.

In order to increase the efficiency of the converter, many researchers have improved the conventional converters topology and modified to newer version in order to increase the power conversion efficiency. Voltage gain and efficiency has increased with modified topology of bi-directional DC-DC converters. With the help of switched-capacitor structure and sliding mode control, the voltage gain at DC bus increases, the voltage stress at power switches will be decrease. With increase in gain and decrease in losses, the off-time of switch will increase and meanwhile the losses will decrease [12].

2.4.1 Buck Converter:

It is a DC-to-DC power converter which is designed for the stepping down the fixed input DC signals to another lower value of DC signals at the output. Initially the fixed DC voltage is applied across the input circuit and switch S1 is closed. The inductor in the path stores energy in the form of magnetic field. The capacitor in the circuit is use for the charge storage and hence voltage appears across the loads. Its circuit operation depends on the conduction state of the MOSFET.

ON-STATE: increase in inductor current and diode blocks.

OFF-STATE: inductor Current cannot change abruptly but the diode must carry current so it commutates and begin conducting.

The buck converter is a step-down DC to DC converter. For a DC-DC converter, input and output voltages both are DC. Power semiconductor device such as BJT, MOSFET or an IGBT is used in the buck converter as a switch to turn on and off the DC supply to the load.

The block diagram of buck converter is shown in figure 2.8 that accepts DC input and uses the pulse-width modulation (PWM) of switching frequency to control the switch. The DC output is produced by external diode, together with external inductor and output capacitor. With the help of buck or step down converter the average output voltage is produced that is lower than its input source voltage.

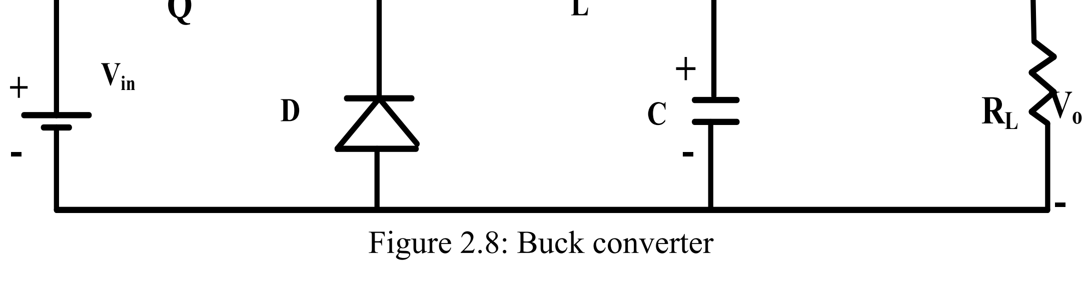

Figure 2.8: Buck converter

Mode I: Switch is ON, Diode is OFF:

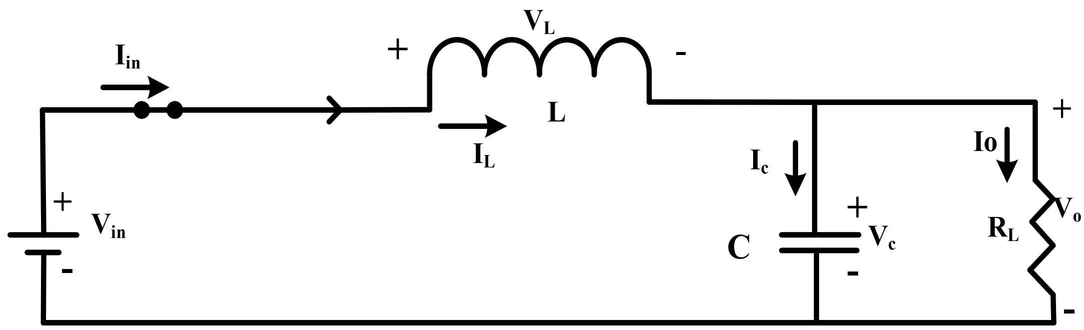

Figure 2.9: Operation of buck converter when switch is on and diode is off

Switching frequency, $f_{switching} = 1/T$, $D = T_{on}/T$

Now when the buck converter is in steady state,

Applying KVL in buck converter:

$$V_{in} = V_L + V_o \tag{2.5}$$

$$V_L = L\frac{di}{dt} = V_{in} - V_o \tag{2.6}$$

$$\frac{di}{dt} = \frac{V_{in} - V_o}{L} \tag{2.7}$$

Since the switch is closed for a time T_{on}=DT hence,

$$(\Delta I_L)_{closed} = (\frac{V_{in} - V_o}{L})DT \tag{2.8}$$

MODE II: Switch is OFF, Diode is ON:

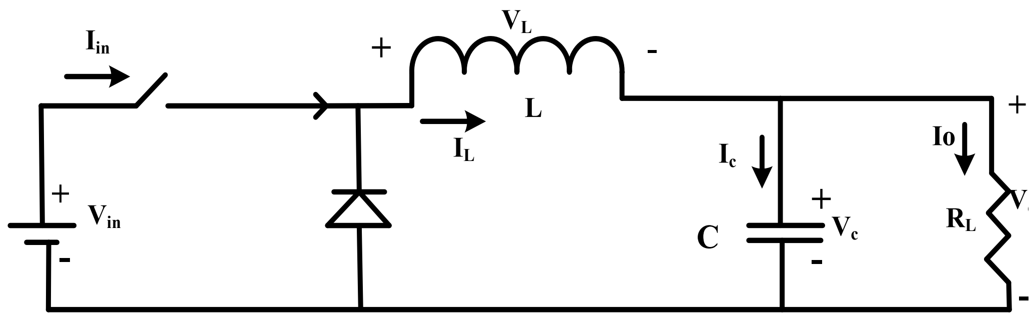

Figure 2.10: Buck converter operation when switch is off and diode is on

The stored energy in the inductor is released and dissipated in the load resistance which helps to maintain the current flows through load.

In steady state operation for mode II

$$0 = V_L + V_o \tag{2.9}$$

$$V_L = L\frac{di}{dt} = -V_o \tag{2.10}$$

$$\frac{di}{dt} = \frac{\Delta I_L}{\Delta t} = \frac{\Delta I_L}{(1-D)T} = \frac{-V_o}{L} \tag{2.11}$$

When the switch is open for the short iterval of time then,

$$T_{OFF} = T - T_{ON} = T - DT = (1-D)T \tag{2.12}$$

Hence, $$\Delta t = (1-D)T \tag{2.13}$$

$$\Delta i_L\Big|_{open} = \frac{-V_O}{L}(1-D)T \tag{2.14}$$

in steady state; $\Delta i_L\Big|_{closed} + \Delta i_L\Big|_{open} = 0$ (2.15)

$$\left(\frac{V_{in}-V_O}{L}\right)DT + \left(\frac{-Vo}{L}\right)(1-D)T = 0 \tag{2.16}$$

$$\frac{V_O}{V_{in}} = D \tag{2.17}$$

2.4.2 Boost Converter:

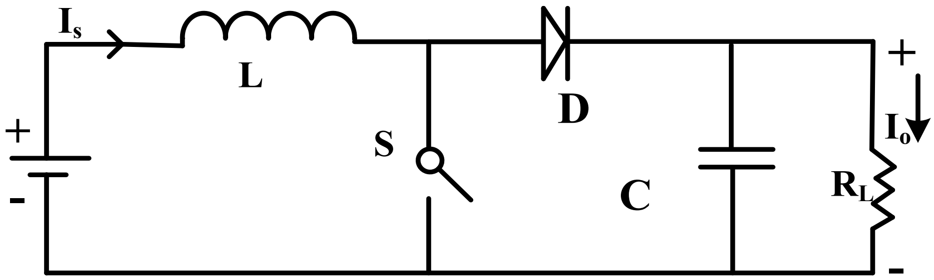

Figure 2.11: Boost converter

MODE I: Switch is ON, Diode is OFF:

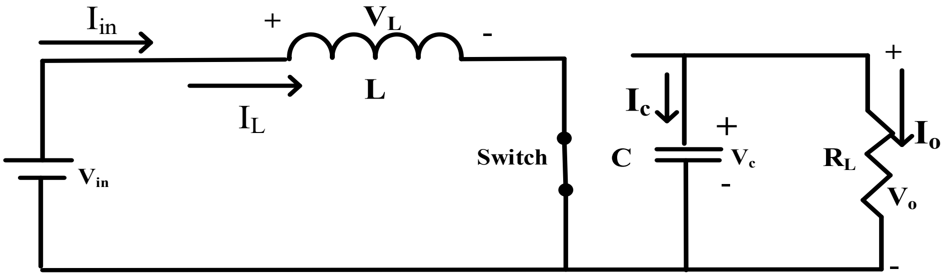

Figure 2.12: Model of boost converter when switch is on and diode is off

When the switch is on, it represents short circuit. Short circuit will offer zero resistance to the flow of current. Whenever the switch is on, current will flow through switch and will back to the DC input source. Now, we define time period, T, as

$$T = T_{ON} + T_{OFF} \tag{2.18}$$

$$V_L = L\frac{di}{dt} = V_{in} \tag{2.19}$$

$$\frac{di}{dt} = \frac{\Delta I_L}{\Delta t} = \frac{\Delta I_L}{(D)T} = \frac{V_{in}}{L} \tag{2.20}$$

When switch closes for time T_{on}=DT,

$$\Delta i_L\Big|_{closed} = \left(\frac{V_{in}}{L}\right)DT \tag{2.21}$$

In this mode,inductor polarity is reversed,the stored energy in the inductor is released and dissipated to the load resistance . Hence the flow of current is maintained in the same direction through the load and the output voltage is stepped up.

MODEII: Switch is OFF, Diode is ON:

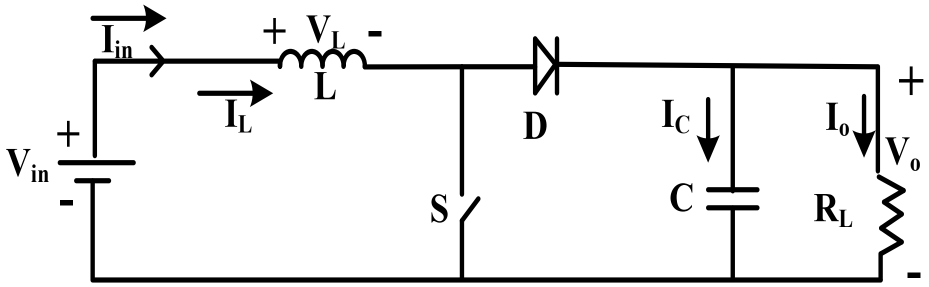

Figure 2.13: Model of boost converter when switch is off and diode is on

Now to analyse the boost converter in steady state operation we use KVL to get

$$V_{in} = V_L + V_o \tag{2.22}$$

$$V_L = L\frac{di}{dt} = V_{in} - V_o \tag{2.23}$$

$$\frac{di}{dt} = \frac{\Delta I_L}{\Delta t} = \frac{\Delta I_L}{(1-D)T} = \frac{V_{in} - V_o}{L} \tag{2.24}$$

When the switch opens for a short duration then,

$$T_{OFF} = T - T_{ON} = T - DT = (1-D)T \tag{2.25}$$

$$\Delta t = (1-D)T \tag{2.26}$$

Therefore, $$\Delta i_L\Big|_{open} = \frac{V_{in} - V_o}{L}(1-D)T \tag{2.27}$$

The net change of inductor current over complete cycle is zero.

in steady state; $$\Delta i_L\Big|_{closed} + \Delta i_L\Big|_{open} = 0 \tag{2.28}$$

$$\left(\frac{V_{in} - V_o}{L}\right)(1-D)T + \left(\frac{-Vo}{L}\right)(D)T = 0 \tag{2.29}$$

$$\frac{V_o}{V_{in}} = \left(\frac{1}{1-D}\right) \tag{2.30}$$

2.4.3 Bidirectional Converter:

Figure 2.14 shows the DC-DC bidirectional converter, the working of converter and its operating modes which depend on state of charge (SOC) of the BESS. The bidirectional converter has two modes of operation, i.e. charging mode and discharging mode of operation. In case of discharging mode, switch S_1 is on, which discharges the battery and power flows from battery to dc bus. In case of charging mode, the switch S_2 is on, which charges the battery and power flows from dc bus to battery.

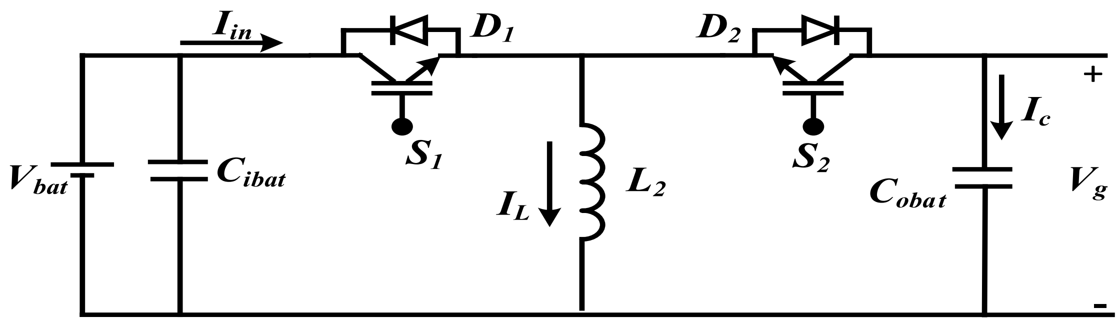

Figure 2.14: Circuit diagram of bidirectional converter

A) Bidirectional Converter in Charging Mode:

In this mode S_2 and D_1 will be in on-state whereas S_1 and D_2 will be in off-state. This mode of operation can further be classified into two intervals:

Interval 1 (S_2-ON, D_2-OFF; S_1-OFF, D_1-OFF): When switch S_2 is on, the inductor L_2 charges. The steady-state analysis of interval-1 can be written as follows:

$$V_g = V_L = L\frac{di}{dt} \tag{2.31}$$

$$\frac{di}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{V_g}{L} \tag{2.32}$$

$$\Delta i_L\Big|_{S_2=on} = \left(\frac{V_g}{L}\right)DT \tag{2.33}$$

Interval 2 (S_2-OFF, D_2-OFF; S_1-OFF, D_1-ON): In this interval, switches S_1 and S_2 both are in off state. The current flowing in the inductor cannot be changed instantly so polarity of voltage across L_2 get reversed and will be in series with input voltage, so diode D_1 will be in forward bias and inductor current will charge the capacitor C_{ibat}. The steady-state analysis of interval-2 can be written as follows:

$$V_{bat} = V_L \tag{2.34}$$

$$VL = L\frac{di}{dt} = L\frac{\Delta i_L}{\Delta t} = V_{bat} \tag{2.35}$$

$$\Delta t = (1-D)T \tag{2.36}$$

$$\Delta i_L\Big|_{D_1=on} = \frac{V_{bat}}{L}(1-D)T \tag{2.37}$$

In steady state,
$$\Delta i_L\Big|_{S_2=on} + \Delta i_L\Big|_{D_1=on} = 0 \tag{2.38}$$

$$\frac{V_{bat}}{L}(1-D)T + \frac{V_g}{L}(DT) = 0 \tag{2.39}$$

$$\frac{V_{bat}}{V_g} = \frac{-D}{(1-D)} \tag{2.40}$$

$$\Delta I_L = \frac{V_g D}{f_S L} \tag{2.41}$$

$$\Delta V_{C_{ibat}} = \frac{I_{bat} D}{fC} \tag{2.42}$$

Where, I_L = inductor current; V_c = capacitor voltage; I_{bat} = average value of battery current; and f_s = switching frequency.

B) Bidirectional Converter in Discharging Mode:

In this mode S1 and D2 will be in on-state whereas S2 and D1 will be in off-state. This mode of operation can also further be classified into two intervals. In interval 1, S1-ON, D2-OFF, S2-OFF, D1-OFF; whereas in interval 2, S1-OFF, D2-ON, S2-OFF, D1-OFF. The operation of power flow under discharging mode will be similar to charging mode.

TABLE 2.2

Parameters of Bidirectional Converters

Sl. No.	Parameters	Value
1	DC link capacitor (source side)	1000µF
2	DC link capacitor (Load side)	220µF
3	Energy transfer inductance	1mH
4	Switching frequency	5kHz

C) Control Topology of Bidirectional Converter:

In this section, control algorithm (closed loop PID control technique) of bidirectional converter is discussed and it is shown in Figure 2.15. The output voltage (V_g) is sensed and compared with the mentioned reference voltage (V_{ref}) to obtain the error and further this error is applied to PID controller. The output of PID controller is compared with carrier frequency signal ($V_{carrier}$) for constant switching frequency operation and resulting gate pulses are generated. The voltage control provided here is to maintain the value of 48V at the output DC bus. So, the output voltage is modified from this control loop and returns to its normal position. The design parameter of bidirectional converter is mentioned in Table II.

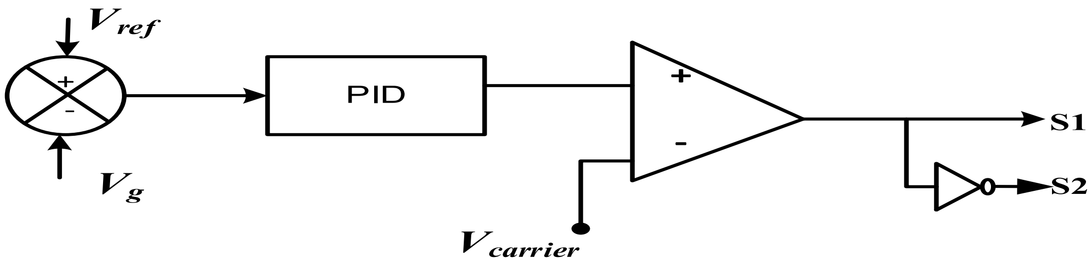

Figure 2.15: Control algorithm of buck-boost converter

2.6 Battery Sizing

Table III details the particulars of the DC load.

TABLE 2.3

Considered DC Load for Household Applications

Sl. No.	Appliances	Quantity	Power Required (W)	No. of Hours
1.	Desktop (100W)	1	100	6
2.	LED Bulb (20W)	3	60	5
3.	Fan (60W)	1	60	5
4.	LCD-TV (150W)	1	150	4
5.	Refrigerator (80W)	1	80	1
Total			**450W**	

Total energy consumption from the load appliances:

$$Wh_{load} = (100\times1\times6)+(20\times3\times5)+(60\times1\times5)+(150\times1\times4)+(80\times1\times1)$$

$$= (600+300+300+600+80)=1880\text{Wh}$$

No. of autonomy days (*N*) = 1 day (considered)

The nominal voltage of dc bus voltage is used in the proposed manuscript is $V_{bus} = V_g = 48V$

Battery efficiency $\eta = 85\%$; Depth of discharge of battery (DOD) = 50%

$$Battery\ capacity = \frac{Wh_{load}\times(N+1)}{\eta\times DOD\times V_g} = \frac{1880\times2}{0.85\times0.5\times48} = 184.3Ah$$

For safe criteria battery capacity is to be taken as 200 Ah.

Peak load demand $= (100+60+60+150+80)$

$= 450\text{W}$

Maximum load current $= \frac{450}{48} = 9.375A$

Nominal discharge current is to be taken as 10A for transferring excess PV power to battery without disturbing bus voltage during high insolation period and with low power demand, nominal discharge current to be taken as 10A.

$$\text{Now, C-rating of battery}\left(\frac{200Ah}{10}\right) = C/20$$

Hence from this calculation it is seen that battery will provide 10A of current continuously for 20 hours in the absence of PV array. It is seen that 200Ah of battery with 48V of system will be used for 1 day of autonomy.

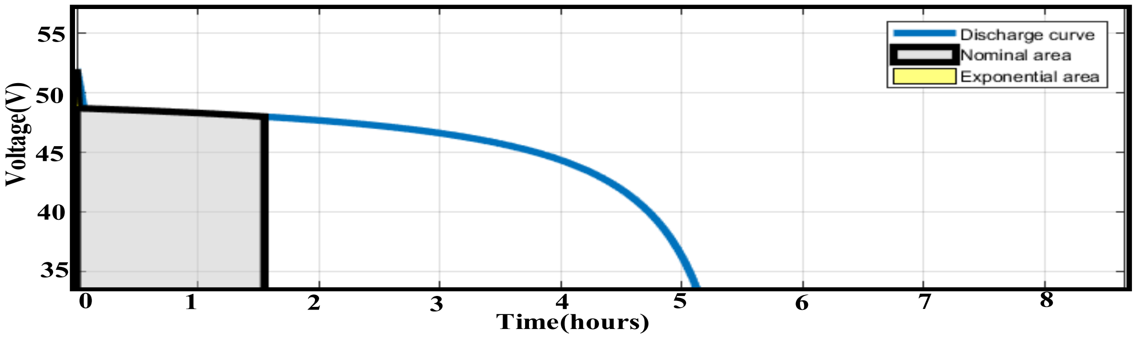

Figure 2.16: Battery discharging characteristics single C-rate with constant voltage

Figure 2.16 shows the discharging characteristics of lead acid batterry for 200Ah capacity,48V and 50% of SOC. This discharging characteristics consists three sections, first section represents exponential voltage drop when battery is charged. Second section represents the charge extraction from the battery until the voltage drops below nominal voltage.The third section represents the overall discharge of battery when voltage drops rapidly.

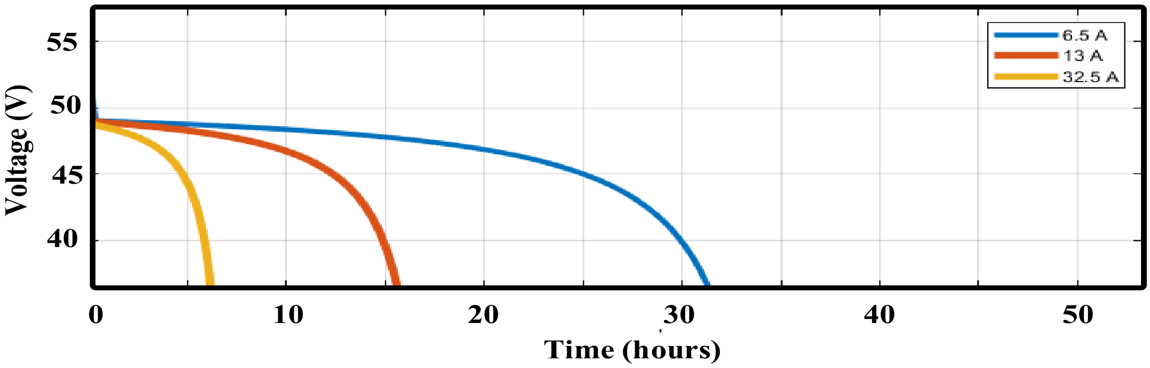

Figure 2.17: Battery discharging characteristics for at different C-rates.

Figure 2.17 represents the time taken by the lead acid battery to discharge at different C-rates. The battery will take 6 hrs to discharge the current of 32.5A, it will take 15.5 hrs to discharge the 13A of current. The lowest discharge current of 6.5A will take 32hrs to complete the whole discharging process of the battery.

CHAPTER: 3

BESS CHARGING AND POWER MANAGEMENT

3.1 Introduction:

Battery energy storage is a technology which enables power system operators for storing energy. BESS acts as an electromechanical device which charges from grid and then discharges the energy at later time for providing eletricity to grid services as when required. The battery chemestries are under investigation for grid applications which includes lead acid battery, lithium ion battery, redox flow and molten states. This batteries shows unique advaantages and disadvantages.

BESS is one of the technology which are required for speeding up the replacements of conventional and fossil fuels source reserves. The renewable energy sources increasingly considered for both grid connected and stand alone modes of operation. It is the device which enables the energy from renewables like solar and wind, which is stored and released further when the customer needs the most. It is one of the technology options which enhances the flexibility of the power system and enables the integration with multiple renewable energy resources.

3.2 Battery Energy Storage

In the solar PV system battery is one of the major component which is used for the purpose of storing energy, Battery stores power whenever there is surplus of power generated by the PV array. It will supply the required power to the load whenever there is no solar irradiance i.e. during rainy days or night time.

One of the other reason to use batteries in PV system to operate PV array at maximum power point, when the irradiances varies. DC bus demand stable voltages to power the electrical loads and surge current to the loads when the generation deficit occurs. In this section we used the lead-acid batteries which have some advantages over other batteries when it comes to supplying power to the residential premises. 200Ah lead acid batteries are considered for powering the whole system.

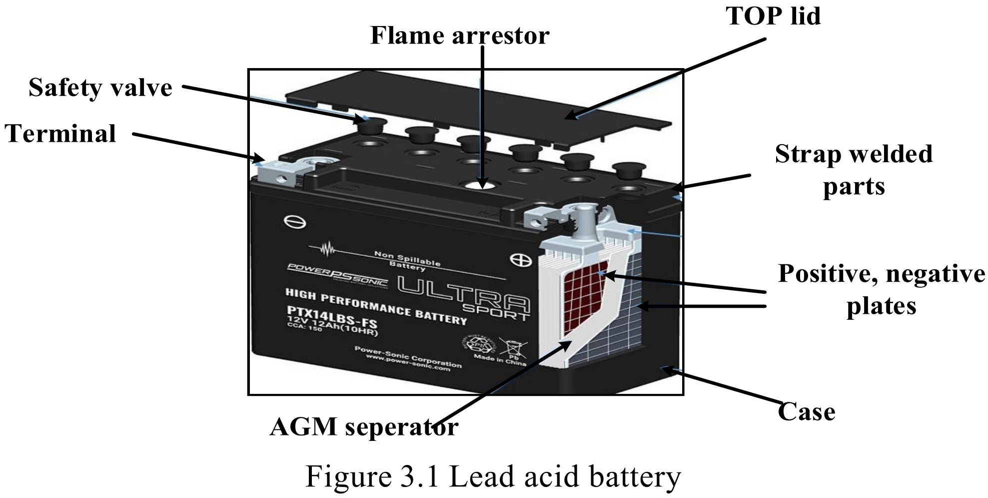

Figure 3.1 Lead acid battery

It is one of the most sought storage element in the solar PV standalone system. The stored energy in the chemical form is converted into electrical energy and vice-versa. The lead acid batteries have high power density, it can be easily recycled as compared to other energy storage device. The other singular advantage of lead acid battery is that they are commonly used for most of the rechargeable battery application. Lead acid battery is generally a mature technology which is relatively cheap to manufacture. It have the capability to produce the large current which can be further useful for variety of applications. It can be tolerant of overcharging and also have the available specifications for wide range of sizes. This ranges varies from large battery system used in load levelling to small batteries application in hand tools. The major applications of lead acid batteries are in starting, lighting and ignition. In industries it is used for traction and powering the electrical motors.

3.2.1 Constructions of Lead Acid Battery:

This section includes the construction details and steps regarding the maintenance of lead acid batteries.

The construction of lead acid battery shown in fig.3.3 consists of following main components:

I) Container II) Plates III) Active component IV) Separator

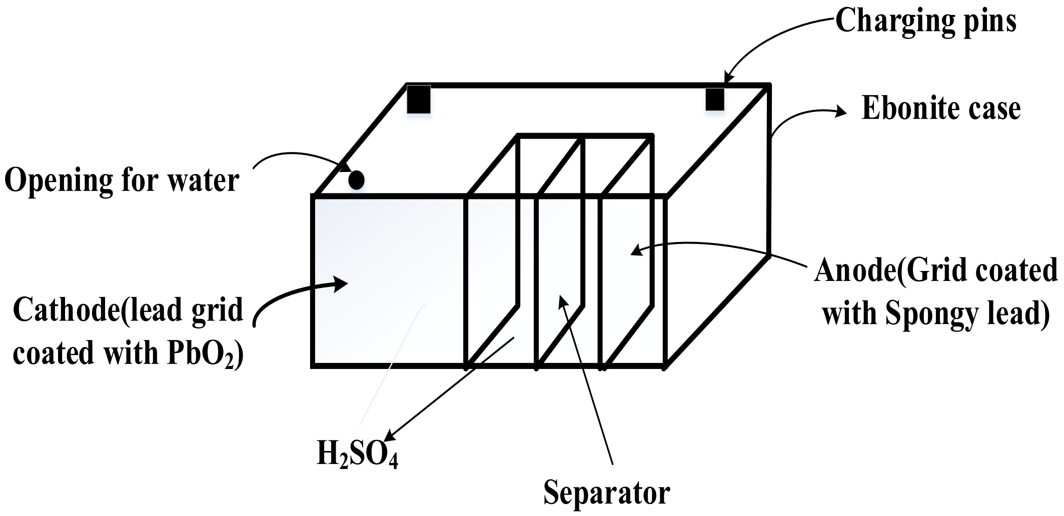

Figure 3.3 Construction of lead acid battery

I) Container:

It is constructed with ebonite, lead-coated wood, glass and ceramic material that placed on the top to eliminate any kind of electrolytic discharge. In the bottom section of the container, four ribs exists in which two are placed on the positive plates and other two are placed on negative plates. The container acts as a base for both the plates. It safeguards the plates from getting short circuited. The container is constructed from the components that should be free from sulphuric acid. Container should not hold any kind of impurities which leads to damage the electrolyte.

II) Plates:

Plates of the lead acid battery have the construction in a different way which are made up of similar type of grid that is constructed of active components and lead. The formed grid is very crucial in the establishment of the current conductivity and spreading equal amount of current to active components. Two types of plates in the battery is used i.e. formed plates and pasted plates. Formed plates are basically employed for static batteries, which are costly and heavy in weight. The pasted process utilised in the construction of negative plates, the negative active component is complicated which experiences small modification for charging and discharging process.

III) Active Elements:

The components which are actively involved in the chemical reaction processes are:

(PbO_2) Lead peroxide- Forms positive active component.

Sponge lead- Forms negative active components

Diluted H_2SO_4- Utilized as an electrolyte

IV) Separators:

Separators are made up of thin sheets that is mostly constructed of porous rubber, lead wood and glass fibre. Battery separators provide active insulations and it is positioned between the plates. It is also known to be polymeric membrane which is positioned between the positively charged anode and negatively charged cathodes. Battery separators are positioned in such a way which prevents electrical short circuiting.

3.2.1.1 Maintenance of Lead Acid Batteries:

This section includes tips and guidelines regarding to charge the lead acid battery correctly. It further includes maintenance, safety and longevity of the battery:

I) **Charging of battery in well ventilated area**: well ventilated area is required for charging the lead acid battery because it releases hydrogen gasses which can be potentially explosive. The battery room must be ventilated to prohibit the build-up hydrogen gas.

II) **Avoid flattening the battery**: Flattening of battery should be avoided to prevent the shortening of battery life. It is also observed that once the battery is flattened, then its capacity gets reduced significantly and become totally discharge.

III) **Avoid the battery overcharging**: One should avoid the charging of battery above temperature 49°C or 50°C. Gas bubbles on the plates indicates that battery is fully charged. When its start appearing on plates, it indicates that battery should start splitting the water molecules into hydrogen (negative plates) and oxygen (positive plates).

IV) Freezing of lead acid battery should be avoided to prevent the battery from irreparable damages.

V) Overfillment of battery should be avoided to prevent the spill out of acid while charging

3.2.2 Working of Lead Acid Battery

Lead acid battery consists of two electrodes i.e. positive and negative. Fig.3.2 shows the working of lead acid battery. From fig.3.2 it is seen that the positive electrode consists of lead oxide (PbO2) and negative electrode made up of spongy and porous lead. Both of the electrodes get immersed into sulphuric acid (H_2SO_4) and water (H_2O). When the electrodes comes in the contact with each other by a physical movement of battery or through changes in the thickness of the electrode, the two electrodes get separated through chemically permeable membrane. Most commonly the lead acid battery used in the power station and sub-stations due to its higher cell voltage and lower cost.

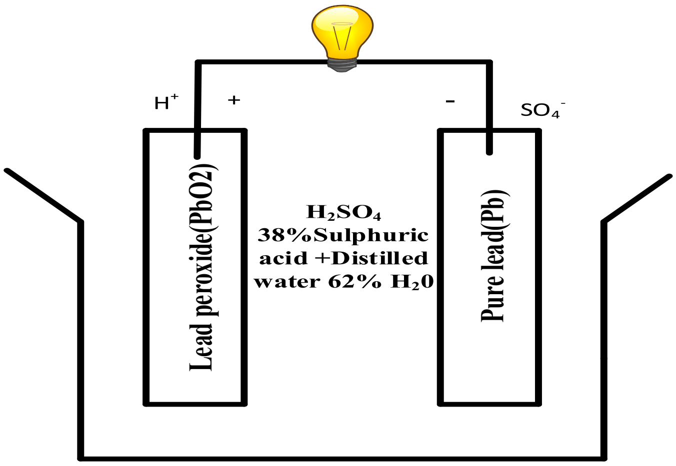

Figure 3.2 working of lead acid battery

At anode:	At cathode
$PbSO_4 + 2H_2 + SO_4 \downarrow$	$PbSO_4 + 2H \downarrow$
$PbO_2 + 2H_2SO_4$	$Pb + H_2SO_4$

The overall chemical reaction is:

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O \qquad (3.1)$$

At the negative terminal charging and discharging reaction are:

$$Pb + SO_4^{2-} \Leftrightarrow PbSO_4 + 2e^- \qquad (3.2)$$

At the positive terminal the charging and discharging reactions are:

$$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \Leftrightarrow PbSO_4 + 2H_2O \qquad (3.3)$$

The charging/discharging of battery represented from the equation-(3.2) and (3.3). This equation cause the formation of lead sulphate crystals at both the negative and positive terminals. The electrons releases due to change in valence charge of lead. Formation of lead sulphate from sulphuric acid electrolyte surrounds the battery. Lead sulphate formation will dilute the electrolyte and makes the aqueous solution less concentrated. The full discharge of battery will results that both of the electrode is being covered with lead sulphate and water rather than sulphuric acid around the electrodes. Since the electrodes are made up of same material so when battery discharges there is no chemical potential or voltages between the two electrodes.

Discharging stops at the when the cut-off voltage gets below the battery voltage .The battery energy storage device are unable to discharge. In case of fully charged and discharged states, the lead acid battery experiences a gradual reduction in the voltage. SOC of the batteries are indicated by the voltage level.

The battery capacity reduces permanently, if the battery is at left of low state of charge for external period of time, large lead sulphate crystal grows which permanently reduces the battery capacity. The large crystals are unlikely the typical porous structure of lead electrodes that are very difficult to convert back into lead [24], [25].

3.2.3 Internal Operation of Lead Acid Battery

In the aqueous solution of the battery, sulphuric acid will act as an electrolyte. Whenever these electrodes dipped in the aqueous solution of battery, it will provide DC supply, the positive ions (+ve) will have the movement towards the direction of negative edge of the battery. Alike, the –ve ions will move towards the positive edge of the battery. Whenever the molecules of H_2SO_4 dissolve in the solution, it get dispersed into two ions SO_4^- (-ve ions) and $2H^+$ (+ve ions) and these ions will move freely in the solution. Whenever these electrons dipped in the aqueous solution, it will provide DC supply. Hydrogen and sulphate ions collects one electrons and two –ve ions from the cathode and anode respectively. It reacts with lead oxide and forms lead peroxide (PbO) which is coloured as dark brown. In the absence of DC supply, voltmeter is connected between the electrodes. It displays the potential difference between the electrodes. Whenever the wire is connected between the electrodes, the passage of current flows from negative to the positive plate with the help of an external circuit. This flow of current will signify that the cell holds the ability to provide an energy in the electrical form.

3.2.4 Types of Lead Acid Battery:

There are three distinct types of lead acid battery. It consist same type of charging/discharging phenomenon as explained in section 3.1.2.1. When the cell starts discharging, lead (Pb) and diluted sulphuric acid (H2SO4) undergoes into the chemical reactions which produces lead sulphate (PbSO4) and water (H2O). While charging, the lead sulphate (PbSO4) and water (H2O) turned back into lead and acid. In case of lead acid battery designs, the charging current will adjusted in order to match the ability of energy absorption by the battery. If the charging current high, the phenomenon of electrolysis will occur which decomposes the water into hydrogen and oxygen. After the electrolysis phenomenon lead sulphate and water converted into PbO2, Pb and H2SO4.To prevent this gases from escape, the battery requires the addition of water from time to time. In contrary, the VRLA batteries have tendency to retain the generated gasses within the battery until pressure remains within the safe level. During the normal operation the gasses get recombined within the battery itself, the recombination of gasses in the battery is done with the help of catalyst where no additional electrolyte is needed. If the safety limits of batteries exceeded by the pressure, the VRLA batteries have safety valves which opens and allow the excess gasses to escape, and by doing so it regulates the pressure back to safe levels. During the normal operation, the gasses get recombined within the battery itself where no additional electrolyte is needed. If the safety limits of batteries exceeded by the pressure, the VRLA batteries have safety valve which opens and allows the excess of gasses to escape. Regulating gasses will make the pressure back to safe levels. This type of battery consists of pressure relief valve which activates when battery builds pressure of hydrogen gas while charging. The cell covers of this battery generally have the gas diffusers which allow the safe dispersal of excess hydrogen which formed during overcharging. During the normal operation, the gasses get recombined within the battery itself. The recombination of gasses in the battery is done with the help of catalyst where no additional electrolyte is needed. If the safety limits of batteries exceeded by the pressure, the flooded acid batteries have the safety valves which opens and allows the excess of gasses to escape. Pressure will be maintained at the safe levels when the excess of gasses are allows to escape.

I) Flooded lead acid battery(FLA batteries):

This type of battery is one of the oldest and most basic type of lead acid battery in which the electrolyte (acid) is added in the liquid form. While charging/discharging of FLA batteries, the volatile gasses are produced which are vented out of the battery to prevent the build-up of pressure. This battery types are mostly used for backup power applications, utility and grid energy storage. Flooded lead acid battery is developed with robust construction for applications which demands regular deep discharge. The FLA have long service life, but it should be consistently checked and maintained to achieve longer life. These type of batteries have mostly resistant to damage when it gets overcharged. High rates of charge/discharge are supported. It is economical in nature. The applications of such type of batteries in renewable energy based home automations, telecommunication devices and data centres. Its capacity varies from 100Ah up to 3000Ah. Its operating conditions lies between

-20ºC to +55°C. Its battery life is basically designed for 20 years.

II) AGM (Absorbent glass mat):

The AGM batteries have the positive and negative plates that are separated by the absorbent glass mat. The absorbent mat absorbs and hold batteries acid in such a way that it prevents it from flowing inside the battery. The specially designed glass mat separator in this batteries wicks the electrolytic solution between the battery plates. Design of this material allows the fibre glass to be saturated with electrolyte and its storage in a dry and suspended state in comparisons with traditional free liquid form. The type of batteries are also maintenance free because it doesn't require watering service. It have tendency to perform better than flooded batteries in applications where the regular maintenance is not possible. It is also termed as the non-spill able or spill proof. The glass mats presents inside the AGM battery avoids spillage because it holds the electrolyte without letting it flow freely. Apart from the spillage the internal design of the AGM battery results in low internal resistance. Due to low resistances, this batteries have tendency to offer high power output in short interval of time. AGM battery have short charging time when compared with flooded lead acid batteries, it can charge the appliances at faster rate. The life span of AGM batteries are longer than the traditional batteries. The durability of AGM batteries are very high, its application is basically in aircrafts and military vehicles. This battery have tendency to handle vibrations very easily. Internal design of AGM batteries are durable and robust. The accumulation of lead acid sulphate crystal is prevented in the AGM batteries hence sulphation is limited and regular charging is not required.

III) GEL Battery:

A gel based lead acid battery have two electrodes which consists of the electrolyte that is made by mixing H2SO4 (Sulphuric acid) with silica-gelling agent that converts the liquid electrolyte into semi shift paste to make the gel maintenance free. A gel type battery lasts longer than AGM because it improves the heat transfer to the outside. A gel type battery is very similar to the traditional lead acid battery with the addition of silica to the electrolyte which creates the gel like substance. In the gel battery construction is very similar to the AGM type of batteries. However, instead of using absorbent glass material, it used gelled type electrolytes. These gelled type electrolytes solidifies and reduce the risk of spillage and evaporation. These batteries are lighter and have longer lifespan than traditional batteries. It also have tendency to hold the charge for longer time. The advantage of gel cell batteries is that it requires i) Low maintenance ii) Lighter than ordinary batteries. The application of gel cell are generally in phones, camcorders, home appliances and marine equipment's. Due to its low maintenance feature, users are not required to add water regularly to make the electrolytic level normal. When the electrolyte solution transformed into the gel, it is impossible to spill the content. Hence it prevents the seeping acid out of the battery.

3.2.5 Design of Lead Acid Battery:

The two major entity to be measured while designing the lead acid battery i.e. state of charge (SoC) and state of health (SoH).With the estimation of SoC and SoH of lead acid battery, it is possible to have major control over the energy which is stored and facilitate the energy management of the entire system.

One of the other advantage of measuring SoC and SoH that it prevents the battery from overcharging and undercharging. From this proposed measurement of battery, the reduction in the battery life-cycle will be avoided. With emerging technologies and innovation there are many new batteries are developed in the market such as lithium batteries and lithium polymer batteries. The lead acid battery majorly use in the system where the temperature is uncontrolled and robustness is required. Keeping all these assumption in mind the choice is inclined to work with lead acid batteries. The estimation of SoC and SoH are justified [26], [27].

A) State of charge (SOC) :

The amount of charge inside the battery is generally stored by SOC. It describes the difference between a fully charged battery and the same battery in use. SOC also defined as the ratio of remaining charge to the maximum charge that can be delivered by the battery. Equation (3.4) and (3.5) determines the SOC formula of battery.

$$\%SOC = \frac{100(Q_O + Q)}{Q_{\max}} \times 100\% \tag{3.4}$$

Where, Q_o / mAh is the initial charge of the battery, Q / mAh is the quantity of electricity delivered by or supplied to the battery, It is –ve during discharge and +ve during charge. $Q_{\max} / mAh$ = The maximum charge stored in the battery, $\%SOC$ is the initial state of charge of the battery

$$SOC = \frac{Ca - \int idt}{Ca} \times 100\% \tag{3.5}$$

In the SOC, Ca is termed as the discharge capacity of the battery. SOC measures the amount of energy in the battery in such a way that it won't be able to compromise its state of health (SOH). The withdrawn energy from the battery is measured by the integral of the current at small time interval.

B) State of health(SOH):

The SOH of a lead-acid battery is the measurement that reflects the general condition of the battery. State of health (SOH) is used to provide the indication of the performance expected from the battery in its current condition. It’s also provide an indication of useful lifetime of the battery that has consumed and remains before its replacement. In the standby or emergency power plant, the SOH helps the plant engineer to find the problems and diagnosis the fault. SOH also have the ability to track the long term changes in the battery.

R_{EOL} is called to be the internal resistance of the battery, when it is in the state considered as the end of life, R_{EOL} value generally informed by the battery manufacturer. The R_N is the internal resistance of the battery. R_N is the value of internal resistance when the battery is new which is also informed by the battery manufacturer. R_i is the actual internal resistance of the battery. The actual internal resistance of the battery is obtained by the ohms law. Equation (3.6) and (3.7) represents SOH of the battery.

$$SOH = \frac{R_{EOL} - R_i}{R_{EOL} - R_N} \times 100\% \tag{3.6}$$

$$\%SOH = \frac{100 Q_{\max}}{C_r} \times 100\% \tag{3.7}$$

$Q_{\max} / mAh$ is the maximum charge available at the battery, % SOC is the initial charge stored by the battery.

3.3 Charging Configuration of Lead Acid Battery;

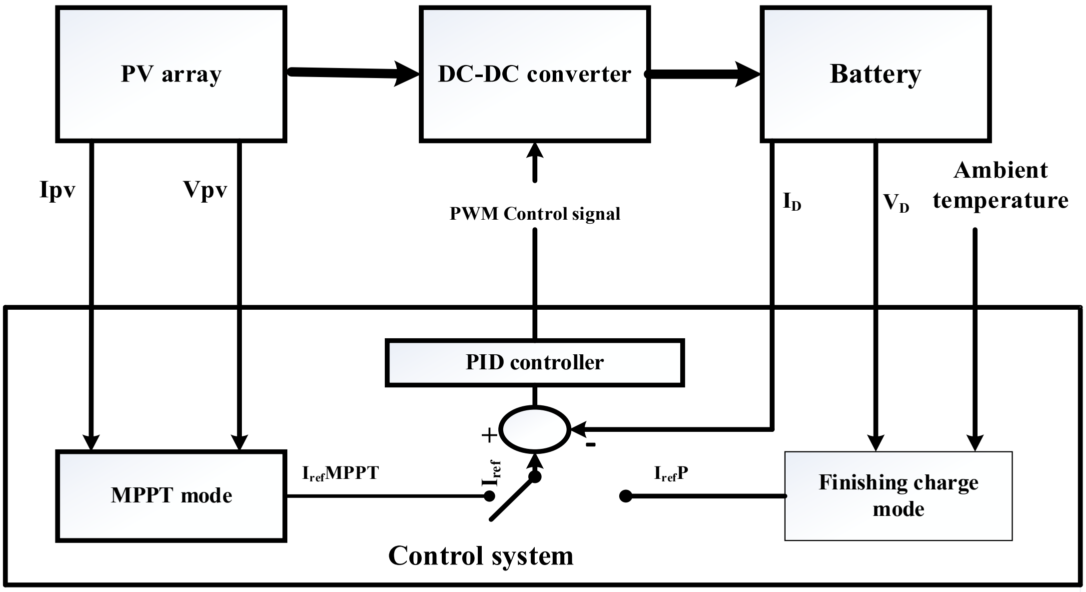

Figure 3.4 Battery charging system

The block diagram of battery charging system is represented by fig.3.4.It represents the block model of battery charging system that includes four components i.e. SPV array, DC-DC bidirectional converter, lead acid battery and the control system. DC-DC bidirectional converter and PID controller proposed as a two major components for the charging algorithm. Fig.3.5 represents the battery charge/discharge controller structure. In this controller the outer loop is voltage control loop that produces reference to the inner current control loop. The reference current value will be positive (+ve) or negative (-ve) depending on its charging/discharging state of the battery storage system. The generated control structure further produces signal which passes to PWM generator and act as the complementary switching for bidirectional converter.

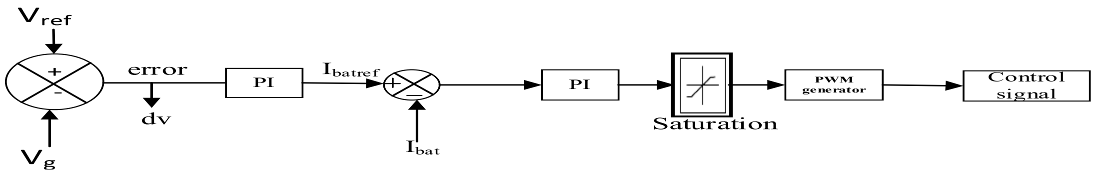

Figure 3.5 Battery charge/Discharge controller

The gate pulse are generated from switching operation. Voltage control technique is provided here to maintain the 48V at the output DC bus. So, the output voltage is modified from the control loop and it will return to its normal position. MPPT P&O algorithm and battery charge controller are two major components of solar charge controller. The PWM control signal is produced by the battery charge controller. This control signal will adjust the duty cycle of DC-DC converter which will turn adjusts the converter input characteristics for the extraction of desired power from PV array and hence transfers it to the battery. The desired power extracted from the PV array is controlled by adjusting the battery reference current I_{ref} . The two modes of control while charging lead acid battery are MPPT control mode and finishing charge control mode. The battery is firstly charges with MPPT reference current $I_{refMPPT}$ which effectively charges the battery from its low SOC to end of charge voltage 0.6V/cell. The finishing charge reference current Iref is utilized very safely to finalize the charging process of battery to 100%.

3.3.1 Solar Charge Controller and DC-DC Converter:

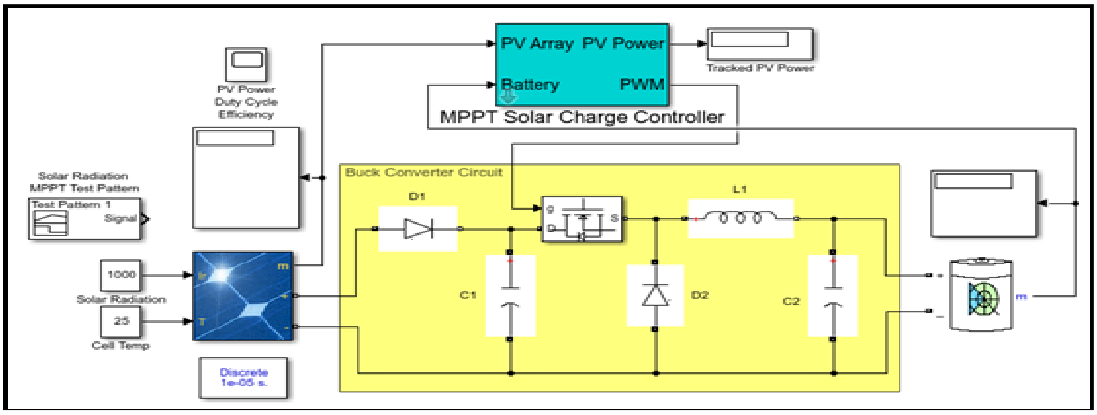

Figure 3.6 Solar PV MPPT charge controller model

Bi-directional converter raises or lower the output voltages from input voltage supply . Fig.3.6 shows the charge controller model of solar PV MPPT. The charge controller model consists of buck converter which is used to step down the input voltage from PV array in order to maintain its power delivery to charge the battery. Battery is charged by stepping down the input voltage and increases the output current delivered to the battery. The step down converter circuit comprises of a high power inductor, MOSFETS as switching device, SCHOTTKY diode and input /output capacitor. Reverse flow of current to the PV array is blocked during night time from reverse blocking diode D1 as shown in fig.3.6. MOSFET resistance sets at 0.02Ω and forward voltage of SCHOTTKY diode sets at 0.5V. The pulse generator of frequency 5000Hz used for switching of MOSFET.

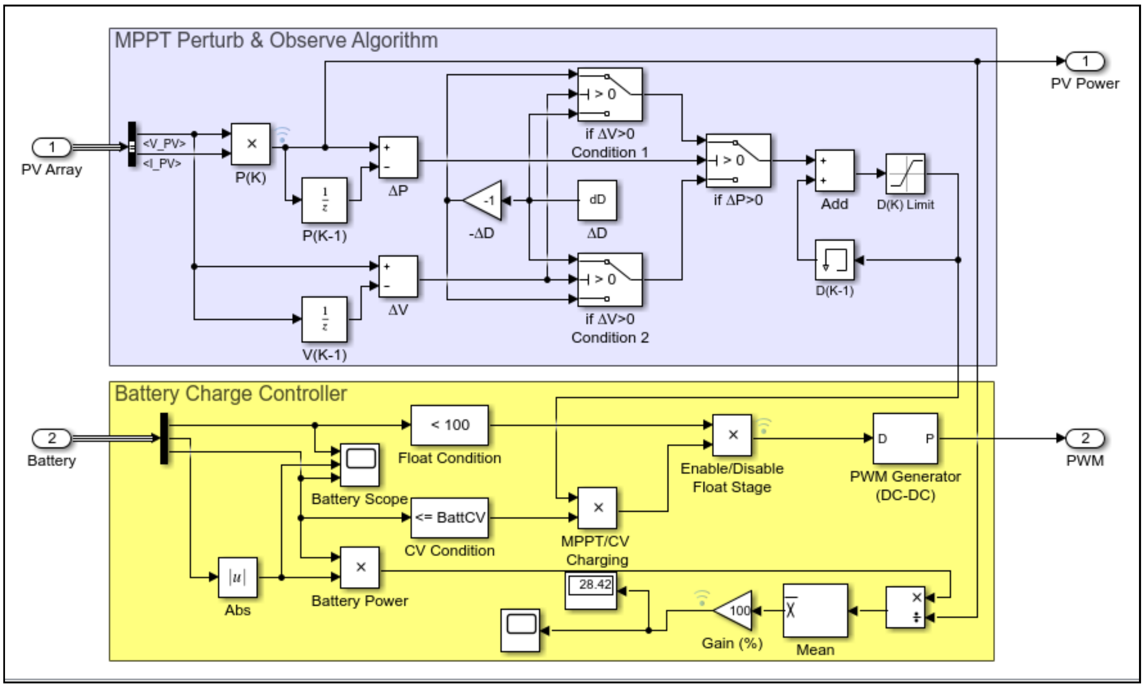

Figure 3.7 Subsystem of MPPT charge controller block

Figure 3.7 shows the subsystem blocks of solar charge controller. This charge controller shows the subsystem of MPPT in which constant voltage charging method is applied. During battery charging the voltage is kept constant throughout the whole process. Using this method, the battery capacity is increased by some percentage (i.e.20%). In the beginning of battery charging, current is high because the battery is in discharged condition. The charging current drops gradually after the charges picked up by the battery.

CV charging is the constant voltage to charge batteries. Since the voltage is constant, so charging current decreases as the battery charges with high current value. The constant terminal voltage is provided at an early stage of charging process. High current provides the fast charging but its stresses the battery too.

In case of CC-CV charging method, constant current(CC) charging is the first stage of charging, whenever the voltage reaches to its maximum value, the charging process shifts to CV charging method. This charging process completes when current levels off or when battery reaches to its full capacity.

The first stage of charging method is constant current. Whenever the voltage reaches to maximum value, charging process shifts to CV charging method. Whenever the current level off or when the full battery capacity is reached, the charging process is complete. CC mode defines the charging time and CV mode influences the capacity utilization.

3.3.2 Charging Stages of Lead Acid Battery:

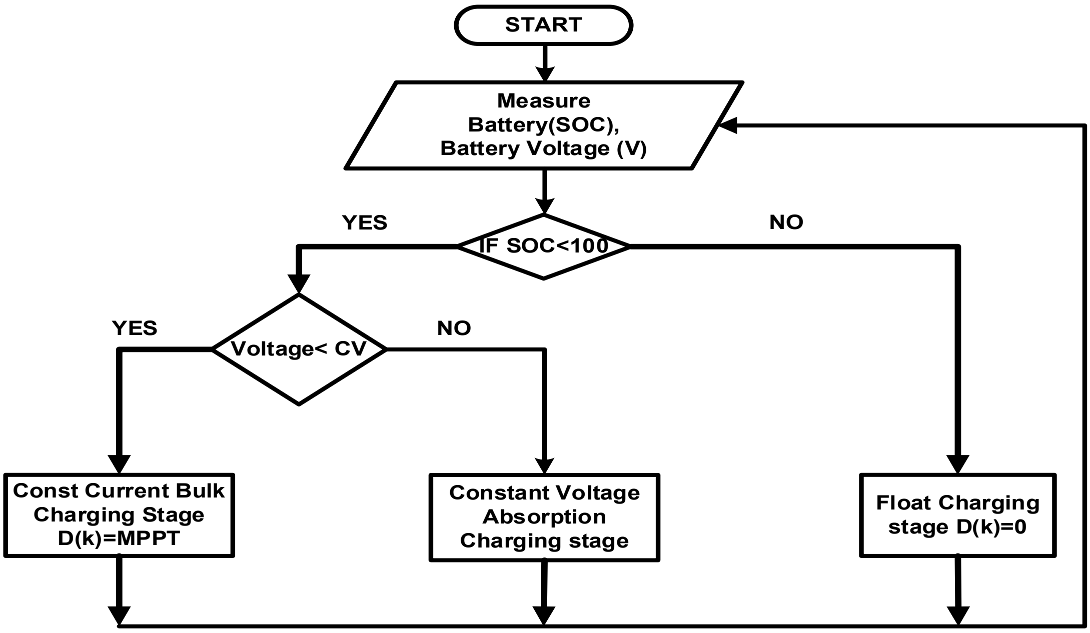

Figure 3.8 Flowchart of lead acid battery controller

Lead acid battery uses the three stages charging method, it includes constant current charging, constant voltage charging and Float charging stage that is represented in figure 3.8.

In the first stage constant current charging referred as bulk charging stage, where the charge current is charge at its rated capacity. The second stage is termed as constant voltage charging that refers as constant voltage absorption stage where the battery is charged at constant voltage. In the second stage of charging the MPPT is disabled. The third stage charge is float charging stage. The float charging stage maintains the battery state of charge (SOC) at 100%.

If SOC is maintained at 100%, the battery gassing reaction is controlled. In order to maintain the battery capacity and to extend the battery life, it is kept at 100% of their full charge or returned to the state quickly after deep discharge. This charging algorithm suggested to charge the lead acid battery quickly and safely to their full charge. This full charge prevents the battery from sulphation phenomenon.

The lead acid batteries are charged by two methods: a) constant current method b) constant voltage method

In case of constant current method, amount of current in amperes will pass through battery in fixed amount till it's fully charged. It is a simple method of charging that uses constant current for charging the battery during the whole charging process. After reaching the predefined value the constant current charging will stop. The battery behaviour is improved considerably. Constant current charging will satisfy both charging time and capacity utilization. Quick charge is provided by the high charging current and affects battery ageing.With the process of low charging current the battery SOC get affected and it will not be convenient for high voltage residential appliances.

3.4 Power Flow Management:

The power management scheme for the DC grid structure has represented in figure3.9.Figure 3.9 consists of power flow management scheme, inner control loop and gating signals for boost converters and buck-boost converters. The objective of power flow management scheme is for the utilization of maximum amount of energy from renewable sources in efficient and reliable manner. With the measurement of available data, the current reference signal is generated from power flow management schemes, the power flow management operation depends upon the operating condition of PV system, battery and load demand. The generated power of solar PV array fulfils the load demand i.e. $P_{spv} > P_L$. The excessive power is utilized for charging the battery to maximum threshold value. If solar PV array power lesser than the load demand i.e. $P_{spv} < P_L$, then (P_{spv}+ BESS) will supply power to essential loads on the priority basis. Further, the battery SOC discharge to lower value of threshold. Below the lower value of SOC, the non-essential load will be powered with priority basis. The proposed scheme operation is based upon the various conditions [21], [23].

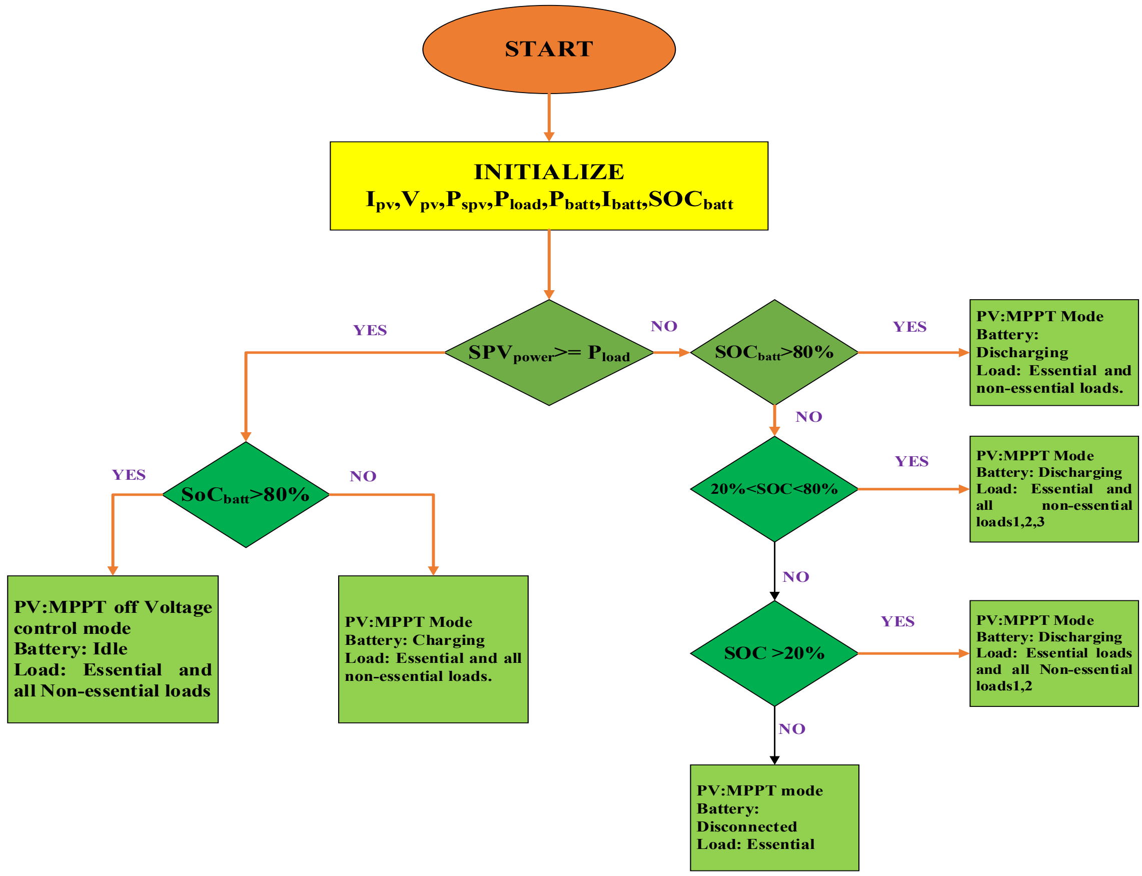

Figure 3.9 Power Flow Management Scheme for DC Micro grid System

CASE I: $SPV_{power} > P_{load}$ **and** $SOC_{batt}^{min} < SOC_{batt} < SOC_{batt}^{max}$

If the solar PV array power exceeds the load demand and if battery SOC lower than its maximum threshold value i.e. SOC_{batt}^{max} . The specified condition checked by the control algorithm and the control algorithm provides control signal to charge the battery. In this case all the essential and non-essential loads are powered by solar PV and battery which is charged to the threshold value.

CASE II: $SPV_{power} > P_{load}$ **and** $SOC_{batt} = SOC_{batt}^{max}$

In this case, SPV_{power} is greater than the load power demand and battery SOC_{batt} is at maximum threshold value i.e. SOC_{batt}^{max}. In this case the battery is disconnected from the system hence the solar PV array alone will meet the requirement of entire load demand.

CASE III: $SPV_{power} = P_{load}$ **and** $SOC_{batt} = SOC_{batt}^{max}$

In this case, the generated power of SPV equals to the load power demand, hence the SOC of BESS equals to the maximum threshold value of battery. In this case BESS not considered for the purpose of optimal operation. The SPV_{power} alone will satisfy the entire load demand.

CASE IV: $SPV_{power} < P_{load}$ **and** $SOC_{batt} > SOC_{batt}^{min}$

If the SPV array power is less than the load power demand and if battery SOC is greater than the minimum threshold value of battery SOC i.e. SOC_{batt}^{min}, then (P_{spv} + BESS) both are require to satisfy the power of load demand. So in this case the power management scheme operates when both (P_{spv} + BESS) delivers power to essential and non-essential loads on the priority basis. Hence the battery SOC gradually reduces to its lower value i.e. SOC_{batt}^{min}.

CASE V: $SPV_{power} < P_{load}$ **and** $SOC_{batt} < SOC_{batt}^{min}$

In this case if the power generated from SPV array is less than load power demand, and if the SOC of battery is less than the minimum threshold value i.e. SOC_{batt}^{min}. Then the load demand of power management scheme operates when both (P_{spv} + BESS) delivers power to essential and non-essential loads on the priority basis.

CHAPTER 4

SPV BASED DC GRID

4.1 Introduction:

The main objective of this research work is to put forward a cost efficient method for DC distribution in rural areas and remote locations. The DC house gets powered by solar PV array which is backed up by battery energy storage elements. The DC powered house is not connected via grid. So, it gets the whole power by solar energy and BESS and hence it is called as standalone PV system. In recent days, the DC grid system are gaining more and more importance. The recent researches is also going on in the leading institutes and developed countries in order to bring the changes in conventional electrification.

The DC grid is one of the major replacements for existing and conventional AC electrification networks due to its high efficiency and lower losses. Rural as well as urban areas both are required for DC electrification. Most of the electronic appliances working today requires DC for their working. The initial conversion and conversion losses are avoided if these devices works directly on DC. The DC electrification does not requires synchronization with AC electrification, it can be drawn directly or indirectly from the renewable sources of energy. The architecture of DC system includes power electronics converters in each stage for rising and lowering the voltage as per the consumer requirements. DC-DC power converters provides stable voltage to distribution lines[22].

4.2 Architecture of SPV Based DC Grid

The schematic representation of standalone PV based DC grid is shown in figure 4.1. The entire system have the capacity of utilizing DC bus as the backbone and it distributes power to the community which consists the various households in a residential premises. DC distribution is considered for the DC loads at three levels of voltage: 48V (representing medium voltage residential appliances), 24V (representing low voltage residential appliances), 310V (representing high voltage residential appliances). 310V DC bus is obtained from 48V DC bus using step up converter. By using step down converter 24V DC bus is obtained from 48V DC bus. Moreover, at each level of voltage two different load resistance values have been considered, that changes with time to represent dynamically changing load. In case of 48V DC bus initially the resistance is represented as 25Ω that is changes to be 40Ω at time t= 2.5sec, In case of 310V DC bus, the load represented by 75Ω that changes to be 55Ω at time t= 3sec, finally for the case of 24V DC bus, the load is initially represented by the resistance of 20Ω that changes to 40Ω at time t=2sec. The PV units in the entire system have linkage with the DC bus that is connected through DC/DC converters. These converters have tendency to extract maximum power of the DC power sources whose fluctuations depends on the intensity of solar irradiance.

Now the spread of DC power feeding is observed widely due to its high efficiency, safety and durability. The DC distribution reduces the facility cost and energy dissipations during the initial conversions. This is because the (SPV+BESS) DC grid connected mostly with the current energy-saving appliances that works on DC.

This system works without the requirement of long transmission lines to carry solar power from remote areas. Renewable energy sources and loads are closely located with each other in the community. The excessive and deficiency of powers are the variable factors that is to be compensated to keep balance between energy supply and load demand. The power compensation and short term fluctuations from solar system is done through storage batteries and bidirectional converters.

The SOC of BESS measures the time integral difference between supply and load demand in DC grid system. The amount and direction of grid regulation connection requires protective relays. This scheme connected with bidirectional converter in order to charge the battery during day time when the irradiances are high and power the loads during night time. The DC grid have a good self-adjustability. A storage battery system have a large capacity that easily respond for changes in supply and demand. DC grid have the advantage of great resistance from disasters. Even when the electric powers and fuels are not supplied from the outside, we have the electric power generation source that can be used independently and continue to meet the load demand.

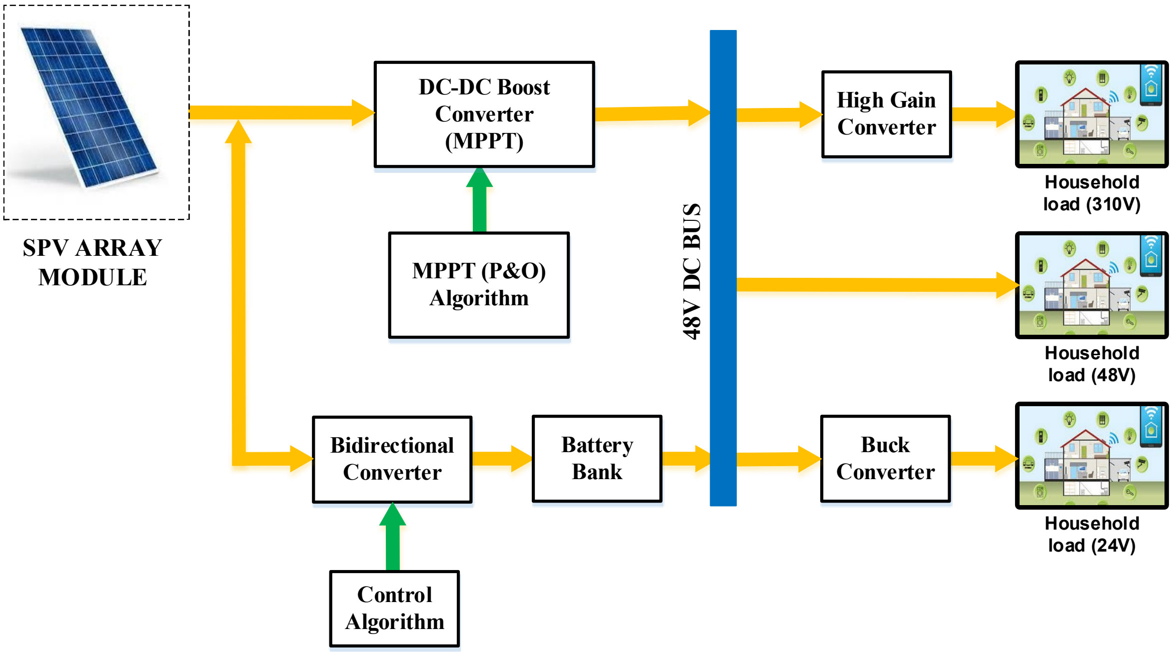

Figure 4.1 SPV System Integrated With BESS and Household Loads

Figure 4.1 shows the DC grid integration which consists of renewable energy sources i.e. solar PV array for power generation, maximum power point tracker (MPPT) with P&O algorithm, power electronics converter, battery energy storage elements and household appliances.

4.3 Benefits and Challenges of SPV Based DC Grid:

The design of DC houses are more beneficial in the area where less or no access of electricity through the grid supply. The unfortunate houses are powered to improve the life style of living. From figure 4.1 in the section 4.2 represents the solar PV based standalone DC homes which shows the autonomy and independency from the utility grid.

The advent of power electronic devices made a huge impact on DC distribution in the remote and rural area for DC electrification. It can easily be integrable with PV system and simple coupling with battery energy storage system (BESS). One of the major advantage for DC distribution system are that it is feasible for low, medium and high voltage applications. Researches also proven that if losses in DC-DC converters are reduced, then efficiency of the system improved significantly. The efficiency of converters varies from 85-90 % depending upon the manufacturing. While the construction of DC house, following conditions should be follows:

1) There should be minimum energy losses when the transfers of power from source to load.
2) There should be nominal voltage drop across each appliances
3) Cost of Solar PV based DC electrification should be more economical when compared to conventional AC electrification.
4) The installation and control of DC electrification must be simple and safe for the users.

Some of the benefits of solar PV based DC electrification are as follows:

1) It can be easily interlinked with renewable energy source and removes initial stage of conversions.
2) It can be easily interlinked with the battery energy storage system without any further conversions.
3) DC electrifications for low and medium voltage appliances are safer and reliable when compared to conventional AC electrification.
4) There is no skin effect and negligible transmission losses.
5) The value of DC appliances ratings are very lower than AC appliances.
6) The voltage conversion from one level to another level is omitted in the DC electrification system.

The challenges faced by the DC house electrifications are as follows:

1) DC appliances are not as much familiar as AC appliances.
2) The conductor diameter increases due to its high current carrying capability when compared with AC system.
3) Transient current in case of DC switching is higher.

Safety requirement for the DC low voltage installation are as follows:

In order to design the low voltage DC house, safety requirement for DC system installation are mentioned below. Following conditions determines the wire diameter which are as followed below:

1) Temperature tolerance of the conductor is very high.
2) Voltage drop will be limited in the wire diameter.
3) DC low voltage installation is expected to sustain mechanical forces caused by short circuits.
4) The other mechanical forces should check the endurance of conductors.
5) Short circuit protection works at maximum value of impedance.

4.4 Application of DC Grid

a) 24V DC Voltage:

It is one of the standard voltage level at which energy is supplied to electronic devices and IT equipment's. At 24V DC supply the energy is supplied safely and efficiently. With the use of 24V DC distribution the energy savage is from 15% to 45%. Electricity supplied at the lower voltage level is very safe and efficient. 24V DC supply has the advantage of producing less arc generation. Risk factor in the 24V DC is very less because at this voltage level the person have very less chance to get electric shock. LVDC appliances working more efficiently with DC voltages. This voltage level application is mostly used for relay operation, protective devices and SCADA operations.

b) 48V DC Voltage:

48V DC bus is the standard DC bus lines which power up the most data processing centres, electric vehicles and industrial equipment's. 48V DC voltage is sufficient for microprocessors and its related peripherals to operate electric motors and pumps. This voltage is low enough not to cause human hazards and chosen as a standard value for manufacturing lead acid batteries for power back up. Cost of cables and energy consumption is lowest at this voltage. As number of converters reduced in the DC system, more the savings will be achieved by integrating with renewable energies.

C) 310V DC Voltage:

The 230V AC appliances insulation can withstand on 310V DC voltage without any rupture. The 310V DC is one of the best chosen voltage due to the reduced number of converters and higher efficiency. With the help of BESS and battery backup, the reliability of the system increased further in every critical condition. 310V is higher and safer voltage of DC system. This system is applicable for heavy duty appliances includes refrigerators, washing machine and air conditioners. In case of DC 310V system the AC to DC conversion steps is removed. 230V AC appliances can easily run on 310V DC system, so replacement cost also become less than the other system, since most of the existing conventional appliances do not need to change circuits and cables. With the computer networks popularization and fast developments of data service, the power supply of UPS reflects more problems in the reliability of power supply, safety and have high energy consumption. Meanwhile, DC electrification for high voltage provides higher safety, higher performance price ratio, higher efficiency and high energy saving with the help of intelligent control management techniques.

4.5 Energy Efficiency in DC Grid

In a DC distribution system the efficiency depends upon the losses in the cables and the converters (power electronics+ electro-mechanical) conversion stage.

$$P_{losses} = P_{cables} + P_{converter} + P_{mechanical} \tag{4.1}$$

P_{cables} - It indicates losses occurs in distribution cables. Distribution line also depends upon losses in power cables.

$$P_{cables} = \left(2\frac{\rho}{A}\right)\left(\frac{P}{\eta N V_{dc}}\right)^2 2l\left(\frac{N^2+2N+2}{6}\right) \tag{4.2}$$

Where ρ is the electrical resistivity, A is the cross- section area of cable, L is the total length of the cable, P is the power that load absorbs, η is the converter efficiency, V_{dc} is the voltage level of DC distribution line. N is the number of blocks in the building.

$$P_{converter} = \left(\frac{1}{\eta}\right)P \quad (4.3)$$

The $\mathbf{P_{converter}}$ is the losses occur in the converter that is inversely proportional with the converter efficiency. DC-DC converter efficiency (η) is much higher than DC-AC-DC converter. The present efforts and research is focused towards enhancing the efficiency of a DC distribution for residential households. The DC/DC solid state transformer (SST) is capable for replacing the conventional transformer. This researches further aims for investigation for the efficiency improvement of the system via using modular architecture of DC/DC SST. The converter losses decrease and system efficiency increase from this architecture. The efficiency of power electronic transformer is crucial for the efficiency of the entire system.

4.6 Protection of SPV Based DC Grid

In the protection strategies of DC grid, two types of protection is classified i.e. unit type and non-unit type. The unit type protection schemes works for the protection of fixed zones of DC grid, DC bus, converters, energy storage devices, loads etc. Unit type protection scheme unable to procure back up protection. On the contrary non unit type protection depends upon threshold setting of electrical quantities. Unit type protection have the advantages of providing large protection coverage area and free operation for protection devices of neighbouring zone. It's also includes overcurrent, under/over-voltage, current and voltage derivative schemes.

The speed and accuracy of severe communication outage is accomplished by unit protection, whereas, reliability and necessary discrimination assures by the non-unit protection schemes. For fault detection the local measurement of voltage and current signals relies on single ended protection schemes. Communication of advance sensing device and intelligent electronic device comes under double ended protection schemes.

The line impedance in the DC grid is very low, Due to the fault current the duration become too high. During small interval, fault current reaches to hundreds of amperes. As a result, the sensors used in the protection of DC grid have high sampling rates and speed. The communication system will be very fast and reliable. With the impedance sensor device communication and control system of the protection devices are identified in a fast, reliable and high precision manner. The faulty section is identified and detected by several protection methods in DC distribution system which consists of current derivative, overcurrent differential protection and directional overcurrent distance scheme which have been proposed to detect and identify faulty parts.

DC protection schemes evaluated on the following features:

Speed: Identification of fault is done very fastly in order to protect the equipment from getting damaged.

Selectivity: The faulty section is identified by the protection method, protection of the device will not operate for the external fault.

Sensitivity: All the faults includes high-impedance fault which must be detected.

Reliability: The faulty section of the protection system gets isolated, when primary protection or communication system fails to operate.

4.6.1 Overcurrent Protection:

One of the most common and permeating protection devices for MVDC and LVDC system is over current relay. Due to transient nature of DC fault current, the appropriate coordination of overcurrent relay become challenging. The selectivity is ensured to follow specific time delay margin. The modern converter is equipped with over current relays which considered as fast acting current limiting CB for fault current interruption. The relays embedded into the converter to identify the fault in an interval of few milli-seconds.

For the high resistance fault in DC grid, the magnitude of fault current is very low. So it is very resilient job to identify the fault in DC grid. In order to detect high resistance fault, the voltage transient of damping frequency generated by capacitor and inductor equipped with over current relay. The setting up-gradation of relay is assisted by communication. With the help of direction blocking features, relay selectivity improves. The relays of one end sends trip signal to CBs of both end of protection line and such process is called inter-tripping of relays.

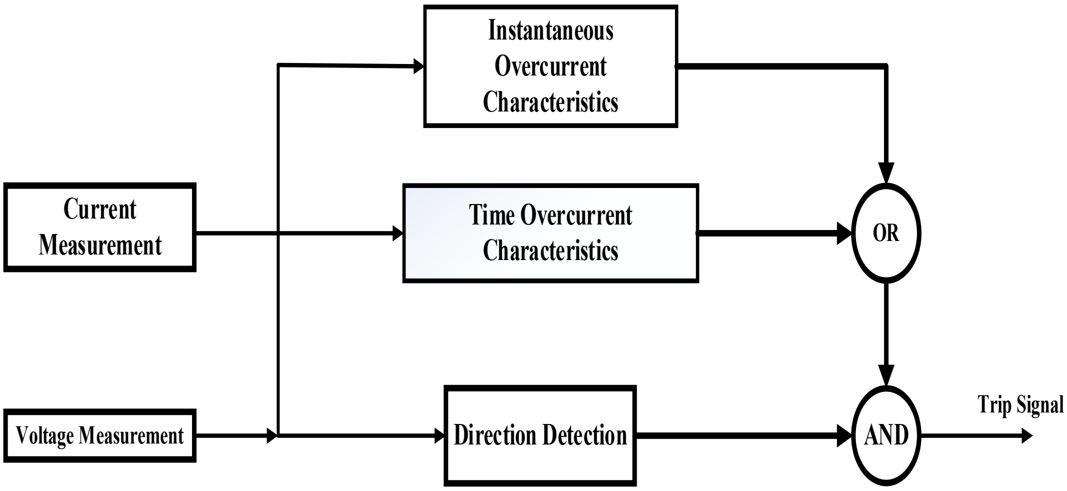

Figure 4.2 Block diagram of directional overcurrent relay

The change in the direction of fault current to detect and locate the fault system is called as protection algorithm. The protection redundancy increases with the help of directional overcurrent based strategy. Overcurrent protection with different features approaches the accomplishment of necessary protection requirements excluding the event of rapid transient. Current measurement error causes due to DC fault current and stray inductance effect of DC circuit breaker. Figure 4.2 represents the block diagram of directional overcurrent relay.

4.6.2 Differential Current Protection:

The differential protection scheme consists of differential relay which have tendency to measure the current amplitude of source and load by using current transducer. It measures the difference between incoming and outgoing current named as differential current. With the value of differential current the fault occurrence is predicted. The poor synchronization between the DC linkage of source and loads influences the operation of differential protection scheme, such phenomenon is known as transient behaviour system . Further, this analysis also quantifies the requirements for fast and accurate fault detection.

The DC differential current measurement is designed to achieve high speed differential protection. The differential protection scheme are mostly used for medium voltage DC appliances. It includes communication based protection which uses the current transducer to facilitate the transducer output to integrate easily with the digital processing devices. The communication delay ensures by the employed ethernet cables. For synchronization purpose, this scheme uses synchronizing relay that necessitates the installation of GPS transducers. The differential protection scheme have the advantages of high selectivity and fast operation which makes current differential protection scheme as a viable protection solution for complex DC grid.

4.6.3 Voltage Based Protection:

The extensive voltage variation, voltage drop and rate of change of voltage during the faults are utilized for the establishment of voltage based protection strategy. In order to get better protection sensitivity, the fault location point and state of DC grid operation can be made independent. Local measurement and fast protection scheme does not require any communication infrastructure in the voltage based protection scheme. Voltage protection scheme is single-ended.

4.6.4 Distance Protection:

Distance protection usually aided in the transmission and distribution system because it requires stricter selectivity and sensitivity. This scheme have tendency to isolate the fault without the requirement of any communication scheme between each relay. It calculates the impedance between the relay location and fault point. Measuring voltage and current at the relay point calculates the line impedance. The fault is identified within the protection zone.

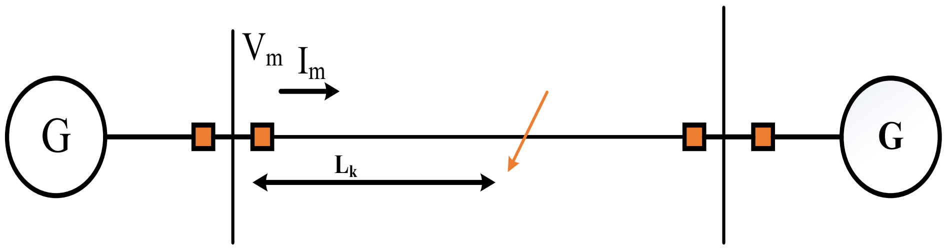

Figure 4.3 Schematic representation of distance protection

The calculation of Z_m is based upon the measuring voltage and current at the relay point. When the system working under the normal operation, Z_m equals to the load impedance Z_L. If the fault occurred on the line segment the measuring impedance (Z_m) equals to line impedance Z_L.

$$Zm = \frac{V_m}{I_m} \tag{4.4}$$

With the calculation of measuring impedance and comparing it with setting Z_{set}, it realises detection and isolation of the fault.

Figure 4.3 represents the schematic diagram of distance protection relay. Voltage and current measurements are done by CTs and VTs. The signals further sent to zone 1, zone2 and zone3 respectively. The measurement of direction in the relay is based upon the cross polarization in order to ensures the dependable fault direction. From figure 4.4 it is observed that there are three protection zones are available here.

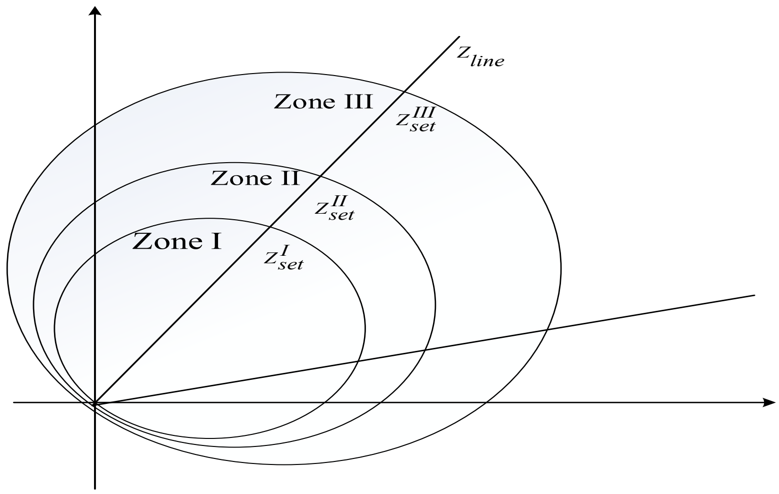

Figure 4.4 Characteristics of Mho-based distance relay

Z_{set}^{I} applied to zone I protection. Z_{set}^{II} applied for zone II protection that provides protection for the remaining protected lines that is not covered by Zone I and backup protection for the remote end bus. Z_{set}^{III} is applicable for Zone III that provides remote back-up protection for adjacent lines. The protection zones can be expressed as $Z_{set}^{I} < Z_{set}^{II} < Z_{set}^{III}$. Zone I is set as an instantaneous protection zone. Zone II and Zone III have definite time-stepped delay. Figure 4.4 represents the characteristics of Mho-based distance relay.

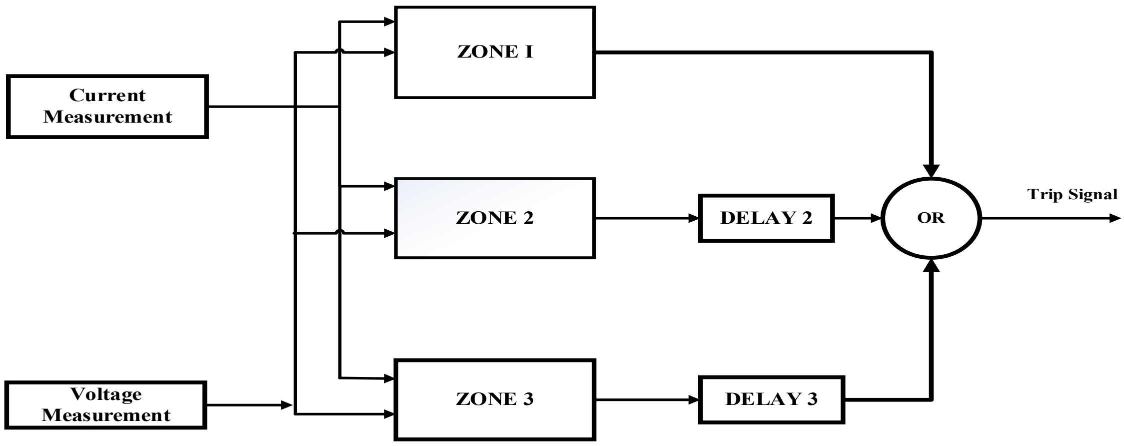

Figure 4.5 Block Model of Time Stepped Distance Relay

Distance protection with mho-based characteristics (forward direction) is adopted in this test. From the amplitude comparisons between Z_m and Z_{set}, relay decides whether to trip the breaker or not. If $Z_m < Z_{set}$, occurrence of the fault takes place in the protection zone. The fault does not occur in the protection zone when $Z_m > Z_{set}$. Figure 4.5 represents the block diagram of time stepped distance relay.

Table 4.1 represents the Comparison of protection method of DC grid.

TABLE 4.1

Comparison of Protection method in DC grid

Protection method	Principle of fault detection	Advantages	Disadvantages
Over-current protection	When predetermined value of current gets exceeded, it indicates the presence of fault (short circuit).	a) Algorithm is simple. b) Applicability in fault interruption method.	a) Limited to low and medium voltage DC equipment. b) It should be used in combination with other methods or via communication networks to give selectivity.
Differential protection	When the differential current (difference between input and output currents) is higher than pre-set threshold value, the fault is detected.	Better sensitivity Independent from fault impedance Independent from current direction.	Needs fast and accurate data synchronisation.
Voltage based protection	Utilizes Park-transformation of voltage distribution at the terminal of Distributed Energy resources.	Effective for solid fault detection.	Doesn't ensures protection against high impedance fault.
Distance protection	Its basic principle is to divide the voltage at the relaying point by the measured current. The apparent impedance is measured so that it can be compare to the reach point impedance. If the measuring impedance is less than the reach point impedance, there is an existing fault between the relay and the reach point.	Simple algorithm is required.	Sensitivity to the fault resistance is more. Need a backup unit. Limited accuracy in short lines.

4.7 Standardization of DC Voltage Distribution:

Levelling of the DC voltage distribution is one of the main challenges in the DC grid system. Different voltage level is required in distribution generation with residential, commercial and industrial loads. The non-standardization voltage level became a great resistance in DC grid system. Without standardizing the voltage, it is not possible to standardize the appliances, devices and equipment's directly. Sometimes it become very difficult for the industries and manufacturers to design the products to handle different voltage levels and standards. In order to speed up the adoption of DC grid technology and related products, standardizing the voltage should be the highest priority. The voltage standardization will attract stakeholders for taking this technology at serious note. Table 4.2 shows DC distribution and their power application with various voltage level. Table 4.3 shows standard comparison of DC grid.

TABLE 4.2

DC Distribution with Various Voltage Level

	APPLICATIONS	VOLTAGE(V_{DC})
1	USB and other small electronic equipment's	<5V
2	Cars, desktop computers	12V
3	LED lights, trucks, fans	24V
4	Future PV installation	48V
5	Power over Ethernet	50V
6	Energy Storage System(ESS/Batteries)	10V/220V
7	Future residential and commercial building distribution	310-400 V

TABLE 4.3

Standard Comparison Table for Dc Grid

Standard	Title/Description	Scope/application	Status
IEEE P2030.10	DC micro grid applicable to access rural and remote electricity access.	Design, operation, and maintenance of a DC micro grid for rural or remote applications are covered. The standard also specifies low-voltage DC and AC power requirements for off-grid loads.	Active
IEEE 946-2004	Design of DC Auxiliary Power Systems for	It gives out a blueprint for developing DC auxiliary power systems for	Active

	Generating power stations.	nuclear and non-nuclear power plants. It also includes a roadmap for BESS, equipment ratings, interconnections, and instrument protection.	
IEEE 1547-2018	It provides the connectivity and interoperability standards for distributed energy resources, as well as the related Electric Power Systems Interfaces.	Its application is to Characterize the various interconnection issues of DERs, technical requirements and penetration level.	Active
IEEE DC@ Home	DC-Powered House.	Standard DC micro grid for LVDC application	Active
IEC SEG 4	A) Applications in LVDC appliances. B) Applicable for low voltage power distribution. C) Safer protocol for use in Developed and Developing Economies.	A) Low voltage direct current applications (up to 1500V) . B) Focuses on energy efficiency. C) EMC reduction, protection, and Grounding issues.	Active
IEC SEG 6	Applicable for non-conventional distribution networks / Micro grids. Applicable for rural and developing market which serve the need of potential huge market.	A) Evaluate the usage of LVDC in different environments to increase energy efficiency. B) Evaluate to establish new ideas for optimal use of LVDC power.	Active
IEC SEG 9.	Smart Home/Office Building Systems	For a Smart Home/Office Building System, standard, gaps in electrical installations, and communication technologies are all important.	Active

4.8 Case Studies and Results:

The operation and control of standalone SPV and BESS based DC grid system uses power flow management scheme which is simulated under MATLAB/ Simulink environment. The voltage and power ratings of SPV array, BESS and loads are represented in Table 4.4. The battery time constant plays a major role in developing the charge/discharge techniques in the simulation analysis. The battery time constant is taken for time t=5sec. With this large time constant battery takes more times for charging and discharging. Smaller changes in SoC, proves the working of controller and its circuit is good enough to prove the control stratergy of the DC grid is robust.

with the essential and non-essential loads the performance of DC grid is analysed. The various practical conditions is observed for the power flow management in DC grid such as variation of irradiance pattern, charging/discharging of battery and different modes of operation for DC grid:

The different irradiation level is considered for the operation of PV system, battery and load in DC grid i.e. from 1000W/m^2 to 0 W/m^2 for time t=0 to t=5 sec.

TABLE 4.4

Representation of System components and its parameters used in simulation

COMPONENTS	PARAMETERS	VALUES
PV MODULE	Max. Power @1000 W/m^2 V_{OC} I_{sc} I_{max}	250.15 W 37.3 W 8.66 A 8.15 A
BATTERY	Capacity Nominal voltage No. of battery in series Initial state of charge	200Ah 48V 2 50 %
DC LINK	Voltage a)Low voltages b) Medium Voltages c) High Voltages	(24V)- 40W (48V)- 142W (310V)- 2085W
DC LOADS	Desktop LED Bulb Fan LCD-TV Refrigerator	100W 20W 60W 150W 80W
BIDIRECTIONAL CONVERTER	DC link capacitor(source side) DC link capacitor (Load side) Energy transfer inductance Switching frequency	1000µF 220µF 1mh 5khz

Case I: When irradiance level is 1000W/m^2 and time duration t=0 to t=2 sec;

In this case the irradiance level is 1000W/m^2 and SPV standalone system operates at maximum power point (MPP). The power generated by the source at this point is more than the power required by the load. So it delivers power to all the essential and non-essential loads. The excess power is fed to the battery. The battery will be in charging state. The SoC of battery will increase from its minimum threshold to maximum value. So with this condition SPV array supply power to load and battery both. Equation 4.5 represents balance current of SPV, BESS and load.

$$I_{SPV} = I_{battery} + I_{Load} \tag{4.5}$$

Case II: When the irradiance level decreases from 1000 W/m^2 to 800W/m^2 during t= 2 to t= 3 sec;

In this case the generated power from SPV array is equal to the load power demand. The solar PV array system operating with MPP and it fulfil the requirement of both essential and non- essential loads. Hence source currents equals to load current as shown in equation 4.6.

$$I_{SPV} = I_{Load} \tag{4.6}$$

Case III: When the irradiation level changes from 800 W/m^2 to 600 W/m^2 during time t=2 to t= 3 sec;

In this case the irradiance pattern changes from 800 W/m^2 to 600 W/m^2 during the time duration of t= 2 to t= 3 sec. Hence the generated power is less than the load power demand. So in order to meet the power balance sum of the power from PV system and battery is fed to all the essential and non-essential loads. So, battery gets discharges and supply the power to meet the requirement of load demands. Battery SoC decreases gradually. Equation 4.7 represents balance current of SPV, BESS and load.

$$I_{SPV} + I_{battery} = I_{Load} \tag{4.7}$$

Case IV: When irradiation level changes from 600W/m^2 to 400W/m^2 during time t= 3 sec to t=5 sec;

When the irradiation level changes from 600W/m2 to 400 W/m2 during time t= 3 sec to t =5sec. In this case SPV power is much lesser than the load demand. The Battery power is constant. (SPV+BESS) both cannot meet the requirement of load power demand. So the non-essential loads in the households are curtailed and the battery SoC is gradually decreases towards its lower value of threshold. There will be deficiency in Source power generation and it is not in the position to supply load current I_L.

$$I_{SPV} < I_{Load}$$

The operation mode of DC grid is shown in TABLE 4.5

TABLE 4.5

Different operating mode of DC grid

CASES	Irradiation (W/m^2)	Time(sec)	SPV, Battery operating condition
CASE-I	1000	t= 0 to t= 1 sec	P V: MPPT mode Battery: Charging
CASE-II	800	t= 1 to t= 2 sec	PV: In MPPT mode Battery: Disconnected
CASE-III	600	t= 2 to t= 3sec	PV: MPPT mode Battery: Starts discharging
CASE-IV	400	t= 3 to t= 5 sec	PV: MPPT mode Battery: Supplying power by discharging itself. Loads: Non-essential loads disconnected.

The Battery Energy storage system integrated with DC grid which is implemented by using MATLAB Simulink Platform. The system parameters are represented in Table 4.4. The irradiance level of SPV array is settled to 400,600,800 and 1000 W/m2. The DC loads have been considered at three different voltage levels- 48V, 24V and 310V.

Case A: For 24V DC Distribution:

This voltage is applicable for low voltage DC appliances. For this voltage two different load resistance value is considered, which are changed at time t= 2 sec to represent a dynamically changing load. For 24V DC bus, initially the load is represented by resistance R_1= 20Ω that changed to R_2= 40Ω after time t= 2 sec. The current will be changing at that point, but the voltage will remain constant. Figure 4.6 represents that current will be changing at t= 2.0 sec but the voltage will remain constant. Figure 4.7 represents that current will be changing at t=2.0 sec but 24 V DC voltage is maintained constant at zero irradiance (i.e. during night time).

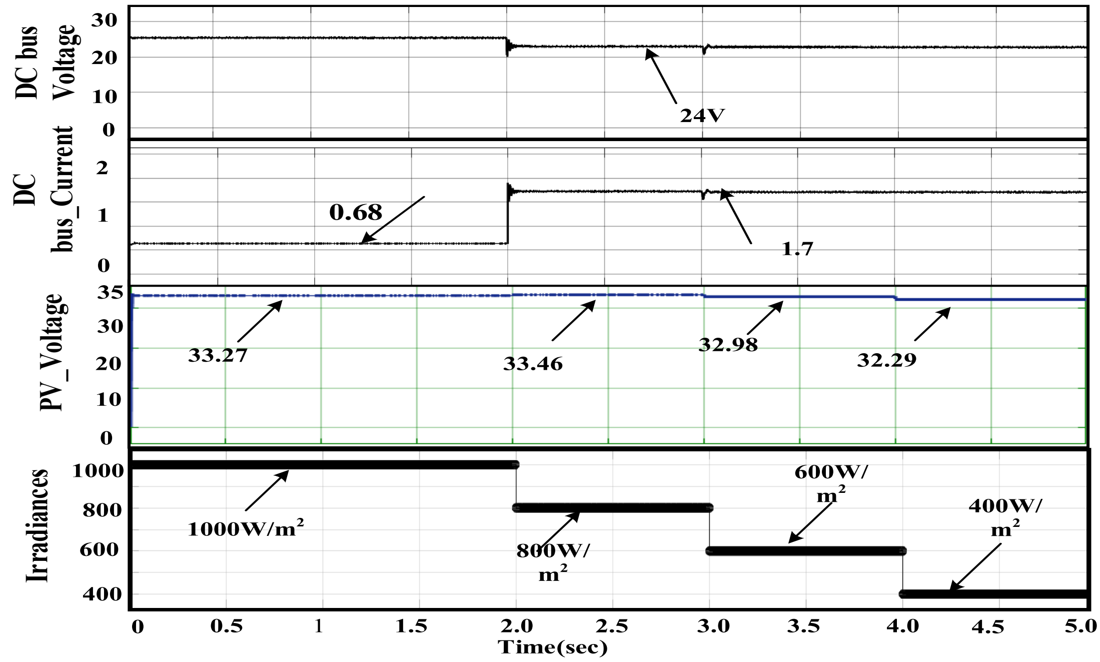

Figure 4.6 Voltage stability of 24V DC bus with different irradiances

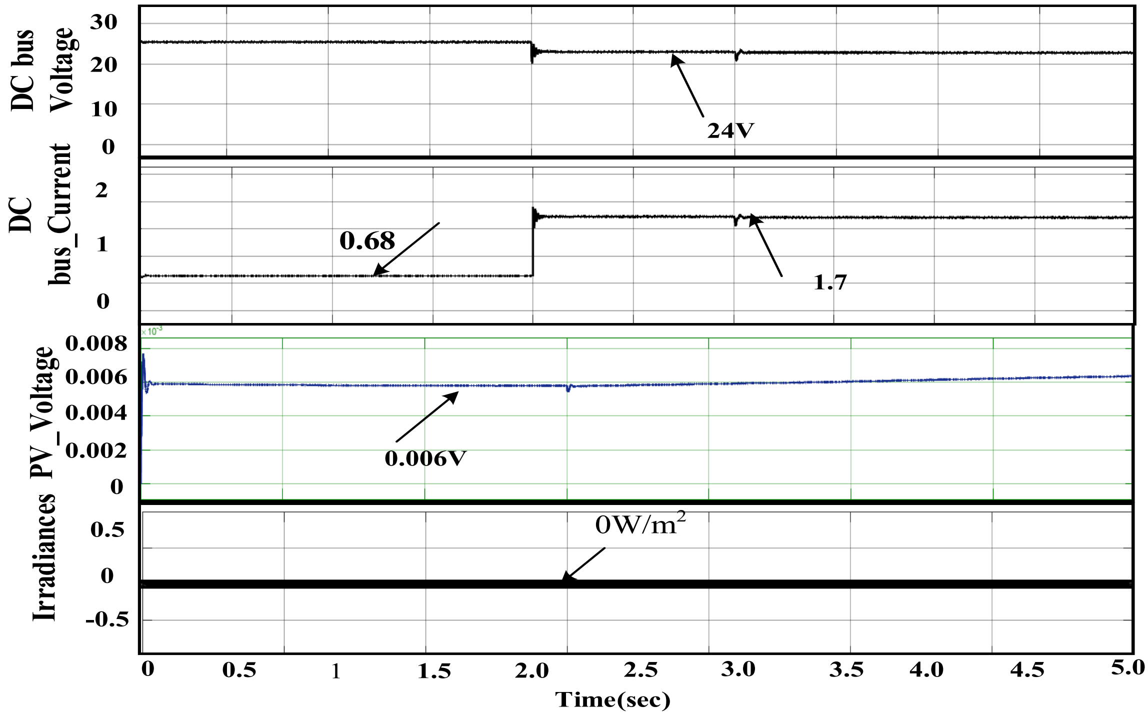

Figure 4.7 Voltage stability of 24V DC bus during night time

Case B: For 48V DC Distribution:

This voltage is applicable for medium voltage DC appliances. For this voltage the other two different load resistance value is considered that changes at time (t=2.5 sec) to represent a dynamically changing loads. For the 48V DC bus, initially the load resistance R3= 25Ω that changes to R4 = 40Ω. At time t= 2.5 sec, the switch is closed and current changes, but the voltage will remain constant. Figure 4.8 represents that current will be changing at t= 2.5 sec but the voltage will remain constant. Figure 4.9 represents that current will be changing at t=2.5 sec but 48 V DC voltage is maintained constant at zero irradiance (i.e. during night time).

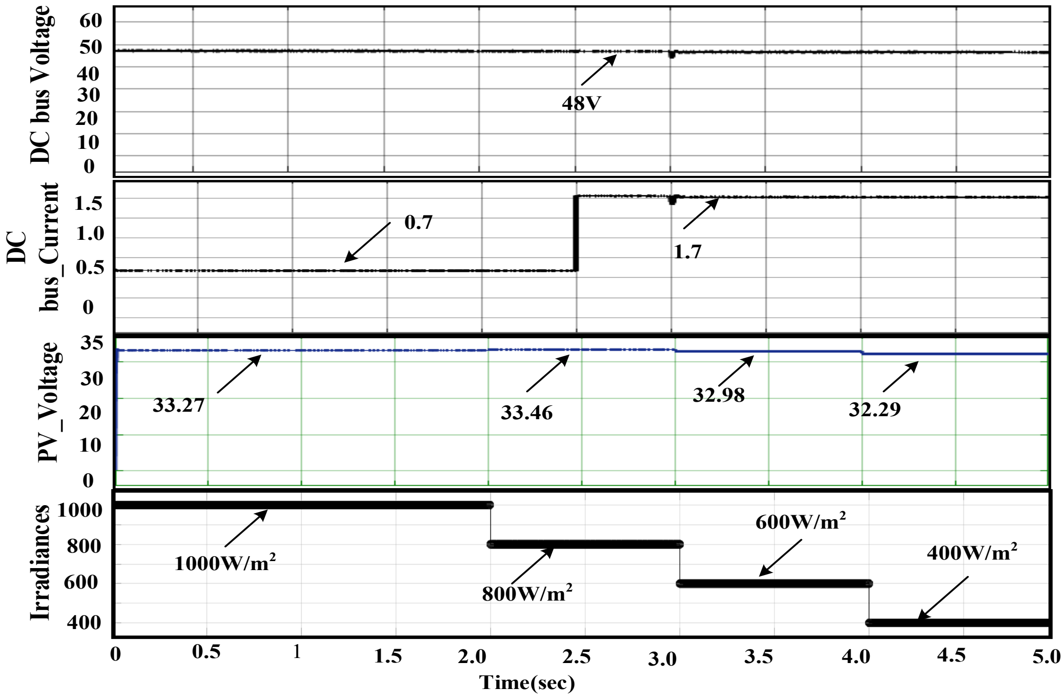

Figure 4.8 Voltage stability of 48V DC bus with different irradiances.

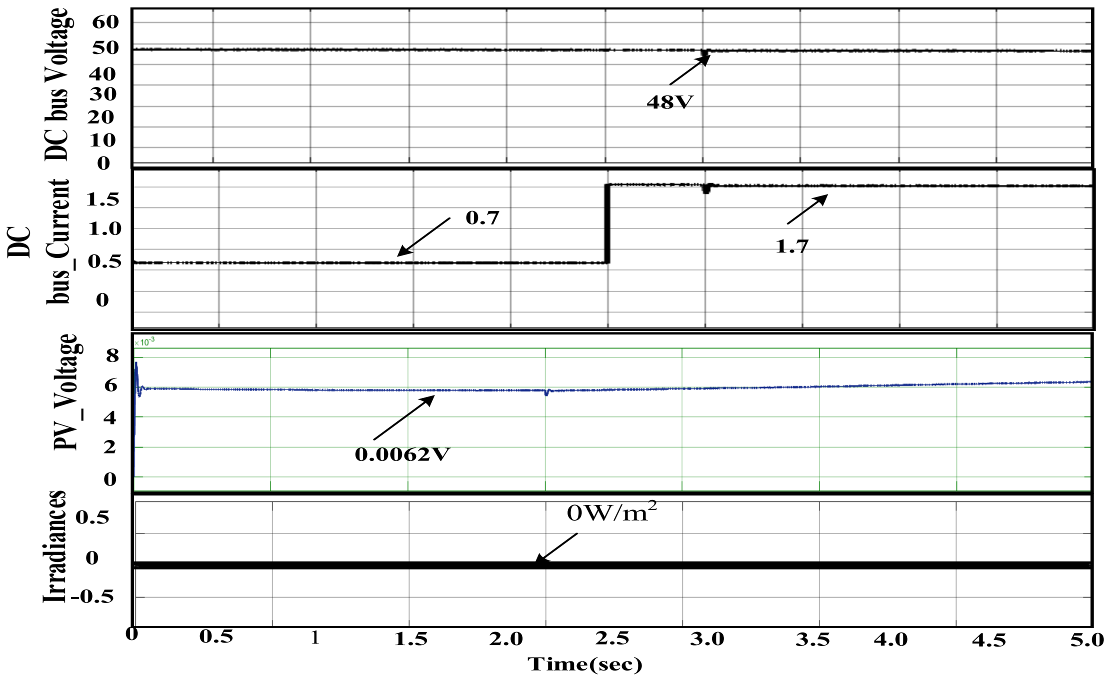

Figure 4.9 Voltage stability of 48V DC bus during night time

Case C: For 310 V DC Distribution:

This voltage is applicable for high voltage DC appliances. For this voltage level two different load resistance value has considered, that is changed (at time t= 3 sec) to represent dynamically changing load. For this voltage level, initially the load is represented by resistance R5= 75 Ω that changes to R6 = 55 Ω. After time t= 3 sec, switch closes and current changes at that point, but the voltage still remains constant. Figure 4.10 represents that current will be changing at t= 3.0 sec but the voltage will remain constant. Figure 4.11 represents that current will be changing at t=3.0 sec but 310 V DC voltage is maintained constant at zero irradiance (i.e. during night time).

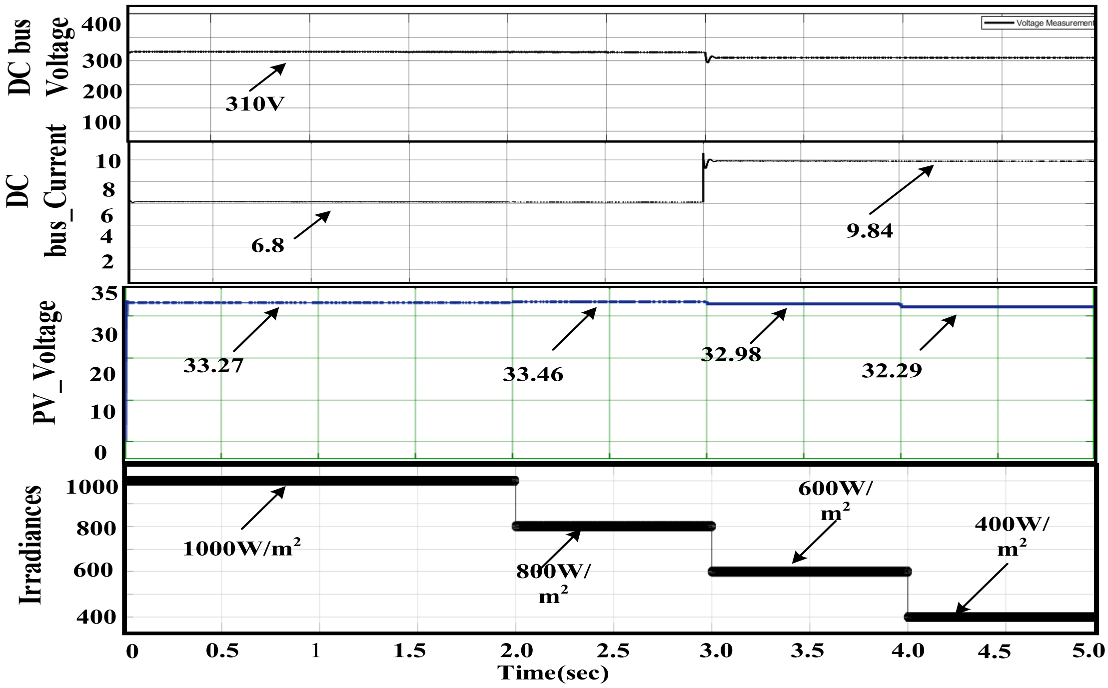

Figure 4.10 Voltage stability of 310V DC bus with different irradiances.

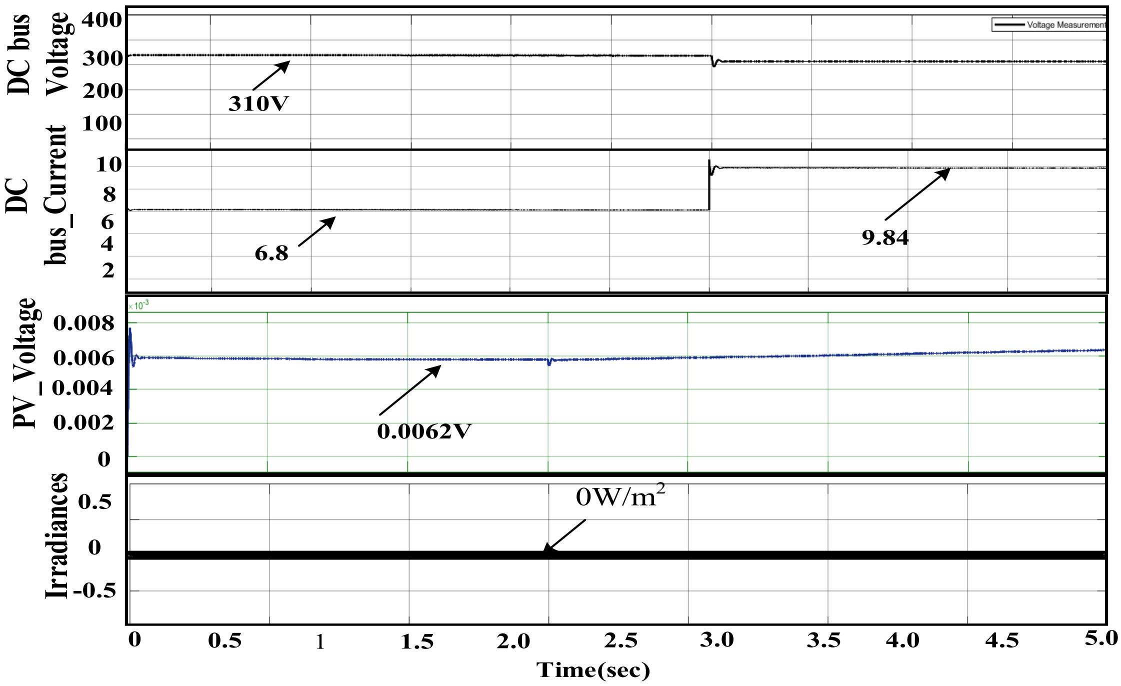

Figure 4.11 Voltage stability of 310V DC bus during night

CHAPTER 5

SPV BASED DC GRID FOR HOUSEHOLD LOADS

5.1 Introduction

This research work mainly discusses to tacle the hinderances with respect to the key development and integration effort for mixed AC and DC distribution with standalone solar system. The innovation of this project is concluded to perform comprehensive benefit analysis of hybrid AC/DC distribution system which considers potential benefits on system voltage, harmonic minimization and loss reduction. This research work develop holistic model for the hybrid AC/DC distribution system and also develop generalized control algorithm for hybrid AC/DC system.

Further more, In order to fulfil the requirement of hybrid loads the following methodology has been adopted; Firstly, PV pannel are connected in series and/or parallel to generate desired DC voltage and current. Then in order to generate alternating voltage of 230V and rated frequency 50Hz, a DC to AC inverters are required. The PV inverter installation is between the PV generators and load. For the LVDC appliances step-down converter is installed at main DC bus to lower the voltage and meet the requirement of DC loads. The energy transfers from DC source to AC load requires various constraints like secure operating conditions, economical efficiency and the environmental benefits.

In todays arena, power used by most of low voltage appliances are DC in nature. So renewable based energy system first converts DC into AC and then back to DC and making it expedient for supplying power into homes and offices buildings. These days many of the modern appliances manufactured internally on DC power so the system and requires two step conversion (DC→AC→DC) which makes the losses of energy up to 30%. This two steps conversion process is done for even low voltage DC appliances which makes losses upto 30%. So, in order to eliminate the losses ,we need to transform present distribution system from AC to DC. (which links DC loads directly to DC Bus), this makes system more economical and efficient.

The schematic representation of standalone PV based DC grid for AC and DC distribution is shown in figure 5.1. The entire system have the capacity of utilizing DC bus as the backbone which distributes power to community that consists of various households with different DC and AC loads. This standalone SPV system is considered for DC loads for two level of voltages. 48V (representing medium voltage residential appliances), 24V(representing low voltage residential appliances) and it consists of AC distribution for supplying electricity to AC loads. The architecture follows the following steps – firstly the SPV is modelled by connecting solar cells in series or /and parallel for producing sufficient amount of power to cater requirement of AC and DC loads. It is also called as “ off grid solar power system”. It is majorly used in the areas where the grid utility power is not available. These systems are mainly independent of any other sources of energy. The generated energy by sun is not only utilized during the day but excess amount of energy is also stored in the battery banks which is used when there is unavailability of sun. These architecture systems are further applicable where supply of electricity is immediately required with minimum price. Its installation requires following components to make entire system working:1) PV modules 2) Charge controllers 3) Battery banks 4) Loads 5) AC inverters for the system where alternating current is required at loads.

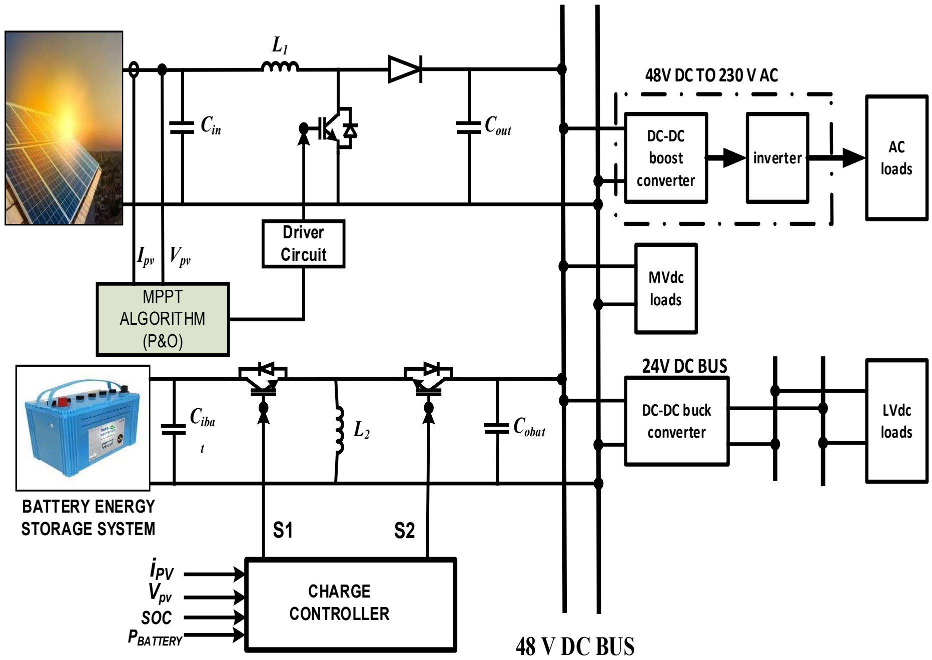

Figure 5.1 SPV integrated system supplying power to AC and DC loads

Lithium ion batteries are used here for the storage of excess electricity and provide power to loads during night time.

230V AC bus is obtained from 48V DC bus using high gain converter and inverter. The 230V AC bus is used for supplying the power to all the connected AC load appliances. The 24V DC bus is used to provide power to low voltage DC appliances. The 48V DC bus provides power to all the medium voltages DC appliances. In case of 48V DC bus, The resistance initially taken as 25Ω that changes to 40Ω at time t= 2.5 sec, for 24V DC bus resistances initially taken as 20Ω that changes to 40Ω at time t=2 sec. The PV units of the entire system have the linkage with DC bus that connected through DC/DC converters. These converters have the tendency to extract maximum power of renewable energy sources whose fluctuation varies with the intensity of solar irradiances.

5.2 Component Design of SPV based DC Grid for Household Loads

5.2.1 Inverters:

One of the most important devices for maximising the efficiency of renewable energy sources is the inverter. Interconnection of DC/DC boost converter and DC/AC inverters meets the AC load requirement of an SPV-based standalone system. The DC/AC inverter control technique must be capable of delivering sufficient active and reactive power to the load. The main goal of this circuit is to provide a sinusoidal output voltage that can be controlled in magnitude and frequency. It controls the unbalanced load voltage with a balanced sinusoidal with constant amplitude and frequency. The switching signals are created in such a way that the desired output is produced. Sinusoidal control signals of the desired frequency are compared with saw tooth waveform to produce switching signals. The generated switching signals of inverter switches are controlled in a manner to provide three phase output voltage. The harmonic reduction of inverter is easily done with SPWM techniques. In SPWM techniques, three sine waves and high frequency saw tooth signals waves are used to generate PWM signal. The sinusoidal waves are referred to as reference signals since they have a 120° phase difference. The frequency of these sinusoidal waves is determined by the frequency of the inverter output. All three sinusoidal modulating signals should be balanced in order to obtain a three-phase output voltage efficiently.

5.2.2 Battery:

Lithium ion battery is used for supply power to AC and DC loads simultaneously. The major reason of using lithium ion batteries for AC loads are that it has better life cycle, it requires no maintenance. It is equipped with a built-in battery management system to monitor changes in battery status, temperature, current and discharge. The deep discharge in Li-ion exhibits a constant decrease, which shows lithium ion batteries remain stable during deep discharge to supply power to load. A lithium-ion battery has opted for the power compensation.

Figure 5.2 represents the model of Lithium-ion battery with battery charge controller. Batteries are connected in series/parallel in order to increase the voltage and current as per required application. The voltage (V_o) of battery can be represented as the sum of voltage across internal resistors and internal voltage represented by equation 5.1.

$$V_0 = V_{B_{\min}} + (V_{B_{\max}} - V_{B_{\min}})\sqrt{\frac{SOC}{100}} \quad (5.1)$$

For the safety operation battery has to be kept within the minimum and maximum voltage(V_{Bmin} and V_{Bmax}).The battery charged by constant voltage V_{Bmax} till the voltage reaches to it maximum value. Meanwhile, the charging current starts decreasing. The SOC and internal resistances determine the battery current. The charging and discharging of lithium-ion battery represented by equation 5.2 and 5.3.

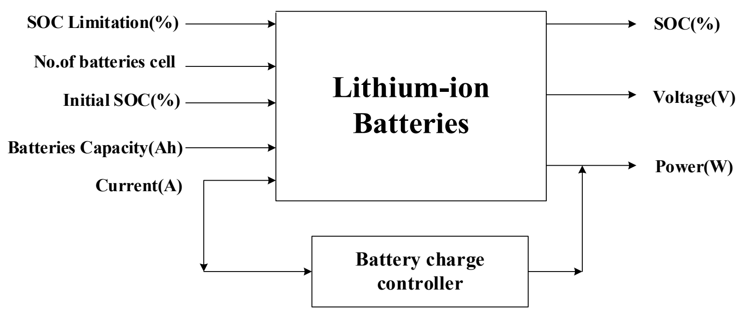

Figure 5.2 Structure of Li-ion battery system

$$C_{ch\_batt}(t) = (t-1)(1-\sigma)C_{\_batt} - [\frac{P_b(t)}{\eta_{inv}} - P_{pv}(t)] \quad (5.2)$$

$$C_{dis\_batt}(t) = (t-1)(1-\sigma)C_{\_batt} - \eta_{batt}[P_{pv}(t) - \frac{P_b(t)}{\eta_{inv}}] \quad (5.3)$$

Where, C_batt(t) and C_batt(t-1) are the available capacities(Wh) at t and t-1 respectively, σ is the self-discharge rate, P_{pv}(t) is generated energy by SPV system. P_L(t) is the load power demand at time t, η_{inv} is efficiency of inverter and η_{batt} is charging/discharging efficiency of the battery[30].

5.3 Battery Charging Algorithm and Load Design:

5.3.1 Battery Charging Algorithm

The constant current - constant voltage (CC/CV) charging technique is used with lithium ion batteries. A three-step charging method is used in the CC/CV charging algorithm. Constant current is delivered to charge the battery until the battery voltage increases to the maximum pre-set voltage ($V_{\max pre\_set}$), after which the charging voltage is retained constant at V_{pre_set} and the charging current decreases exponentially. The charging process is divided into three stages. In the first, the battery is in its original state, and the temperature and open circuit voltage (OCV) are evaluated. If both are within normal limits, OCV is less than the cut-off voltage (V_{cutoff}), then the battery is charged using the trickle charging (TC) technique.

In the second stage, when the battery voltage exceeds V_{cutoff} the CC mode sets in and start charging the battery. Further, the charging current is set to vary between 0.5 and 3.2 ° C. using lithium ion batteries. The battery voltage is charged to the pre-set value V_{pre_set} inside the third stage. After the third stage, the battery charging process shifts to CV mode, and the charging current begins to decrease. The minimum charging current ($I_{\min} < 0.1C$) or the maximum charging duration ($t_{\max} < t_{pre-set}$) are used to terminate the charging current.

5.3.2 Battery Sizing

In this section we have taken two types of loads, DC loads which consists of low voltage residential appliances that runs with the help of stepping down the voltage of DC bus, the other one is considered AC loads for high voltage residential appliances (i.e. Refrigerator, air-conditioner etc.). From the conventional consideration the compressor of refrigerator and air-conditioner composed with an induction motor which is ac in nature that runs with fixed speed. The rotational speed is working at particular input frequency and compressor works with fixed speed which produces high impact on compressor mechanics and its control mechanism.

Meanwhile, the inverter based technology for air-conditioner and refrigerator has invented now, which depends upon power electronics components for handling its driving equipment's. The higher loads appliances designed for 230 V AC, while lower and medium voltage residential appliances are made to work on 24 V and 48V DC respectively. Table 5.1 represents the respective loads of household.

TABLE.5.1 Load considered for household appliances

SR. NO.	Appliances	Quantity	Power Required(W)	No. of hrs.
1.	LED BULB(20W)	4	80	1
2.	Laptop(50W)	1	50	2
3.	Fan(40W)	1	80	2
4.	Air-condition(1200W)	1	1200	2

5.	Refrigerator(100W)	1	100	1
	TOTAL		**1510W**	

Overall energy consumption from the load appliances:

$$Wh_{load} = (20\times4\times1)+(50\times2\times1)$$
$$+(40\times2\times1)+(1200\times2\times1)+(100\times1\times1)$$
$$=(80+100+80+2400+100)=2760\text{Wh}$$

The nominal dc bus voltage is used in the proposed manuscript is taken as $V_{bus} = V_g = 48V$

Autonomy days (N) =1 day

Efficiency of battery $\eta = 85\%$

Depth of discharge of battery (DOD) = 70%

$$Battery\ capacity = \frac{Wh_{load}\times(N+1)}{\eta\times DOD\times V_g} = \frac{2760\times2}{0.85\times0.7\times48} = 193.277Ah$$

So, for safety criteria battery capacity to be taken as 200Ah.

$$\text{Peak load demand} = (80+50+80+1200+100)$$
$$=1510W$$

$$\text{Maximum load current} = \frac{1510}{48} = 31.45A$$

Hence from the above calculations the discharging current is taken to be 32A for transferring excess PV power to battery without disturbing the bus voltage during the high insolation period and low power demand,

$$\text{Now, C-rating of battery}\left(\frac{200Ah}{32}\right) = C/6$$

Hence, battery will provide 32A of current continuously for 6 hours in the absence of PV array with 200Ah capacity of 48V system that will be used for the autonomy of 1 day.

5.4 Control Objectives and Scope:

When it comes to DC grid reliability, the stability and performance of the control structure are important. Many researchers have investigated on operational and control challenges in DC grids in order to ensure reliable operation in both grid connected and independent modes. This research work represents standalone SPV based DC grid which integrates SPV array, battery energy storage system and load together to build small power system unit. In order to control such system, three major types of control objectives is required. The hierarchical control structure has proposed in this system which consists of three level of controls i.e. primary, secondary and tertiary control shown in figure 5.3.

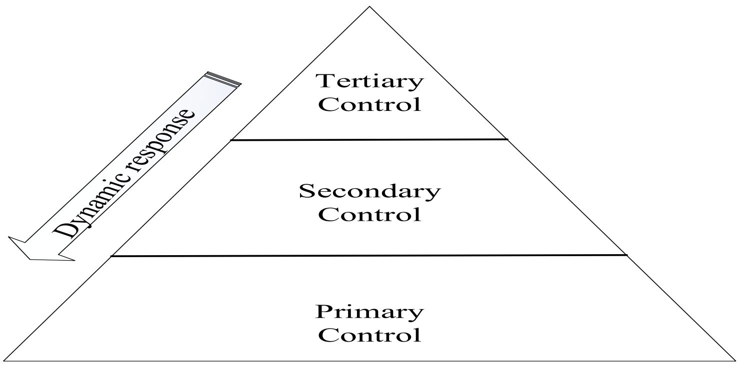

Figure 5.3 Hierarchical control levels in a DC grid structure.

Primary control is used on both the SPV array and the BESS, and its key objective is to regulate the load voltage and currents. It controls the breakers/switches (on/off and protection functions) as well as the loads. During the insertion and removal of loads, voltage variations induced by the primary control. This entire system runs abnormally or dropped into under or over voltage protections. Its primary objective is to provide a secondary control scheme for improving voltage quality and adjusting for voltage imbalances. Droop control is recommended for managing voltage among DC grids in order to regulate DC bus voltage. The tertiary control structure provides optimal power flow, economic dispatch and optimal energy scheduling problems in the DC grid to formulate the energy management scheme. It carries out scheduling and optimization procedures. It also determines the optimal set points for distributed energy resources and load operation in DC grid. Figure 5.4 shows the control objectives and functions of DC grid [23].

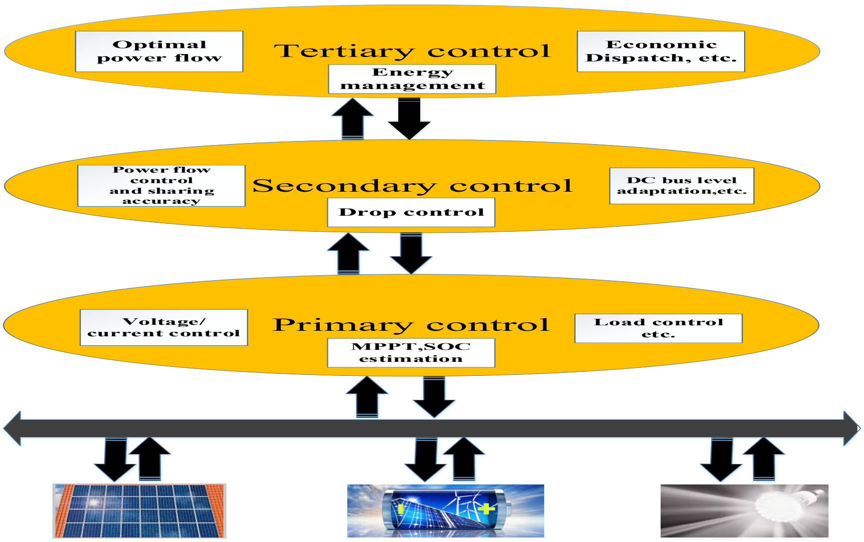

Figure 5.4 Typical control objectives and functions of DC grid

5.5 : Benefits and Challenges for Household Loads under Standalone Condition

There are certain benefits of using the autonomous standalone SPV system for AC loads:

1) Due to high voltages AC i.e. 230V, the current carries by the conductors are less, that leads to lesser I^2R losses, which decreases the cost of conductors.
2) AC power can be easily step up or step down with the help of transformer and can be transmitted over longer distance.

3) AC electrification is safer at higher level of voltage.
4) Dropped AC voltage can easily be bring back to its normal value by using capacitors.
5) It is easily available for AC household appliances.

The certain challenges faced by the AC electrification are as follows:

6) Complexity in power calculations.
7) AC distribution maintains 50 Hz frequency across all equipment's.
8) Reactive power is taken care off when calculations is based upon AC.
9) Conductor size increases due to skin effect in AC electrifications.
10) Inverter installation causes to decrease the system efficiency and increase the costs.
11) Unnecessary voltage drop occurs when the reactance comes into account.

5.6 Case Studies and Results:

Case A: For 230V AC-

This voltage is obtained from 48V DC bus by using the interconnection of boost converter and inverter. It is applicable for all AC appliances. For this level of voltage three phase non-linear load is considered whose switching time is taken for two time intervals t= 1sec and t= 5 sec. The voltage and current is seen to be balanced for both interval of time. During night time battery fulfils the requirement of power demand by the loads. Figure 5.5 represents the variations of 230V AC voltage with time at different irradiances. Figure 5.6 represents the variations of 230 V AC voltages with time at zero irradiances (i.e. during night time).

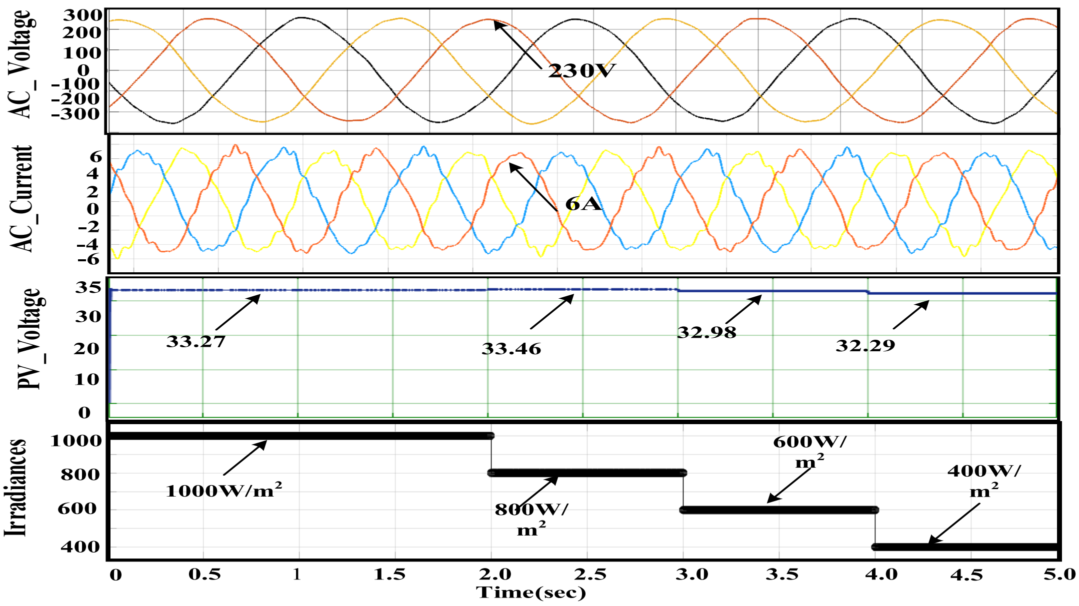

Figure 5.5 Variation of 230V AC voltage with time at different irradiances

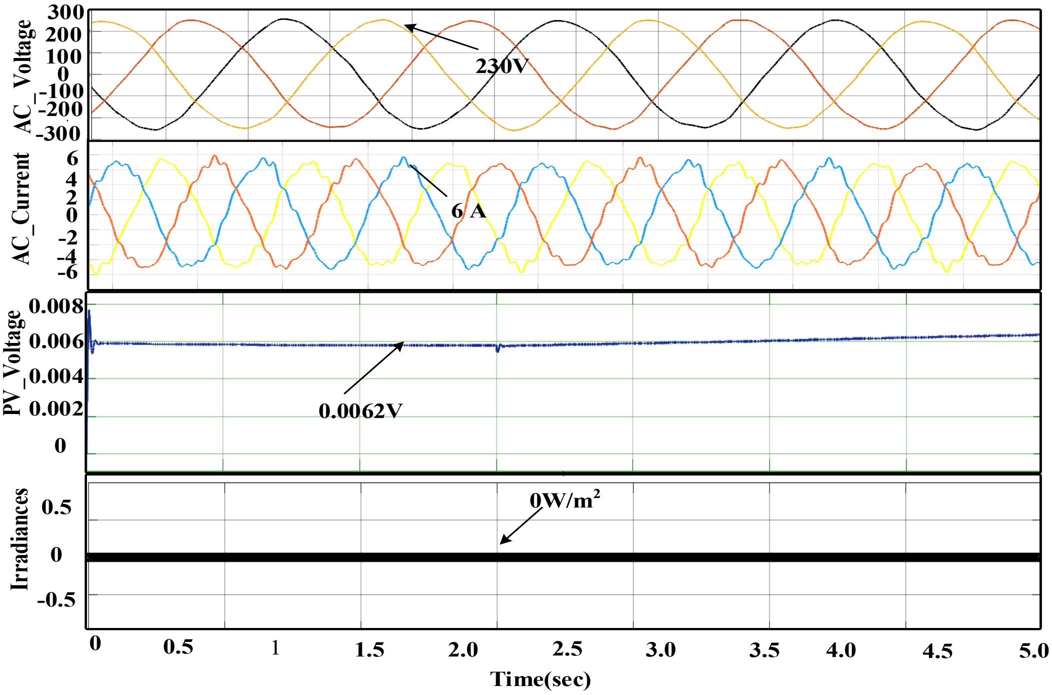

Figure5.6 Variation of 230V AC voltage during night time.

Case B: For 24V DC Distribution:

This voltage is applicable for low voltage DC appliances. For this voltage two different load resistance value is considered, which are changed at time t= 2 sec to represent a dynamically changing load. For 24V DC bus, initially the load is represented by resistance R_1= 20Ω that changed to R_2= 40Ω after time t= 2 sec. Figure 5.7 represents that current will be changing at t= 2.0 sec but the voltage will remain constant. Figure 5.8 represents that current will be changing at t=2.0 sec but 24 V DC voltage is maintained constant at zero irradiance (i.e. during night time).

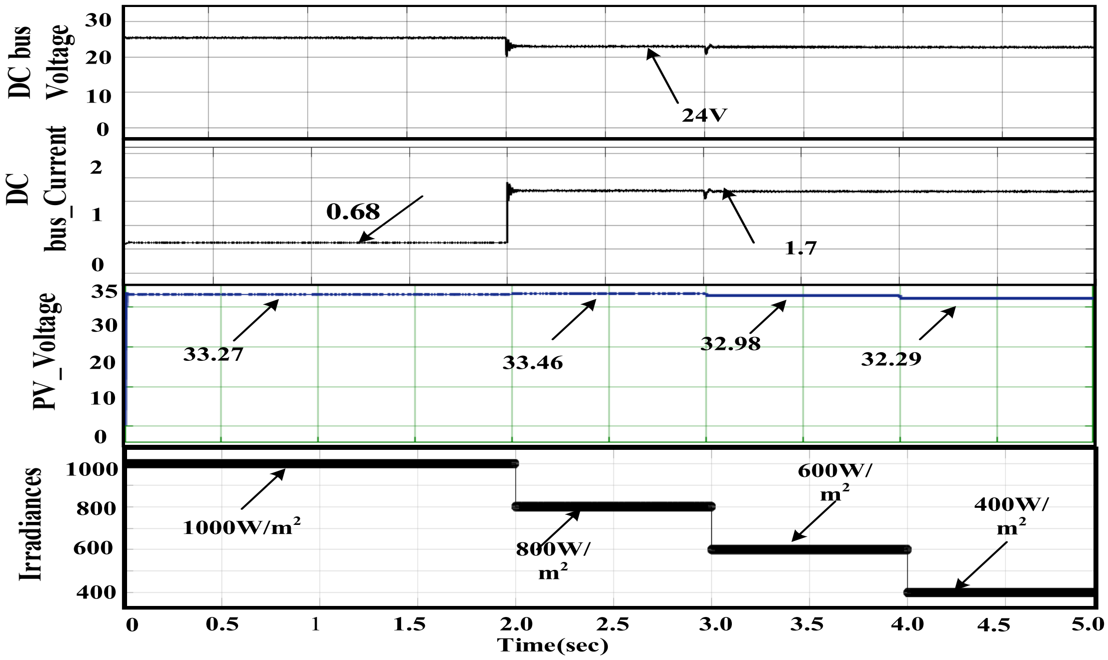

Figure 5.7 Voltage stability of 24V DC bus with different irradiance

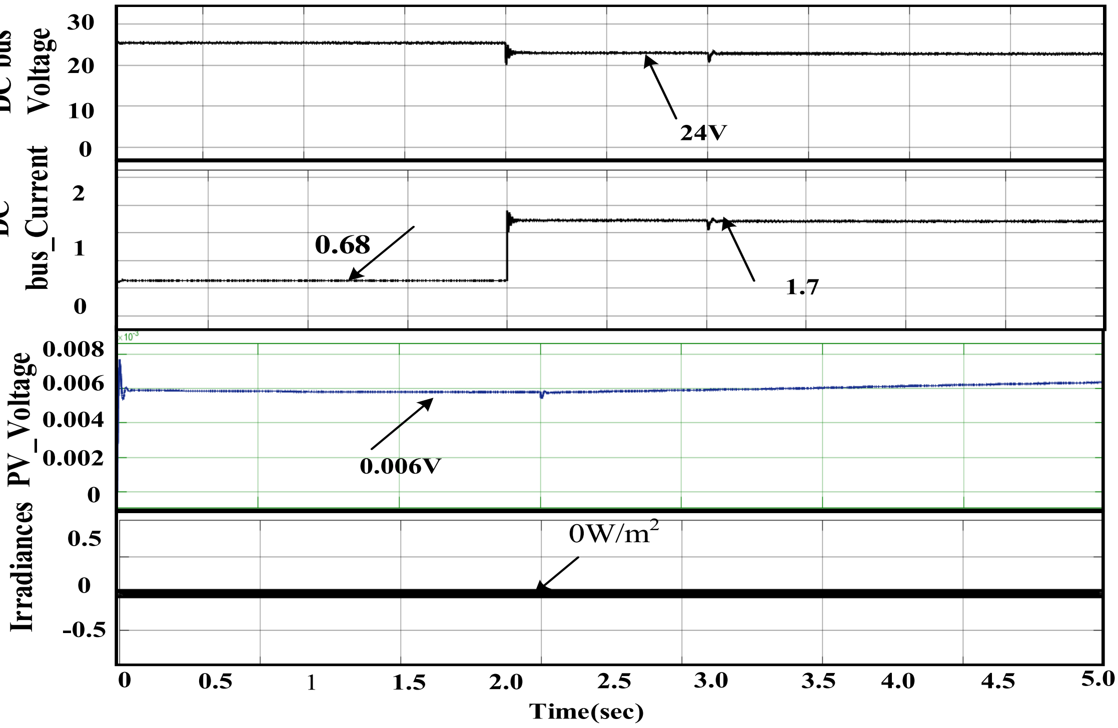

Figure 5.8 Voltage stability of 24V DC bus during night time

Case C: For 48V DC Distribution:

This voltage is applicable for medium voltage DC appliances. For this voltage the other two different load resistance value is considered that changes at time (t=2.5 sec) to represent a dynamically changing loads. For the 48V DC bus, initially the load resistance R3 = 25Ω that changes to R4 = 40Ω. At time t= 2.5 sec, the switch is closed and current changes, but the voltage will remain constant. Figure 5.9 represents that current will be changing at t= 2.5 sec but the voltage will remain constant. Figure 5.10 represents that current will be changing at t=2.5 sec but 48 V DC voltage is maintained constant at zero irradiance (i.e. during night time).Fig 5.11 shows the Variation of no load output AC voltage with time at each phase and Fig 5.12 shows Variation of three Phase RMS AC Voltage with time.

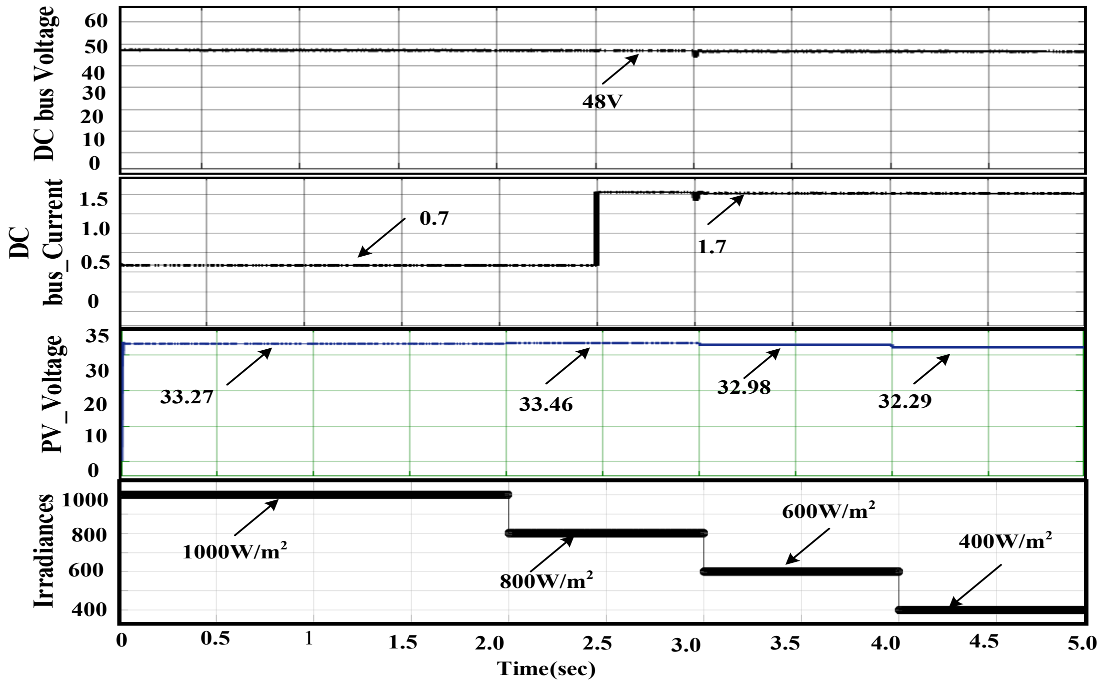

Figure 5.9 Voltage stability of 48V DC bus with different irradiances.

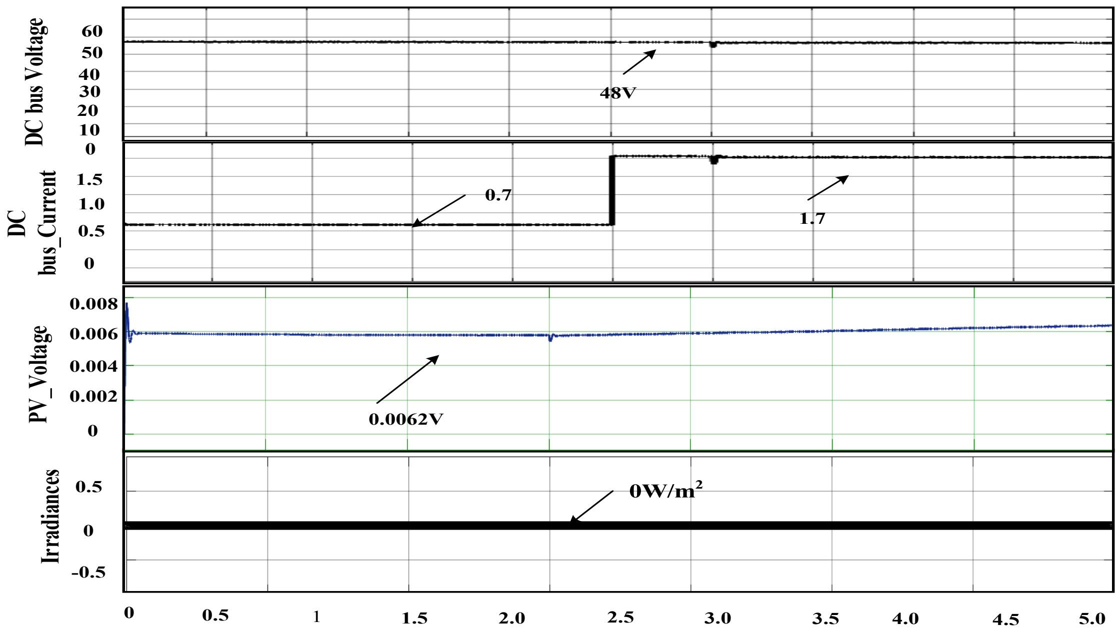

Figure 5.10 Voltage stability of 48V DC bus during night time

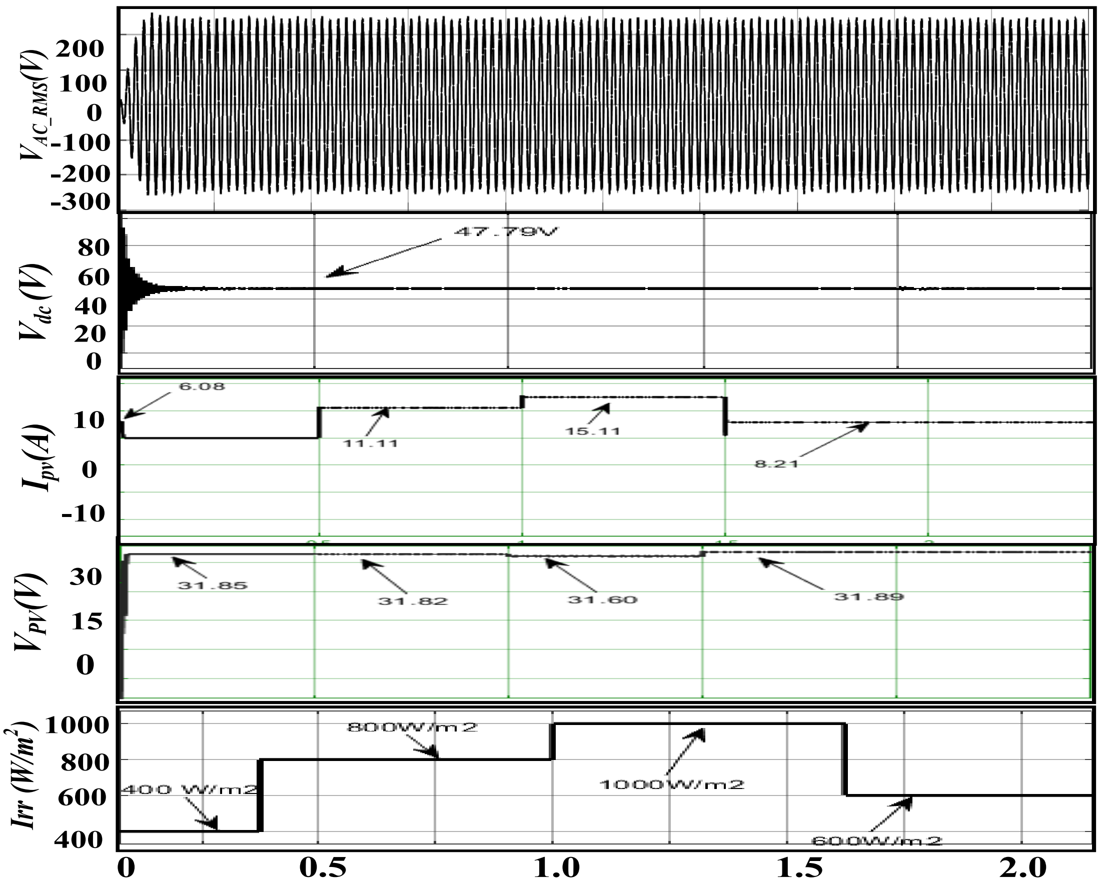

Figure5.11 Variation of no load output AC voltage with time at each phase

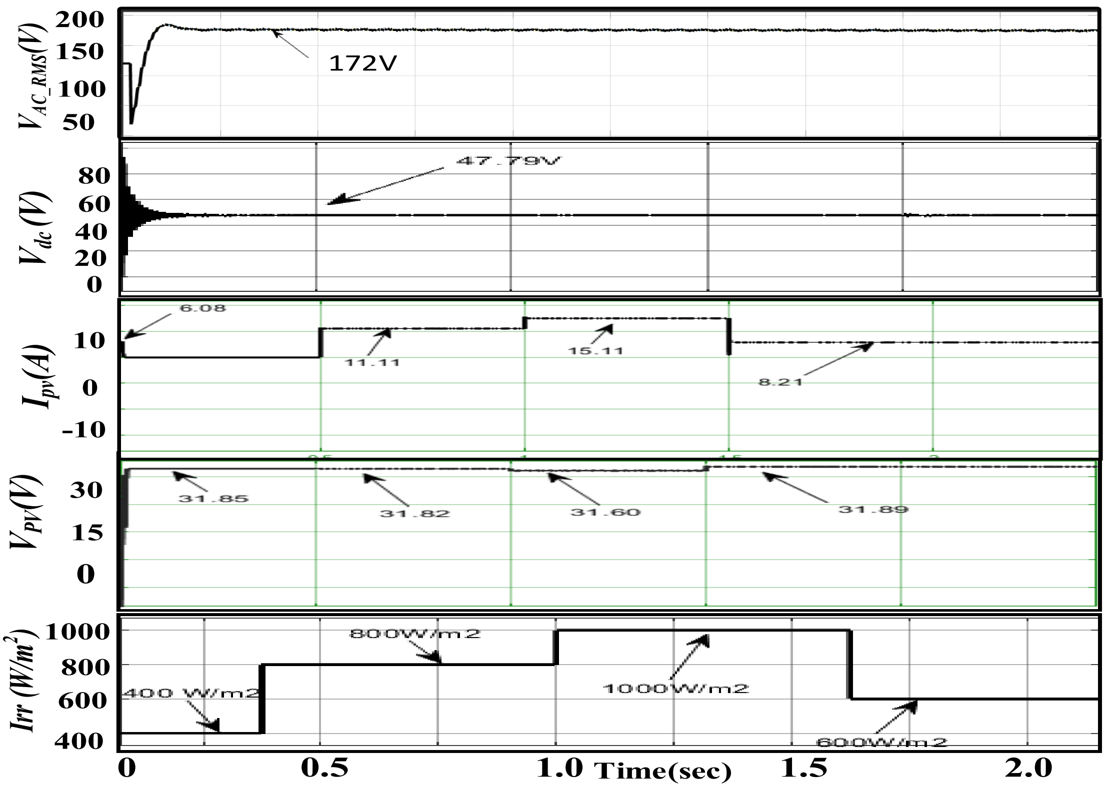

Figure5.12 Variation of Three Phase RMS AC Voltage with Time

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE

This research work proposes the concept of integration of solar PV array, DC grid and energy storage devices for various load applications. Power exchange with the energy storage devices is done using a bidirectional converter which is accustomed to supply power to DC bus from a solar PV array. For MPPT, P & O technique has been used to extract maximum power from solar panels. The first part of this thesis is to improve the stability of the DC bus at all three levels of voltages i.e. 24V, 48V and 310V which is maintained constant using battery charging/discharging techniques vis-à-vis varying solar irradiance levels and varying load. The second part of this thesis is to carry out the hybrid electrification at 24V and 48V DC for low and medium voltage DC appliances along with single phase, 230V, 50 Hz AC voltage for high voltage household appliances. Multiple case studies carried out on the MATLAB- Simulink platform validates the proposed technique.

SCOPE FOR FURTHER WORK

- Variations of weather conditions like solar irradiance, clouds (shading) and temperature needs to be considered.

- Artificial intelligence based techniques can be used to improve the response time and efficiency of MPPT control technique.

- Multiple sources of energy other than solar radiation like wind, fuel cells etc. can be considered and realizing the concept of DC microgrid.

- Checking the feasibility of commercialization of the proposed technique.

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LIST OF PUBICATIONS:

1) **"**Power Flow Management and DC bus Stabilization for SPV based Battery Energy Storage System" is accepted in IEEE International Conference for Emerging in Technology (3rd INCET) 2022.
2) "Feasibility Study of 48V DC Power Network and its Energy management for Household Supplies" is accepted in Asian Conference on Innovation in Technology (2nd ASIANCON) 2022.