Design and Study the Effectiveness of Smart Grid PV System

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Electrical and Electronic Engineering

Khulna University of Engineering & Technology
Khulna 9203, Bangladesh

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Declaration

This is to certify that the thesis work entitled "***Design and Study the Effectiveness of Smart Grid PV System***" has been carried out by ***Md. Jahangir Hossain*** in the department of Electrical and Electronic Engineering, Khulna University of Engineering & Technology Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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Approval

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ABSTRACT

Sustainable energy sources are required to meet the electricity demand and overcome the threat of energy security. Renewable energy comes forward to solve the above problem. Though there are several sources of renewable energy, solar energy is the largest source all over the world. The developments of grid connected configuration are urgently required to meet the future energy demand. There are many technological issues to utilize PV energy in smart grid system. The improved quality charge controller, inverter and their control circuit needs to implement grid connected PV system. For this reason an algorithm has been developed that makes the circuit easy, cost effective and good performance with 96.26% efficiency. Microcontroller based grid connected inverter and control circuit have been developed. The inverter circuit sense feedback from grid. After processing the signal in microcontroller it generate different controlling signal, operation modes and synchronization with grid. The inverter also shows better performance with 88.16% efficiency. Finally, cost analysis has been performed to implement the grid connected PV system. To justify the economic viability the feasibility study has been performed with 10kWp grid connected PV system for commercial building. The stability analysis has also been performed. The above achievement indicates that the potentiality of smart grid PV system may be the key solution to meet future energy demand and pollution free environment.

Dedicated

To

My Beloved Parents

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LIST OF ABBREVIATIONS

PV	Photo Voltaic
DC	Direct current
AC	Alternating current
MPPT	Maximum power point tracking
LV	Low voltage
MV	Medium voltage
VR	Voltage Regulation
ARV	Array reconnect voltage
LRV	Load reconnect voltage
LVD	Low voltage load disconnect
VRH	Voltage regulation hysteresis
LVDH	Low voltage disconnect hysteresis
SW	Square wave
MSW	Modified sine wave
PSW	Pure sine wave
PWM	Pulse width modulation
VSC	Voltage source converter
CSC	Current source converter
IRR	Internal Rate of Return
NPV	Net Present Value
DCF	Discounted cash flow
BCR	Benefit cost ratio
GHG	Green house gas
DG	Distributed generation
SVC	Static Var Compensators
LPI	Line performance index

NOMENCLATURE

I_A	array current
V_A	array voltage
q	electron charge ($1.6\times10^{-19}C$)
k	Boltzmann's constant ($1.38\times10^{-19}C$)
n	ideal factor
T	ambient temperature
I_0	reverse saturation current
R_S	array series resistance
I_{SC}	cell short circuit current
G	solar insulation (W/m^2)
N_{SM}	number of modules connected in series in the photovoltaic array
N_{SP}	number of modules connected in parallel in the photovoltaic array
I_r	reverse saturation current at standard temperature
T_C	operating temperature
T_r	reference temperature at standard test condition
E_G	energy band gap of solar cell at operating temperature
I_{ph}	photocurrent at standard condition
α	cell temperature coefficient for short circuit current
a_n	coefficients of the cosine terms at the n^{th} harmonic
b_n	coefficients of the sine terms at the n^{th} harmonic
$v_S(t)$	line voltage
$i_L(t)$	nonlinear load current
$p_L(t)$	instantaneous real power
$q_L(t)$	instantaneous reactive power
I_{PV}	DC/DC converter inductor current
V_{PV}	DC/DC converter capacitor voltage
I_{dc}	coupling inductor current
V_{dc}	DC link capacitor voltage
m	VSC modulation index

δ	phase angle
V_S	grid bus voltage
X_t	impedance between inverter terminal and the grid bus
V_d	d-axis converter voltage
V_q	q-axis converter voltage
P_{12}	real power flow from network 2 to network 1
V_1	voltage of network 1
V_2	voltage of network 2
δ_1	phase angle of network1
δ_2	phase angle of network 2
Q_{12}	reactive power flow from network 2 to network 1
An	annual net profit
Cc	capital cost
e	inflation rate
i	interest rate
y	project life time
Ao	annual saving
O&M	operation and maintenance cost
P_t	percentage contribution to the grid
CEF_t	emission factor for specific technology and or fuel type (tons CO_2/MWh
$CEF_{wt.avg}$	weighted emission factor for a fuel mixture in grid (tons CO_2/MWh)
OP	power generation in megawatt

CHAPTER I

Introduction

1.1 Background Information

The primary source of non renewable energy is fossil fuels which are limited and the security of electricity supplies is under threat. To meet up the huge energy demand, natural gas and fuel are running out. From the report of the "Oil & Gas Journal, World Oil", the most optimistic proved reserves estimates that coal, oil and natural gas will be available for 417, 43 and 167 years respectively. Due to shortage of fossil fuel and highest demand, price is increasing rapidly. Also it is costly for transporting in remote areas. Due to increasing fuel cost electricity generation cost increases. Technological development and new scientific innovation increases the demand of electricity day by day. New power stations are necessary to meet up excess energy demand. Thus dependency on fossil fuel is increasing. Due to excess burning of fossil fuel carbon dioxide and other green house gas are increasing that is creating the environment pollution [1]. For this reason global warming and climate changes are happening, snows of Antarctica are melting and sea level is increasing. As a result Bangladesh as well as many other coastal countries may lose their low lands. On the other hand, nuclear energy may be the sustainable solution for energy security but the scarcity of nuclear energy also poses a risk to national and regional resource security, autonomy as well as to international security [2]. The difficulty as well as cost of safely disposing radioactive materials, and toxic waste, makes the use of nuclear energy a questionable solution [3]. It is the burning question to meet the consumer's future energy demand without creating any harmful impact on the environment. Therefore, renewable sources of energy need to be considered seriously. There are several sources of renewable energy among them solar energy is the largest and available all over the world. Solar energy reaching the earth's surface is almost 6,000 times the average energy consumed by humans. These figures encourage us to look for ways to harness solar energy and convert it into suitable technique. It is considered as a clean and environment friendly source of energy. Bangladesh is a tropical country so solar energy has great potential. Average solar radiation and temperature in Bangladesh is 4.59kWh/sqm and 26.93 °C respectively [4].

Solar energy can be used in different ways such as solar cell, solar water heater; solar cooker etc. The solar cell works in the principle of photovoltaic effect. The photo voltaic (PV) is the direct process of converting sunlight into electricity [5]. PV panel is composed by a number of solar cells connecting in series and parallel arrangement. The main applications of PV systems are in either off grid or grid connected configurations. Off grid PV generation systems are attractive as indispensable electricity source only for remote areas [6]. The challenge to utilize solar energy from off grid PV system is high capital cost, low efficiency, weather dependent and more operation and maintenance cost [7]. On the other hand, grid connected system is connected to a larger independent grid and feeds energy directly into the grid. The optimum power received from PV system can be shared by a residential or commercial building before or after the revenue measurement point. This is a form of decentralized or distributed electricity generation. The feeding of electricity into the grid requires the transformation of DC into AC by a special, synchronized grid connected inverter.

1.2 Motivation and Scope of the Present Study

PV energy is very much popular at the preset days. There are various techniques to utilize PV energy among them, smart grid technology is very important. However, a good number of research works have been carried out to make it user friendly. Several findings shows that the generation cost of an off grid system is 20.78BDT/kWh, IRR -19.40%, benefit cost ratio 0.03 and pay back period beyond the life time of PV system. On the other hand, generation cost of smart grid system is 10.90BDT./kWh, IRR 8.8%, benefit cost ratio 1.07 and Pay back period 11 years [8]. Above discussion shows that smart grid PV system will be the roadmap to utilize solar energy more effectively. The project cost and cost analysis shows that installation cost per megawatt capacity of gas turbine require 59.6 million taka (a project taken by ashugonj power station company, capacity 100MW and estimated cost 5960 million taka, 2012) and cost per megawatt capacity combined cycle require 91.5 million taka (a project taken by BPDB in Bhola, capacity 225MW and estimated cost 20580 million taka, 2012) but for PV power generation require 143.6 million taka per megawatt generation capacity installation. The Diesel power plant, gas turbine and combined cycle power plant need huge amount of operation and maintenance cost while the PV generation is almost operation and maintenance cost free.

The generation of electricity situated in specific region and loads are distributed far ways from generating station so there is a technical loss for transmission and distribution of electrical energy. The distributed PV generation is capable for injecting real power with minimum technical loss. Moreover, in the smart grid system, PV and grid act like as alternative source for each other. Though, distributed storage is required to meet the peak demand reduction as well as grid stable condition. Synchronization and stability of PV and grid electricity is the major challenge in this extent. Grid connected inverter incorporating MPPT algorithm and automation protective scheme makes the grid more stable. In such a way the smart grid can optimize traditional fuel sources by integrating the renewable energy sources to the grid.

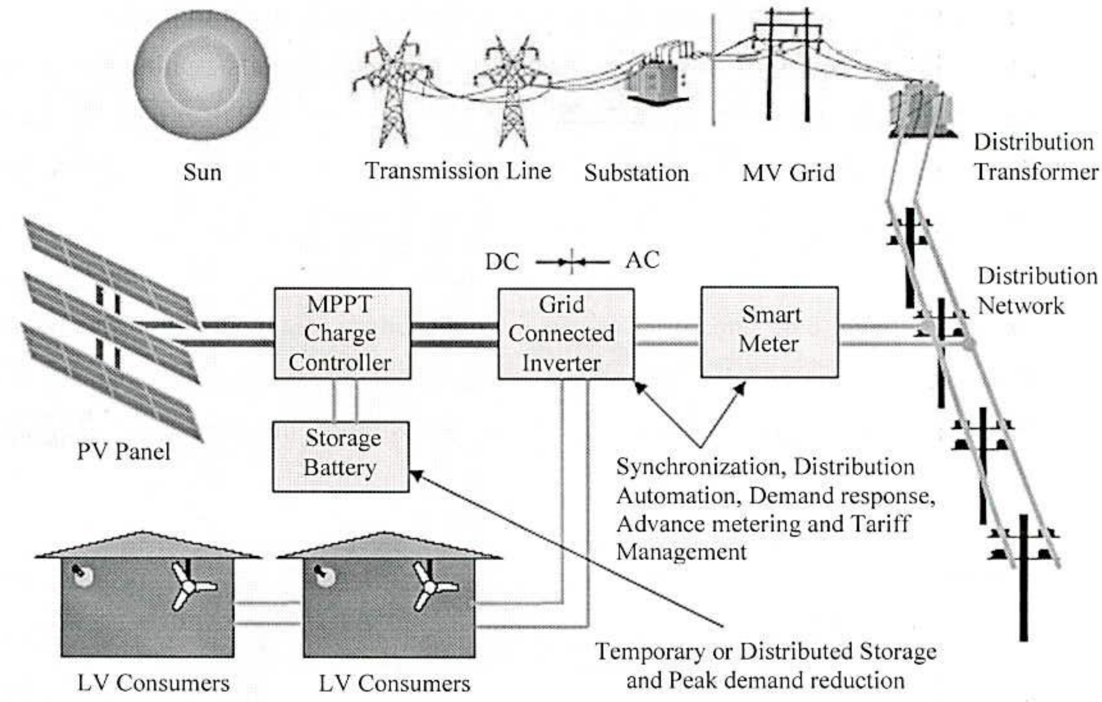


Fig.1.1 Typical Smart Grid PV System

The schematic diagram of smart grid system briefly discuss in Fig.1.1 that bring several benefits such as it enables real time, two way infrastructure development of the whole electrical system consisting generation, transmission, distribution and end use consumption. The important issue in this context is the distribution automation, demand response, advance metering, tariff management, temporary storage, reduction of peak demand and increase grid stability [9]. It also acts like a reliable marketplace with multiple producers, consumers and arbitragers buying and selling. Prices are dynamic and information flows freely in both directions to optimize the efficiency of the marketplace [10]. Small producers of low carbon power get easy access to sell into the marketplace, and consumers have access to price signals that let them save money by shifting power consumption to off peak times. Many research works has been done to implement the smart grid [11-14]. Tous et al has compared the house hold tariff between the grid connected PV energy and utility power [15]. Infrastructure development, technical potentiality and regulatory barriers and implementation procedures are also discussed in several reports [16-18]. To the best of our knowledge, there is no detail understanding about the design procedures, feasibility study and stability analysis of the smart grid PV system.

1.3 Important Issues Towards the Implementation of Smart Grid PV System

Smart grids are complex systems that incorporate a number of technologies, consumer interactions and decision points. This complexity makes it difficult to define detailed development and deployment scenarios. Smart grid technologies are being developed worldwide, so much of the research, development and demonstration can be discussed in a global context. But deployment needs to be discussed at the regional level, where important factors such as the age of infrastructure, demand growth, generation make-up, regulatory and market structures vary significantly.

There are some technological issues to be overcome such as effective power extract need for conversion of DC electricity to AC according to the grid phase, frequency and amplitude. Smart grid PV system includes photovoltaic array, DC/DC converter, DC/AC inverter and their controllers. Traditional controller has some drawbacks such as low power rating, poor charging efficiency and performance is not so satisfactory. These problems have been overcome by incorporating MPPT algorithm. There are several researches; most of them are in simulation level, some are implemented for practical applications but those are complex and expensive [19]. Now a day's research is going on various types of grid connected inverter topologies to make it easy; user friendly and cost effective. The performance of the system directly depends on the performance of converters and controllers. So performance optimization is badly needed in this context.

Although, there are various challenges which has been briefly discussed in the earlier section, the smart grid system is a very important candidate for the future high performance photovoltaic system.

1.4 Objectives

There are several challenges in the smart grid PV system, which has briefly discussed with respect to each task, it is imperative to take an iterative approach addressing these challenges simultaneously to successfully develop smart grid PV system. This iterative process is further divided into the following tasks,

i) Design and modeling of smart grid PV system and study the effectiveness.
ii) MPPT charge controller and grid connected inverter has been implemented.
iii) Synchronization between grid and PV system has been achieved.
iv) Cost analysis, feasibility study and stability analysis has been performed.

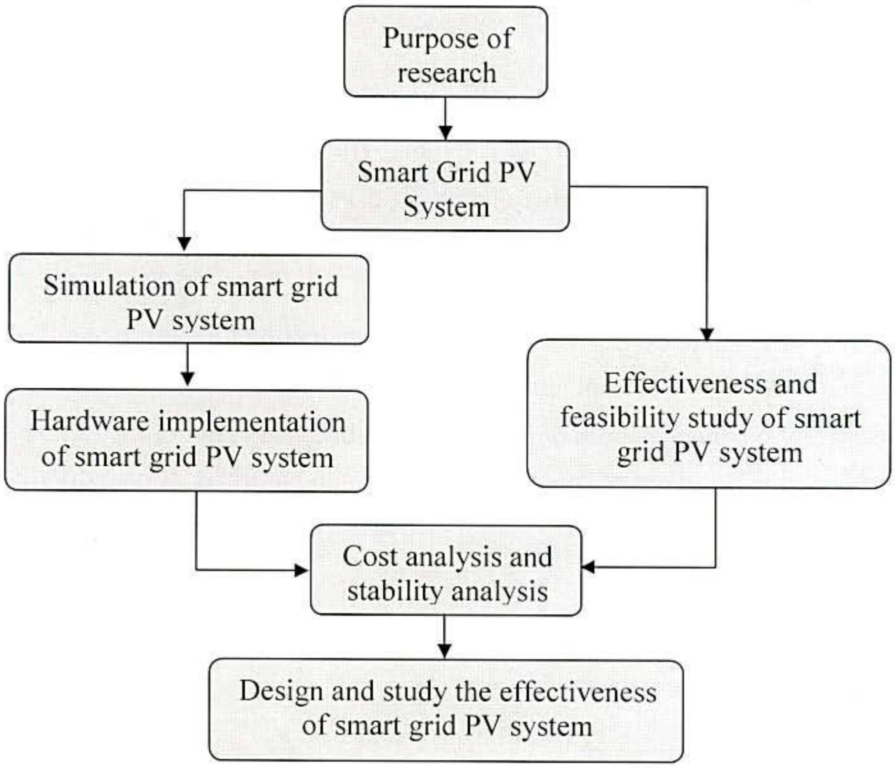


Fig.1.2 Flow diagram of thesis objectives

1.5 Thesis Organization

The research work has been described in several chapters due to the potentiality of different topics. The objective of this thesis and importance of smart grid PV system competitive with the conventional PV system application to meet the increasing energy demand of the world are discussed in **chapter 1**.

The technological and recent development of photovoltaic system, their controllers and set points are briefly discussed in **chapter 2**. This chapter also describes the different PV model and their optimization technique.

The design procedure of smart grid PV generation system modeling has been discussed in **chapter 3**. The cost and feasibility study has been performed by RETscreen software. Transient stability of smart grid PV system is analyzed by equal area criterion.

The **chapter 4** describes the simulation and implementation of hardware which is necessary for smart grid PV system. The working principle of hardware; software development and algorithm are discussed here. The charge controller, inverter and their control circuits also converse here.

The chapter 5 is dedicated to simulation and experimental results of charge controller inverter and PV system. Feasibility study and transient stability analysis are discussed here; also compare with off grid and on grid system.

Overall conclusions of whole thesis work with few proposals are discussed in **Chapter 6**. This also contains the future direction, how to utilize PV energy in smart grid system.

CHAPTER II

Fundamental Study of the Smart Grid PV System

2.1 Introduction

Photovoltaic is a method of generating electrical energy by converting solar radiation into direct current using semiconductors that exhibit the photovoltaic effect. It is the direct process of converting solar energy into electricity [6]. PV power generation employs solar panels composed of a number of solar cells consisting of photovoltaic material. The main applications of PV systems are in either standalone or grid connected configurations. The brief discussions of PV system, MPPT charge controller; inverter and control systems are described below.

2.2 Solar Cell Innovation and Development

Nineteen years old Edmund Becquerel, a French experimental physicist, discovered the photovoltaic effect in 1839, while experimenting with an electrolytic cell made up of two metal electrodes. Willoughby Smith discovered the photoconductivity of selenium in 1873. Adams and Day observed the photovoltaic effect in solid selenium in 1876. During the year of 1883 Charles Fritts, an American inventor described the first solar cells made from selenium wafers. In 1887 Heinrich Hertz discovered that ultraviolet light altered the lowest voltage capable of causing a spark to jump between two metal electrodes. Photosensitive of copper and cuprous oxide was discovered by Hallwachs in 1904. Einstein published his paper on the photoelectric effect. In the year of 1914 the existence of a barrier layer in PV devices was reported. Millikan provided experimental proof of the photoelectric effect in 1916. Albert Einstein received the Nobel Prize in 1923 for his theories explaining the photoelectric effect. In 1951 a grown p-n junction enabled the production of a single-crystal cell of germanium.

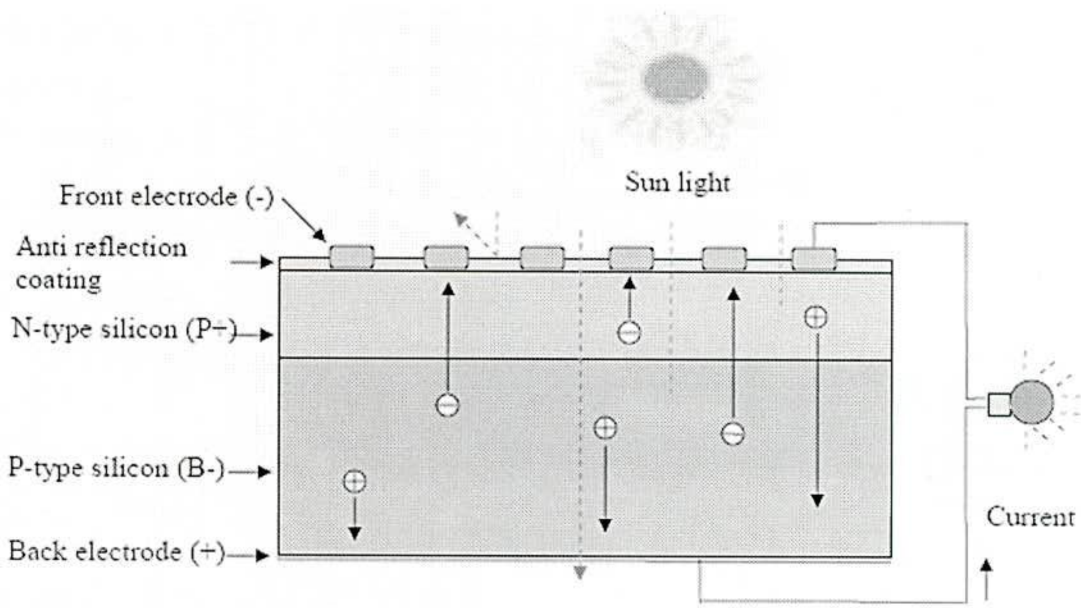


Fig.2.1 Schematic diagram of solar sell electricity generation

The development of solar cells begins with the invention of single crystal silicon solar cell in 1954 at Bells laboratory. Bell Laboratory researchers Pearson, Chapin, and Fuller reported their discovery of 4.5% efficient silicon solar cells; this was raised to 6%. Hoffman Electronics achieved 9% efficient PV cells in 1958. Vanguard I, the first PV-powered satellite, was launched in cooperation with the U.S. Signal Corporation. The satellite power system operated for 8 years. In 1959 Hoffman Electronics achieved 10% efficient, commercially available PV cells and demonstrated the use of a grid contact to significantly reduce series resistance. Hoffman Electronics improves 14% efficient of PV cells in 1960. The majority of solar cells currently in use are crystal silicon solar cells (Fig. 2.1). Under standard test condition (in the vicinity of room temperature), these solar cells have a high conversion efficiency of 14% to 16%.

The first generation solar cells consist of large-area, high quality and single junction devices that are predominately made of silicon. The highest efficiencies on silicon have been achieved on mono crystalline cells with commercial efficiency (22%) are produced by Sun Power. The University of New South Wales has achieved 25% efficiency on mono crystalline silicon in the lab. The second generation materials have been developed to address energy requirements and production costs of first generation cells. The most successful second generation materials have been cadmium telluride (CdTe), copper indium gallium selenide (CIGS), amorphous silicon and micro amorphous silicon. The US national renewable energy research laboratory (NREL) achieved an efficiency of 19.9% for the solar cells based on CIGS.

Third generation technologies aim to enhance poor electrical performance of second generation (thin-film technologies) while maintaining low production costs. Current research is targeting conversion efficiencies of 30-60%. There are a few approaches to achieving these high efficiencies, such as Multi-junction solar cells, multiple spectrum solar cells, multiple absorption path solar cells, multiple energy level solar cells, and multiple temperature solar cells. Fourth-generation solar cells do not use a traditional p-n junction to separate photo-generated charge carriers. They consist of photo-electrochemical cells, polymer cells, and nano-crystal solar cells, where polymers and nano-particles are mixed together to make a single multi-spectrum layer.

From the very beginning so much research and development has been achieved to increase the efficiency and reduce the cost of solar cell. Many scientist, researchers and manufacturing company developed solar cell day by day. The most recently, Friedman's team succeeded so spectacularly in bending the rules of the solar spectrum that NREL and its industry partner, Solar Junction, won a coveted R&D 100 award from R&D Magazine for a world-record multijunction solar cell in 2012. The multijunction three-layered cell, SJ3, converted 43.5% of the energy in sunlight into electrical energy a rate that has stimulated demand for the cell to be used in concentrator photovoltaic arrays for utility-scale energy production. 28 December, 2012, that record of 43.5% efficiency at 415 suns was eclipsed with 44% efficiency at 947 suns; both records were verified by NREL [20]. The research is going on all over the word to develop the solar cell and utilize it efficiently.

2.3 PV Array

Solar cell is the basic building block of a photovoltaic array. The performance of solar cell strongly depends on radiation and ambient conditions as reported in [21-22]. As single solar cell is only capable of generating very low terminal voltage and output current, for practical purposes many cells are connected in series to form a module for higher voltage across the terminals. For large scale operation of PV generator, modules are connected in series and parallel to form an array. The array output current equation can be derived from basic solar cell output current equation and can be represented as [21]

$$I_A = I_{SCA}(G) - N_p \times I_0[e^{\frac{(V_A+I_A R_S)q}{nN_S kT}} - 1] \quad \text{..................} (2.1)$$

Where, I_A = array current (A), V_A = array voltage (V), q = electron charge ($1.6\times10^{-19}C$), k = Boltzmann's constant ($1.38\times10^{-19}C$), n = ideal factor, T = ambient temperature, I_0 = reverse saturation current (A), R_S = array series resistance (Ω), $I_{SCA}(G) = N_p I_{SC}(G)$, I_{SC} = cell short circuit current (A), G = solar insulation (W/m^2), $N_S = N_{SC}N_{SM}$, $N_P = N_{SP}$, N_{SM} and N_{SP} respectively represent the number of modules connected in series and parallel in the photovoltaic array, and N_{SC} = number of series-connected cells in a module. Temperature dependency of reverse saturation current of the cell can be expressed as follows [21]:

$$I_0 = I_r[\frac{T_c}{T_r}]^3 \exp[\frac{qE_G}{nk}(\frac{1}{T_r} - \frac{1}{T_c})] \quad \text{........................} (2.2)$$

Where, I_r = reverse saturation current at standard temperature (298 Kelvin) (A), T_C = operating temperature (Kelvin), T_r = reference temperature at standard test condition (1000 W/m^2 and 1.5 AM) (Kelvin), E_G = Energy band gap of solar cell at operating temperature (V). Temperature and radiation sensitivities of the short circuit current can be expressed by the following equation:

$$I_{SC} = [I_{ph} + \alpha(T_c - T_r)G] \quad (2.3)$$

Where, I_{ph} = photocurrent at standard condition (A), α = cell temperature coefficient for short circuit current and G = solar insulation at any instant (W/m^2). Now, the DC output power of PV array can be represented by

$$P_{dc} = V_A I_A \quad (2.4)$$

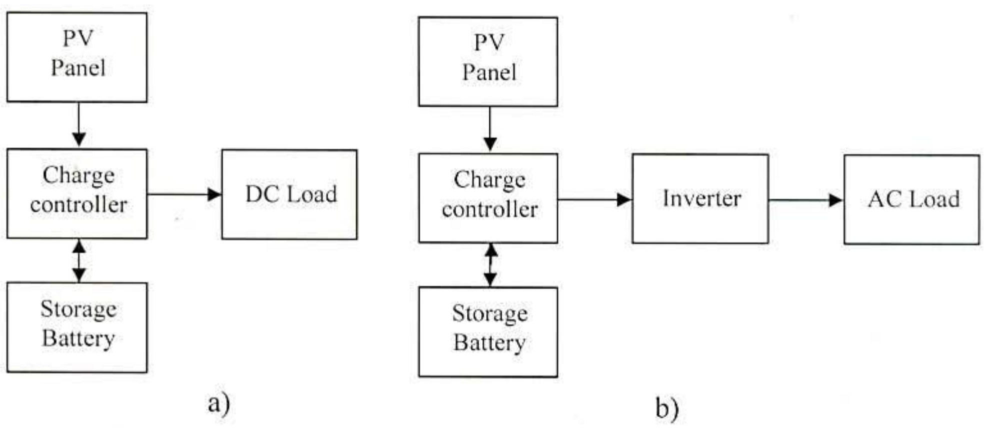
Where, V_A = PV array terminal voltage (V), and I_A = PV array output current (A).

2.4 Application of PV Array

Thereafter, research continued to make progress and during the era spanning the latter half of the 1950s through the beginning of the 1960s, PV array began to be utilized in high value added applications such as the power supply for a man-made satellite. In 1961 the UN conference on Solar Energy in the Developing World was held. After that in 1963 Japan installed a 242Wp PV array on a lighthouse, it was the world's largest PV array at that time. The Nimbus spacecraft was launched with a 470 Wp PV array in 1964. In the year of 1965 Peter Glaser, A.D. Little conceived the idea of a satellite solar power station. The orbiting astronomical observatory was launched with a 1kWp PV array in 1966. 1968The OVI-13 satellite was launched with two CdS panels. French install a CdS PV system in a village school in Niger to run an educational TV in 1972. 1973 The Cherry Hill Conference was held in Cherry Hill, New Jersey. In the 1980s development and cost reduction of PV array had achieved from them it comes to use in commercial application.

2.4.1 Off Grid PV System

The term off-grid refers to not being connected to a electrical grid. It is also known as stand alone systems or mini-grids typically to provide a smaller community with electricity. Off-grid electrification is an approach to access electricity used in countries and areas with little access to electricity, due to scattered or distant population. It may be DC or AC generation system. If there is any backup generator connected to meet the demand at rough weather or any other redundent situation is called off grid system with back up generator. Standalone PV generation systems are attractive as indispensable electricity source only for remote areas where grid is absent or difficult to construct [23].



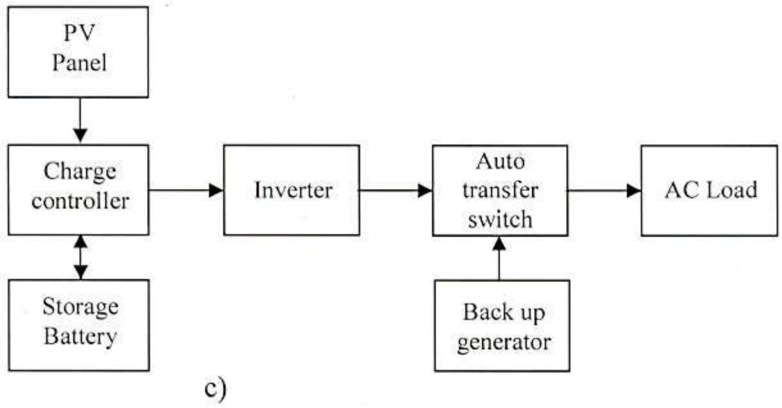


Fig.2.2 Schematic diagram of a) Off grid PV system for DC load, b) off grid PV system for AC load, c) off grid PV system for AC load with back up generator.

2.4.2 Grid Connected PV System

The grid connected system is coupled with a larger independent grid (typically the public electricity network) and feeds energy to the consumers. The consumers receive power from grid treating as a back up sources. The optimum power received from PV system can be shared by a residential or commercial building before or after the revenue measurement point. This is a form of independent decentralized or distributed electricity generation. This system requires the transformation of DC into AC by a suitable grid-tie inverter.

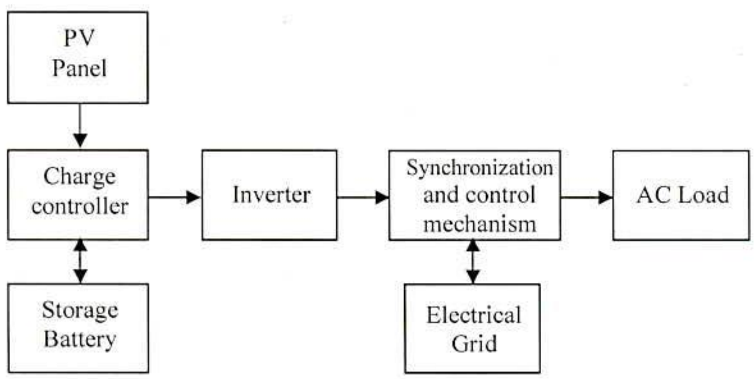


Fig. 2.3 Schematic diagram of on grid PV system

2.4.3 Smart Grid PV System

An electrical grid is not a single entity but an aggregate of multiple networks and multiple power generation companies with multiple operators employing varying levels of communication and coordination, most of which is manually controlled. Smart grids increase the connectivity, automation and coordination between these suppliers, consumers and networks that perform either long distance transmission or local distribution tasks. The European Commission defines smart grid as leveraging advanced computer communications and communications technologies to create a power distribution network that is flexible, accessible, reliable and economic [24]. Similarly, the US congressional research service states the goal of Smart grid is to use advanced, information-based technologies to increase power grid efficiency, reliability, flexibility and reduce the rate at which additional electric utility infrastructure needs to be built.

The term smart grid has been in use since at least 2005, when it appeared in the article "Toward a Smart Grid" by Amin and Wollenberg [25]. The generation, transmission and distribution infrastructure will be better able to handle possible bidirection energy flows, allowing for distributed generation such as from photovoltaic panels on building roofs, but also the use of fuel cells, electric vehicles charging, wind turbines, pumped hydroelectric power, and other low carbon sources. Classic grids were designed for one direction energy flow, but if a local sub-network generates more power than it is consuming, the reverse flow can raise safety and reliability issues. A smart grid aims to manage these situations. There are many smart grid definitions, some functional, some technological, and some benefits-oriented. A common element to most definitions is the application of digital processing and communications to the power grid, making data flow and information management central to the smart grid. Various capabilities result from the deeply integrated use of digital technology with power grids, and integration of the new grid information flows into utility processes and systems is one of the key issues in the design of smart grids.

2.5 Elements Required to Implement Smart Grid PV System

2.5.1 PV panel

Type of the PV module used to design the system is mono-silicon; manufactured by ABC Inc. The designed nominal PV array power 10kWp, PV array coverage area 85.5 m^2, Annual solar energy collected on the surface of 10kWp PV module is 16.07MWh, while renewable energy delivered in the form of electricity is estimated 14.463MWh.

2.5.2 Charge Controller

The charge controller is an important element of a PV system which is used to control the voltage and charging current that is applied to the battery in order to protect it from being over charged and over discharged [23]. Maximum Power Point Tracking, frequently referred to as MPPT, is an electronic system that operates the PV modules in a manner that allows the modules to produce all the power they are capable of.

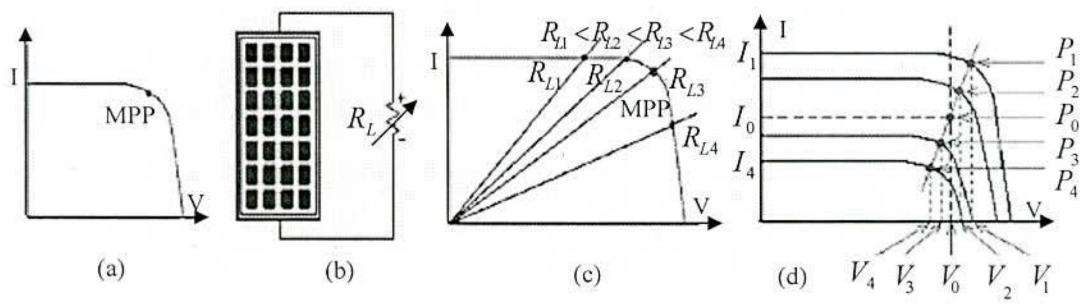


Fig. 2.4 (a) IV curve of a PV module, (b) PV module with variable load resistance, (c) different point of load lines in IV curve and (d) Shifting of maximum power point and the setting the optimum voltage.

Maximum Power Point Tracking (MPPT): The I-V characteristic of a PV module is shown in Fig.2.4 (a), the load resistance is varied, the load lines corresponding to different load resistance; intersect at different points on I-V curve resulting in different amount of power dissipation through RL. But the maximum would be dissipated if RL were adjusted to intersect the maximum power point (MPPT). This situation is shown in Fig.2.4 (c). This is possible if the array is operated at maximum power point every instant, because the maximum power point is fluctuating due to change in insulation and temperature. Thus for maximum power transfer and minimization of mismatch losses, an impedance transformer is needed which will continuously match the dynamic impedance of the PV-array to the fixed impedance of the load for all insulation levels and temperature. Such an impedance matching device is called a maximum power point tracker (MPPT).

Charge Controller Set Points: The battery voltage levels at which a charge controller performs control or switching functions are called the controller set points. Four basic control set points are defined for most charge controllers that have battery overcharge and over discharge protection features. Figure 2.5 shows the basic controller set points on a simplified diagram plotting battery voltage versus time for a charge and discharge cycle. A detailed discussion of each charge controller set point follows.

Voltage Regulation Set Point: The voltage regulation set point is defined as the maximum voltage that the charge controller allows the battery to reach, limiting the overcharge of the battery. When battery terminal voltage becomes greater than preset value 14.4 Volt for 12volt lead acid battery then the control circuit of charge controller disconnects the PV panel from the battery by relay RL2.

Array Reconnect Voltage Set Point: When the battery terminal voltage falls below another preset level 13.0Volt for 12volt lead acid battery then the control circuit of charge controller reconnects the PV panel from the battery by relay RL2.

Low Voltage Load Disconnect: Over discharging the battery can make it susceptible to freezing and shorten its operating life. If battery voltage drops too low, due to prolonged bad weather non-essential loads can be disconnected from the battery to prevent further discharge. For example the terminal voltage becomes less than 10.8Volt for 12volt lead acid battery the controller disconnects the load from the battery and PV panel by relay RL1. So the battery will be saved from over discharging.

Load Reconnect Voltage Set Point: The battery voltage at which a controller allows the load to be reconnected to the battery is called the load reconnect voltage. When the battery terminal voltage increase up to another preset level (12.5volt) then the controller will allow to reconnect the load to the battery by relay RL1.

Voltage Regulation Hysteresis: The voltage span or difference between the voltage regulation set point and the array reconnect voltage is often called the voltage regulation hysteresis (VRH). The VRH is a major factor which determines the effectiveness of battery recharging for interrupting (on-off) type controllers. If the hysteresis is too great, the array current remains disconnected for long periods, effectively lowering the array energy utilization and making it very difficult to fully recharge the battery. If the regulation hysteresis is too small, the array will cycle on and off rapidly, perhaps damaging controllers which use electro-mechanical switching elements.

Low Voltage Disconnect Hysteresis: The voltage span or differences between the low voltage load disconnect set point and the load reconnect voltage is called the low voltage disconnect hysteresis (LVDH). If the LVDH is too small, the load may cycle on and off rapidly at low battery state-of-charge (SOC), possibly damaging the load or controller, and extending the time it takes to fully charge the battery. If the LVDH is too large, the load may remain off for extended periods until the array fully recharges the battery.

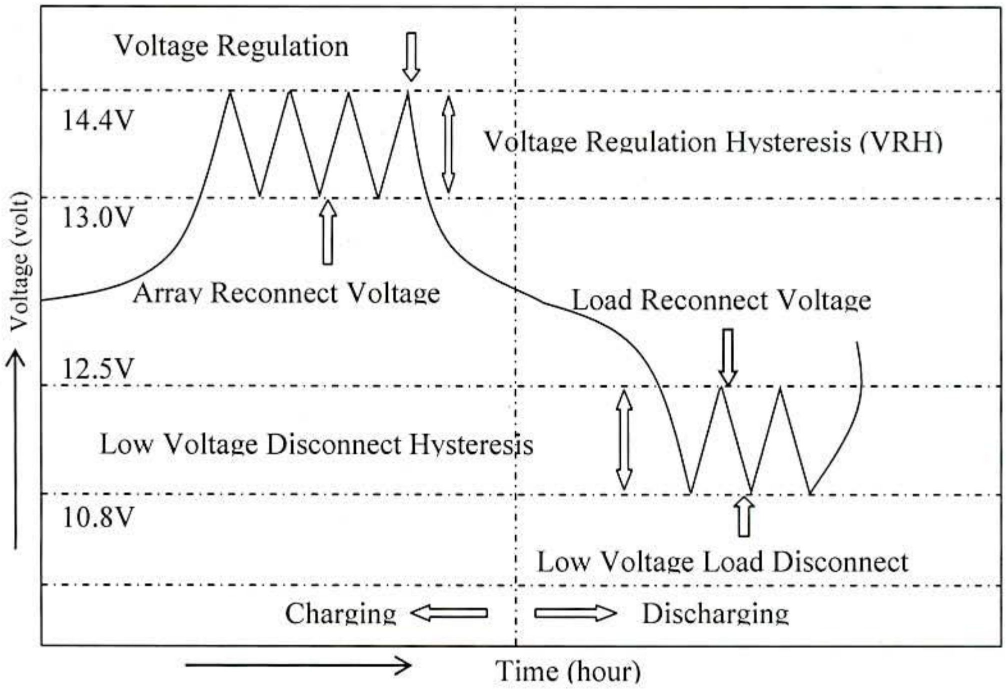


Fig. 2.5 Charge controller different set points

2.5.3 Storage battery

In grid connected system storage battery is require to regulate the dc generation by the PV system. It also increases the stability of power system and reduces the peak demand. Lead acid battery is commonly used because of its features such as wide operating temperature range; low self-discharge, long service life and maintenance free [5].

2.5.4 Grid Connected Inverter

Inverter is an electrical power converter that changes direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. There are three major types of inverter based on waveform, square wave (SW), modified sine wave (MSW), and pure sine wave (PSW). The first type, square wave, is not suitable for marine use because it has no voltage control. This means that the input voltage is proportional to the output. This type of inverter is the simplest and least expensive on the market. However, reliability and output voltage regulation of these inverters are poor. Eventually, it can damage sensitive equipment. Another shortcoming of SW inverter is its lack of surge power which can result in an inability to power motorized equipment.

In order to overcome this problem and maintains the output voltage over a large input voltage range, the second type is used. This is called the step square wave, rectangular wave, or modified sine wave. The MSW inverters operate in line frequency switching; as a result audio frequency interference does not occur. The main advantages of this inverter are low cost; high performance and it can run 95% of general equipment. This makes it the most popular inverter in the market [22, 26].

Pure sine wave inverters are specially used in high sensitive medical instrument and other critical applications. For any device that requires sensitive calibration, it is advisable to use a PSW inverter [9]. Early techniques for designing these inverters incorporated significant linear technology, reducing their efficiency and contributing to their higher cost and cause Radio Frequency Interference. More recent designs used pulse width modulation (PWM) to produce a pulsed waveform that can be filtered relatively easily to achieve a good approximation to a sine wave. However, PWM requires significant control circuitry and high-speed switching.

Grid connected inverter is a special type of power inverter that converts direct current into alternating current and feeds it into an existing electrical grid. It is often used to convert direct current produced by many renewable energy sources, such as solar panels or small wind turbines, into the alternating current used to power homes and businesses. It needs to interface PV system with grid. Grid connected systems are installed in those areas where robust grid is present and able to accept energy feeding from the PV system. The electrical energy injected into the grid depends on the amount of power extracted from the PV system and the efficient processing of this power by the inverter. There are several topologies to design grid connected inverter. The grid and PV energy synchronization is the challenge of designing the grid connected inverter. The above threats are eliminated by designing microcontroller based control circuits and considering feedback from electrical grid. The operational characteristics of PV array and the electrical grid regulations and standards have been considered to design of the inverter.

Analysis of Current Technology: It is well known that any periodic waveform such as that mentioned previously can be represented by a Fourier series, an infinite sequence of sine and cosine, at the fundamental frequency of the waveform and its harmonics. The actual percent distortion is not usually quoted in the specifications for inverters other than the PS wave versions, so it is instructive to compute the distortion products to get a feel for the relative distortion involved with the different approaches.

The coefficients of the Fourier series are computed with a pair of integrals that produce the coefficients of the sine and cosine terms in the series. For a signal $f(\omega t)$ with a zero DC component, the integrals are:

$$a_n = (\frac{1}{\pi})\int_0^{2\pi} f(\omega t)\cos(n\omega t)d\omega t \quad \text{n>0}$$

$$b_n = (\frac{1}{\pi})\int_0^{2\pi} f(\omega t)\sin(n\omega t)d\omega t \quad \text{n>0}$$

Where, a_n and b_n are the coefficients of the cosine and sine terms at the n^{th} harmonic, respectively, in the series. The Fourier series is then:

$$f(\omega t) = a_1\cos(\omega t) + a_2\cos(2\omega t) + a_3\cos(3\omega t) + ... + b_1\sin(\omega t) + b_2\sin(2\omega t) + b_3\sin(3\omega t) + ...$$

Both the square wave and the MS wave have half- and quarter-wave symmetries, therefore, the Fourier series only contains the odd harmonics and the sine terms. Thus, the integral used to compute the coefficients for the conventional square wave becomes:
The series is then: $(4/\pi)\sin(\omega t) + (4/3\pi)\sin(3\omega t) + (4/5\pi)\sin(5\omega t) + ...$

Derivation of Current Commands: In the PV system, once a current command is determined, the output current of the half-bridge inverter will trace the waveform of the reference current to perform power flow controlling and power quality improvement. In the following, an optimal current command is derived. According to the current and voltage definitions the line voltage $v_S(t)$ and nonlinear load current $i_L(t)$ are expressed as

$$v_S(t) = \sqrt{2}V_{rms}\sin(\omega t - \phi)$$

$$i_L(t) = \sum_{n=1}^{\infty}\sqrt{2}I_n \sin(n\omega t - \theta_n)$$

Then, the load instantaneous real power $p_L(t)$ and instantaneous reactive power $q_L(t)$ can be calculated as follows:

$$p_L(t) = v_S(t)i_L(t)$$

$$= V_{rms}I_1\cos(\phi - \theta_1) - V_{rms}I_1\cos(2\omega t + \phi + \theta_1) + \sum_{n=2}^{\infty}2V_{rms}I_n\sin(n\omega t + \theta_n)\sin(\omega t + \phi)$$

$$= \overline{p}_L + \widetilde{p}_L$$

Where, $\overline{p}_L = V_{rms}I_1\cos(\phi - \theta_1)$

$$\widetilde{p}_L = V_{rms}I_1\cos(2\omega t + \phi + \theta_1) + \sum_{n=2}^{\infty}2V_{rms}I_n\sin(n\omega t + \theta_n)\sin(\omega t + \phi)$$

$\overline{p}_L$ Represents the constant part and $\widetilde{p}_L$ denotes the variant component. The instantaneous reactive power can be obtained by multiplying the nonlinear load current with a 90° shifted voltage as follows:

$$q_L(t) = v'_S(t)i_L(t)$$

$$= V_{rms}I_1\sin(\phi - \theta_1) - V_{rms}I_1\sin(2\omega t + \phi + \theta_1) - \sum_{n=2}^{\infty}2V_{rms}I_n\sin(n\omega t + \theta_n)\cos(\omega t + \phi)$$

$$= \overline{q}_L + \widetilde{q}_L$$

Where, $\overline{q}_L = V_{rms}I_1\sin(\phi - \theta_1)$

$$\widetilde{q}_L = V_{rms}I_1\sin(2\omega t + \phi + \theta_1) + \sum_{n=2}^{\infty}2V_{rms}I_n\sin(n\omega t + \theta_n)\cos(\omega t + \phi)$$

Where, $v'_S(t)$ is the line voltage shifted by 90°, $\overline{q}_L$ is the constant part, and $\widetilde{q}_L$ is the variant component of instantaneous reactive power. Apparent power is determined by the eq.

$$S = V_{rms}\sqrt{\sum_{n=1}^{\infty}I_n^2}$$

$$= \sqrt{[V_{rms}I_1\cos(\phi - \theta_1)]^2 + [V_{rms}I_1\sin(\phi - \theta_1)]^2 + \sum_{n=2}^{\infty}V_{rms}^2 I_n^2}$$

in which the first, second, and third terms are the square of real, reactive, and distortion powers, respectively. The reactive and distortion powers of a nonlinear load will be supplied by the PV system. As a result, amplitude of a compensated line current depends on PV power, which is sinusoidal and in phase with line voltage. It can be determined by

$$i_s^* = \frac{\sqrt{2}(P_{MPPT} - \overline{p}_L(t)}{V_{rms}} \sin(\omega t - \phi)$$

In addition, a corresponding inverter output current is expressed as

$$i_c^* = \frac{\sqrt{2}(P_{MPPT} - \overline{p}_L(t)}{V_{rms}} \sin(\omega t - \phi) + i_L$$

Where, P_{MPPT} is the maximum power drawn from the PV arrays and can be represented as

$$P_{MPPT} = v_{PV}(t) \times i_{PV}(t)_{\max}$$

2.5.5 Smart Meter

The smart meter is the revenue management device including net metering (export-import) capability. It also allows for real-time pricing information, so that consumers can make decisions about their timing of electricity use. This does not mean that consumers must continuously monitor pricing information; smart meter incorporating real-time pricing information helps shift consumption to the off peak times [25].

2.6 Conclusion

This chapter describes the photovoltaic cell innovation and development in brief. Also describes the PV array output current, voltage and power equations. Different application method of PV system; their challenge and benefit are present here. Modern concepts of renewable energy integration in smart grid system have described. Also discuss about the element requires to implement smart grid system. Charge controlled different set point, MPPT algorithm, Inverter technology and their importance also discuss here.

CHAPTER III

Design and Analysis of Smart grid PV System

3.1 Introduction

Renewable energy is considered as one of the twin-pillars of sustainable energy along with energy efficiency. Thus, the accelerated deployments of large-scale renewable based generations are seen in many utilities all around the world. As a result, there has been an increasing interest for smart grid PV generator. Most of the large scale PV generation systems will be integrated to main grids for sustainable energy delivery in many parts of the world [27-28]. For efficient grid interfacing both voltage source converter (VSC) and current source converter (CSC) are used. A significant percentage of utility scale PV is equipped with CSC [29] due to the simplicity of control and lower cost, but the impact of this model on oscillatory stability is yet to be examined in detail. This chapter describes the above observations and interest, attention is drawn to the effect of PV systems on power system stability and its financial feasibility, cost analysis and carbon emission reduction.

3.2 Smart Grid System

According to the U.S. department of energy (DOE)'s modern grid initiative, a smart grid integrates advanced sensing technologies, control methods and integrated communications into current electricity grid both at transmission and distribution levels. The European Commission defines smart grid as leveraging advanced computer communications and communications technologies to create a power distribution network that is flexible, accessible, reliable and economic. Similarly, the U.S. congressional research service states the goal of smart grid is to use advanced, information based technologies to increase power grid efficiency, reliability, flexibility, and reduce the rate at which additional electric utility infrastructure needs to be built. The smart grid acts like a reliable marketplace with multiple producers, consumers, and arbitragers buying, selling, and temporarily storing power [11, 15, 29]. Prices are dynamic and information flows freely in both directions to optimize the efficiency of the marketplace. Small producers of low carbon power get easy access to sell into the marketplace, and consumers have access to price signals that let them save money by shifting power consumption to off peak times [30].

3.2.1 Design Procedure of Smart Grid PV System

The block diagram of proposed system is shown in Fig.3.1. This model shows that in rough weather and low irradiation condition PV energy will minimum and grid contribute to meet the consumer's energy demand. On the other hand when PV energy generation is sufficient and consumers are not able to consume the energy then excess energy is automatically exported to the grid. Inverter output voltage, frequency and phase need to synchronize with grid voltage, frequency and phase respectively for injecting power to the grid. If synchronization process are properly achieved generated power are evacuated to grid. Inverter has built in self synchronization process. If synchronization dose not achieve properly generated energy charge the backup battery. Smart meter has bidirectional power measurement facility. Deduction from export and import energy net energy consumption is determined. In addition, due to rough weather or any other circumstances, when the PV electricity generation fails to generate electricity then the load automatically shift to the grid. The flowchart of smart control system has been shown in Fig.3.2; therefore, the system reliability and quality of service will better.

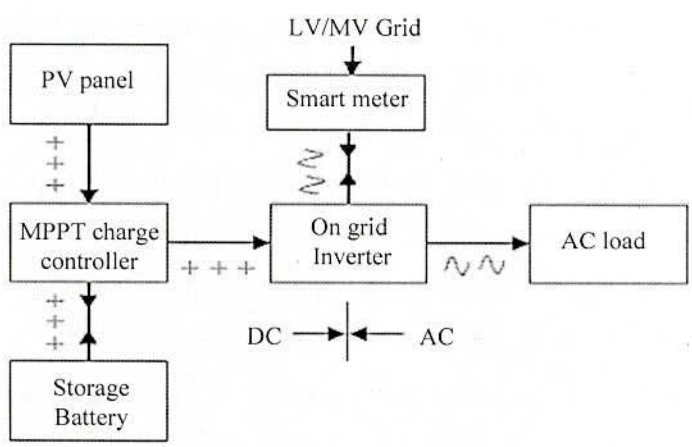


Fig.3.1 Block diagram of smart grid PV system

3.2.2 Flowchart

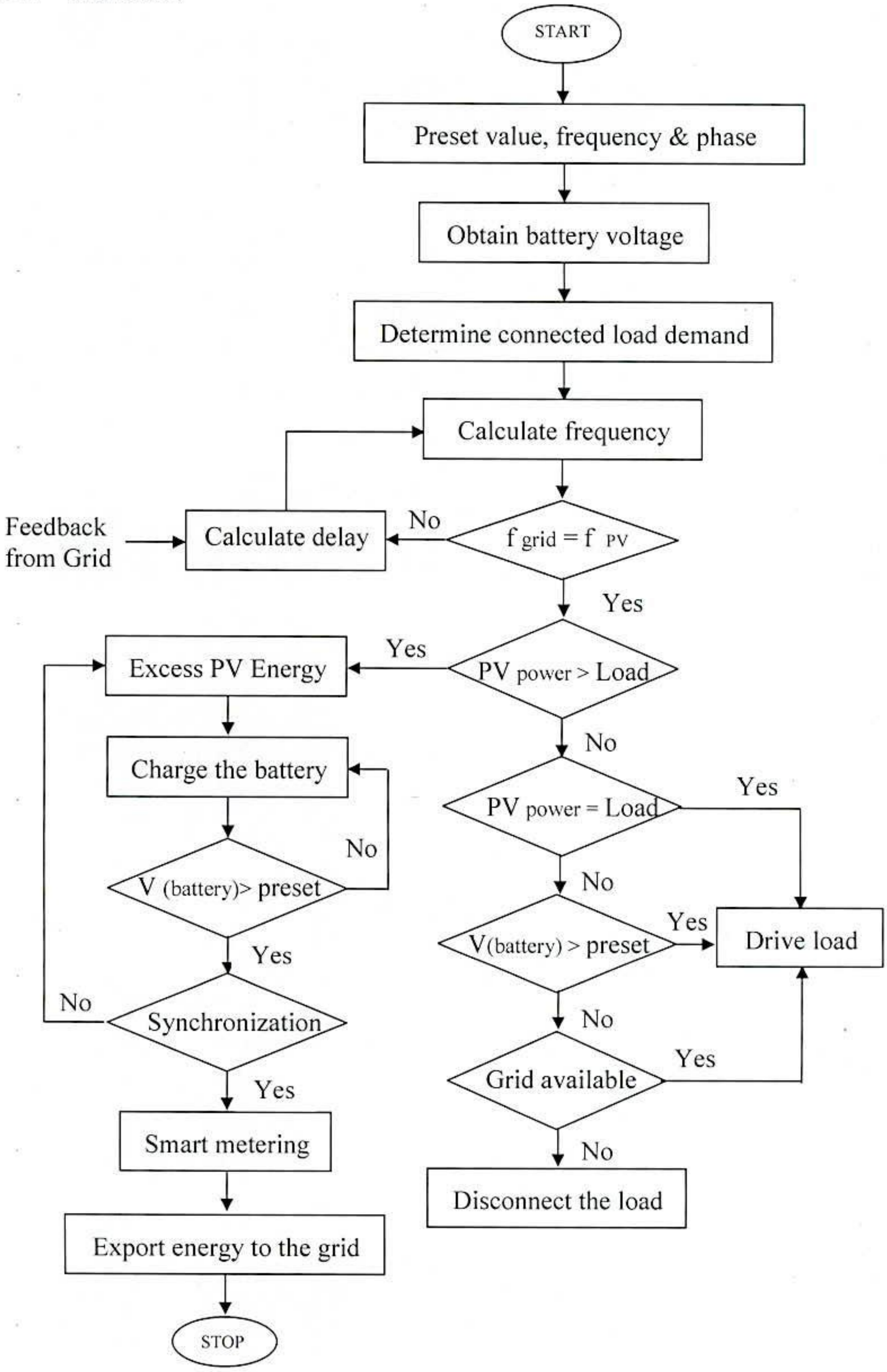


Fig.3.2 Flowchart of smart grid system

3.2.3 PV Generation System Modeling

Photovoltaic generator consists of three major components, namely, PV array, power electronics interface and the associated controllers. Based on power electronic interface and an additional component to smooth out the intermittency of output power, PV generation system can be grouped into three different types:

- System-I: PV array, DC/DC converter, voltage source converter (VSC) and associated controllers.
- System-II: PV array, DC/DC converter, current source converter (CSC) and associated controllers.
- System-III: PV array, DC/DC converter, ultra capacitor, VSC and associated controllers.

System Model – I:

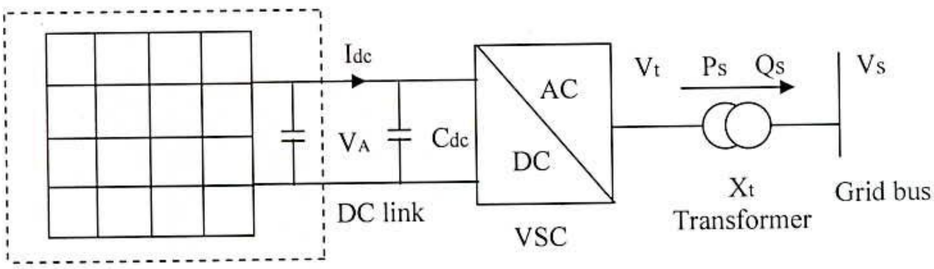


Fig. 3.3 PV generation system – I

In System-I, PV array is interfacing with unidirectional DC/DC converter and VSC. The generalized form of the dynamic model [10] related to converter and their controllers is

$$\dot{x} = f(I_{PV} V_{PV} I_{dc} V_{dc} I_d I_q m \delta)$$

Where, I_{PV} = DC/DC converter inductor current, V_{PV} = DC/DC converter capacitor voltage, I_{dc} = coupling inductor current, V_{dc} = DC link capacitor voltage, I_d and I_q represent d_q - current components of the VSC, m = VSC modulation index, and δ = phase angle control of the converter. Let us assume that the DC power generated by PV array is delivered to the network without loss, then real and reactive power injection of System-I to the bus can be expressed by the following two equations:

$$P_S = \frac{0.6128\ mV_{dc}V_S \sin\delta}{X_t}$$

$$Q_S = \frac{0.6128\ mV_{dc}\cos\delta}{X_t} - \frac{V_S}{X_t}$$

Where, V_S = grid bus voltage (V), V_t (VSC terminal voltage) = $0.6128mV_{dc}$ *and* X_t = impedance between inverter terminal and the grid bus (Ω).

System Model – II:

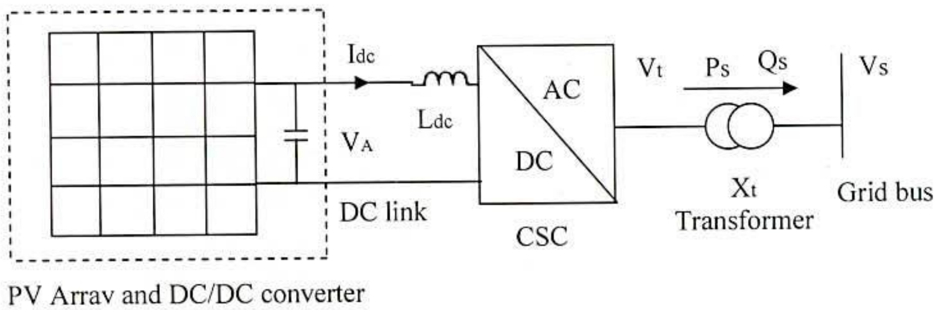


Fig. 3.4 PV generation system – II

In System-II, PV array is interfaced with unidirectional DC/DC converter and current source converter (CSC). The generalized form of the dynamic model [10] related to converters and their controllers is

$$\dot{x} = f(I_{PV}\, V_{PV}\, I_{dc}\, I_d\, I_q)$$

Where, I_{PV} = DC/DC converter inductor current, V_{PV} = DC/DC converter capacitor voltage, I_{dc} = DC link current control, I_d and I_q represent d_q current components of CSC.

Real and reactive power injection to the grid depends only on the grid side current control of the converter, for a lossless converter real power generated by PV generator is equal to the DC power generated by PV array and can be expressed by

$$P_{dc} = P_S = V_d I_d + V_q I_q$$

and expression for reactive power generation by the generator is

$$Q_S = V_q I_d - V_d I_q$$

Where, V_d = d-axis converter voltage and V_q = q-axis converter voltage.

System Model – III:

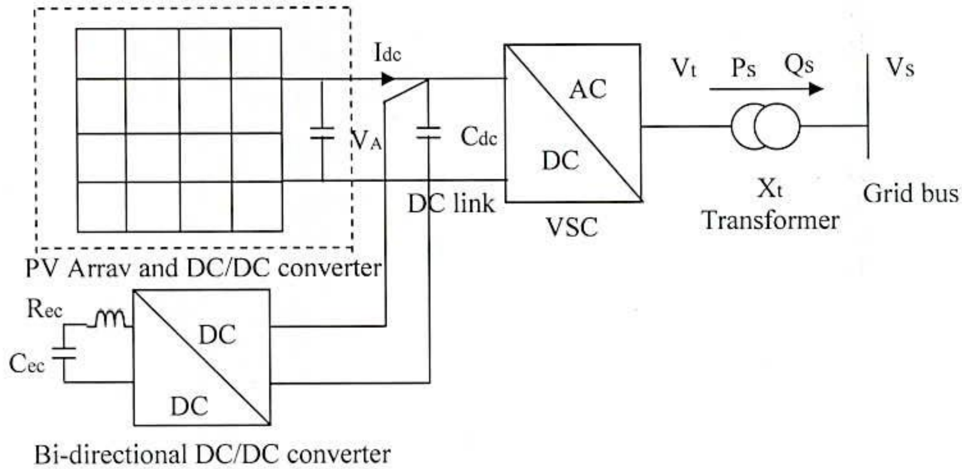


Fig. 3.5 PV generation system - III

In System-III, PV array is interfacing with unidirectional DC/DC converter, voltage source converter (VSC) and ultra capacitor via bidirectional DC/DC converter. The generalized form of the dynamic model [10] related to converters and their controllers can be expressed by

$$\dot{x} = f(I_{PV} V_{PV} I_{dc} V_{dc} V_{uc} I_d I_q dm\ \delta)$$

Where, I_{PV}= DC/DC converter inductor current, V_{PV}= DC/DC converter capacitor voltage, I_{dc}= coupling inductor current, V_{dc}= DC link capacitor voltage, V_{uc}= ultra capacitor voltage, I_d and I_q represent d_q is current components of the VSC, d = duty cycle control of bidirectional converter, m = VSC modulation index, and δ = phase angle control of VSC. The value of ultra capacitor is usually very large while resistance is very small. So, the ultra capacitor can be modeled as a small resistance (R_{ec}) in series with a large capacitor (C_{ec}) as shown in Fig.3.5. The DC link capacitor voltage and the ultra capacitor voltage are related through a duty cycle ratio which control the charging and discharging of ultra capacitor where duty cycle ratio is controlled via proportional-integral (PI) controller. Now, the power balance equations at PV generator bus can be expressed by the power balance equations used in System-I.

3.2.4 PV Power Injection to the Grid

The photovoltaic cells generate dc current, which is converted into ac current by power electronics inverter control. The schematic diagram of a grid integrated PV system is shown in Fig.1.1. The PV generators do not have any rotating mechanical parts as compared to the other generation technologies. The dynamics of such systems are dominated by converter controllers [29]. The power is injected into the ac system by voltage source converter (VSC) operation. The solar irradiation and temperature are assumed to be constant throughout the analysis.

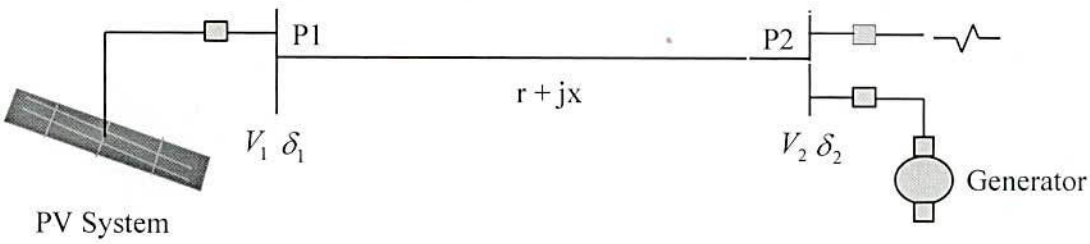


Fig. 3.6 Two bus system

Real and reactive power injection to the grid can be written as

$$P_{12} = \frac{V_1 V_2}{x}\sin(\delta_1 - \delta_2)$$

$$Q_{12} = \frac{V_1^2}{x} - \frac{V_1 V_2}{x}\cos(\delta_1 - \delta_2)$$

Where, P_{12} is real power flow from network 1 to network 2, V_1 Voltage of Network 1, V_2 Voltage of Network 2, δ_1 Phase angle of network1, δ_2 Phase angle of network 2, Q_{12} is reactive power flow from network 1 to network 2, Assuming network 1 is PV generation and network 2 is electrical grid or generator. V_1 , V_2 and x of the above equation will be constant for a particular system. So we can write the equation in following form

$$P_{12} = k\sin(\delta_1 - \delta_2)$$

$$Q_{12} = k_1 - k_2\cos(\delta_1 - \delta_2)$$

From the above equations Real and reactive power flow are functions of voltage, phase angle differences and impedances, especially the reactance of the transmission lines. The power flow can be controlled by controlling phase angle, voltage magnitude and impedance of the line especially, the imaginary part with series compensation.

3.3 Technical Data for System Design

Type of the PV module used to design the system is mono-silicon; manufactured by ABC Inc. The nominal PV array power rating 10kWp, PV array coverage area 85.5 m^2, on grid PV system inverter efficiency 90% and miscellaneous power conditioning losses 5%. Annual solar energy collected on the surface of 10kWp PV module is 16.07MWh, while renewable energy delivered in the form of electricity is estimated 14.463MWh. The location of PV power generation system is the south west zone in Bangladesh; the nearest weather data location at Kolkata, where Latitude is 22.5 °N. Slope of fixed angle PV array is 30.0°N and azimuth angle is 0.0°. According to satellite data of project location annual solar radiation in horizontal surface is 1.77 MWh/m^2 while, solar radiation in tilted surface is 1.85 MWh/m^2 and yearly average temperature is 26.9 °C. RETScreen computer software tools and monthly average solar radiation data from NASA are taken in the study of the project. Monthly average daily temperature and radiation on the horizontal surface of the plane of PV array are given below.

Table.3.1 Average solar energy radiation & temperature

Month	Monthly average daily radiation		Average temperature (°C)
	horizontal surface (kWh/m^2)	plane of PV array (kWh/m^2)	
January	3.97	5.08	20.1
February	4.89	5.78	23.0
March	5.53	5.87	27.6
April	6.22	5.94	30.2
May	6.42	5.66	30.7
June	4.92	4.29	30.3
July	4.64	4.12	29.2
August	4.47	4.16	29.1
September	4.64	4.67	29.1
October	4.53	5.08	28.2
November	4.28	5.31	24.9
December	3.83	5.05	20.8

3.4 Cost Analysis

Project costs are analyzed by RETScreen computer software tools and market price of Bangladesh. The costs are expressed by US dollar. Brief description of cost analysis is described in table 3.2.

Table 3.2 Cost analysis

Description	Quantity	Unit cost	Amount
Initial Costs			
Feasibility study	1	$ 100	$ 100
Engineering	1	$ 100	$ 100
PV module(s)	10kWp	$ 1,250	$ 12,500
Transportation	1	$ 150	$ 150
Energy equipment	1	$ 85	$ 85
Module support	85.5 m^2	$ 8	$ 684
Inverter	12.0 KW	$ 275	$ 3,300
Backup Battery	1	$ 175	$ 175
Electrical equipment	10 kWp	$ 10	$ 100
System installation	10kWp	$ 15	$ 150
Balance of equipment	1	$ 20	$ 20
Training	5 p-h	$ 50	$ 250
Contingencies	2%	$ 17,614	$ 352
		Initial cost total =	$17,966
Annual Operation and Maintenance Cost			
Taxes/ Insurance	1	$ 100	$ 100
O&M labour	12	$ 80	$ 960
Other - O&M	1	$ 60	$ 60
Credit - O&M	1	$ 50	(-$ 50)
Contingencies	2%	$ 1,120	$ 22
		Operation and maintenance yearly =	$1092
Periodic Cost			
Inverter replacement	13 yr	$ 2,900	$ 2,900
Battery replacement	6 yr	$ 275	$ 1100

3.5 Feasibility Study

Feasibility study discuss about objectively and rationally uncover the strengths and weaknesses of an existing business or proposed venture, opportunities and threats as presented by the environment, the resources required to carry through, and ultimately the prospects for success [31-32]. In its simplest terms, the two criteria to judge feasibility are cost required and value to be attained [33]. As such, a well-designed feasibility study should provide a historical background of the business or project, description of the product or service, accounting statements, details of the operations and management, marketing research and policies, financial data, legal requirements and tax obligations [31]. Generally, feasibility study looks at the viability of an idea and precedes technical development for project implementation.

3.5.1 Financial Feasibility

In case of a new project, financial viability can be judged on the following parameters:

- Total estimated cost of the project
- Financing of the project in terms of its capital structure, debt equity ratio and promoter's share of total cost
- Existing investment by the promoter in any other business
- Projected cash flow and profitability

3.5.2 Internal Rate of Return (IRR)

The internal rate of return (IRR) is the rate of return used in capital budgeting to measure and compare the profitability of investments. It is also called the discounted cash flow rate of return (DCFROR) or the rate of return (ROR) [34]. In the context of savings and loans the IRR is also called the effective interest rate. The term internal refers to the fact that its calculation does not incorporate environmental factors (e.g., the interest rate or inflation). IRR calculations are commonly used to evaluate the desirability of investments or projects. The higher a project's IRR, the more desirable it is to undertake the project. Assuming all projects require the same amount of up-front investment, the project with the highest IRR would be considered the best and undertaken first.

3.5.3 Net Present Value (NPV)

Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash out flows [35]. It represents the time series of cash flows, both incoming and outgoing of individual cash flows of the same entity. NPV is a central tool in discounted cash flow (DCF) analysis and is a standard method for using the time value of money to appraise long-term projects. Used for capital budgeting and widely used throughout economics, finance, and accounting, it measures the excess or shortfall of cash flows, in present value terms, once financing charges are met. It compares the present value of money today to the present value of money in future, taking inflation and returns into account.

$$NPV = A_n\left(\frac{1+e}{e-i}\right)\left[\left(\frac{1+e}{1+i}\right)^y - 1\right] - C_c \qquad (1)$$

$$NPV = 1726 \times \left(\frac{1+0.025}{0.025-0.085}\right)\left[\left(\frac{1+0.025}{1+0.085}\right)^{25} - 1\right] - 21266$$

$$NPV = 1108$$

3.5.4 Benefit Cost Ratio (BCR)

Benefit cost ratio (BCR) can be defined as the ratio of the equivalent worth of benefits obtains from a project and the equivalent worth of cost. It is an indicator, used in the formal discipline of cost-benefit analysis, which attempts to summarize the overall value for money of a project or proposal. Benefit cost ratio takes into account the amount of monetary gain realized by performing a project versus the amount it costs to execute the project. If the benefit cost ratio is higher better the investment.

$$BCR = \frac{benefit.of.PV}{capital.\cos t.of.PV + PV.operating.\cos t} \qquad (2)$$

$$RCR = \frac{[A_0 - O\&M.\cos t] \times \left(\frac{1+e}{e-i}\right)\left\{\left(\frac{1+e}{1+i}\right)^y - 1\right\}}{capital.\cos t} \qquad (3)$$

$$BCR = \frac{[2822-1092] \times \left(\frac{1+0.025}{0.025-0.085}\right)\left\{\left(\frac{1+0.025}{1+0.085}\right)^{25} - 1\right\}}{21266}$$

$$BCR = \frac{22426}{21266} = 1.05$$

3.5.5 Pay Back Period

Pay Back Period (y) determines the number of years required to recover the capital invest of the project. In project evaluation and capital budgeting, the payback period estimates the time required to recover the principal amount of an investment.

$$y = \frac{capital.\cos t}{A_0 - O\&M.\cos t} \quad \text{(4)}$$

$$y = \frac{\log\{(\frac{C_c}{A_0})(\frac{e-i}{1+i}) + 1\}}{\log(\frac{e+i}{1+i})} \quad \text{(5)}$$

$$y = \frac{\log\{\frac{21266}{2822} \times (\frac{0.025 - 0.085}{1+0.085}) + 1\}}{\log(\frac{1+0.025}{1+0.085})} = 9.48$$

$$y \cong 10 \text{ Years}$$

3.6 Reduction of Carbon Emission

Carbon dioxide emissions into the atmosphere, and the emissions of other GHGs, are often associated with the burning of fossil fuels, like natural gas, crude oil and coal. While this is harmful to the environment, carbon offsets can be purchased in an attempt to make up for these harmful effects. The Kyoto Protocol defines legally binding targets and timetables for cutting the GHG emissions of industrialized countries that ratified the Kyoto Protocol. Accordingly, from an economic or market perspective, one has to distinguish between a mandatory market and a voluntary market. Typical for both markets is the trade with emission certificates. Carbon as well as green house gas emission reduction for using PV system can be calculated by the following equations. As we are developing country carbon trading will be potential source for developing PV energy.

$$CO_2(emission) = \sum OP * P_t * CEF_t$$

Where, P_t is percentage contribution to the grid (%), CEF_t Emission factor for specific technology and or fuel type (tons CO_2/MWh), $CEF_{wt.avg}$ is Weighted emission factor for a fuel mixture in grid (tons CO_2/MWh) and OP is the power generation in megawatt.

$$CO_2(emission.reduction) = OP \times \sum P_t \times CEF_t$$

$$= OP \times CEF_{wt,avg}$$

$$= 14.46x0.946$$

$$= 13.67 \text{ (Ton } CO_2 \text{ per year)}$$

3.7 Stability Analysis

Power system stability is defined as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. Stability is a necessary condition for the reliable operation of a power system. Instability of the Power system can be classified into following category-

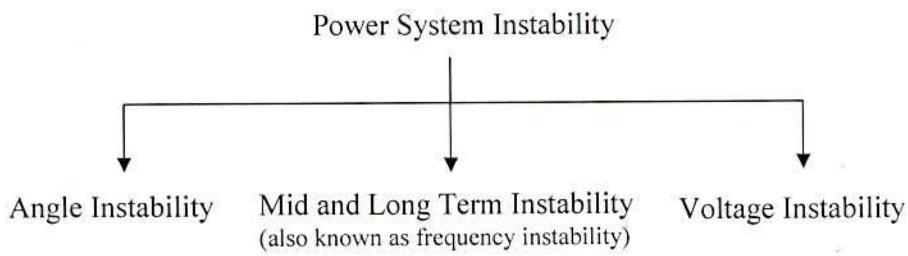


Fig. 3.7 Power system instability

Voltage rise is one of the key technical challenges limiting the amount of additional DG capacity that can be connected to rural distribution networks. Moreover transient voltage variation in the form of oscillation with increase in amplitude and dynamic voltage stability can limit the DG penetration [36]. The large-scale penetration of DG also has an impact on the short-term stabilities (voltage and transient) of a system and, when it increases, its impact is no longer restricted to the distribution network but begins to influence the entire power system [37] by either improving or deteriorating its stability performance.

3.7.1 Angle Instability

Angle instability occurs due to torque imbalance of generators. It can be classified as Transient Stability and Small Signal Stability. In smart grid systems, conventional and non-conventional generators are connected with grid. The dynamics of power transfer in such grid can be categorized by low frequency oscillatory behavior of synchronous generator, static generator and their controllers. Low frequency oscillation of power system is mainly of two types, local mode (frequency range 0.7 Hz to 2.0 Hz) and inter-area mode oscillation (frequency range 0.1 Hz to 0.7 Hz) [38]. Oscillation in power system occurs in a stressed network condition and the main contributing factors for oscillation are [38-40]:

- Weak transmission link (Network topology)
- Inadequate reserve margin for power plants
- Imbalance power generation and demands
- Loading of the system (Load uncertainties)

Due to given nature of PV, power system operation and control, and modulation of real and reactive power on PV and grid tie line are the main challenges for the power system operators and can create undamped oscillation to the electromechanical modes and other lightly damped modes in the system.

3.7.2 Voltage Instability

Voltage instability occurs due to reactive power imbalance in power system. The voltage instability problem occurs due to large disturbance, switching events, dynamics of ULTC (under load tap changers) and coordination of protection and control. It can be controlled easily by injecting real power to the network or compensating reactive power. In power system, generators are scheduled for reactive power support for voltage stability. On the other hand, DG units of small capacity do not contribute reactive power to the network, according to the interconnection guidelines for DG units set by utilities such as Australian Energy Market Operator (AEMO) [41].

In conventional power systems, damping of low frequency oscillations is supported by either power system stabilizers installed at synchronous generators or supplementary control loops of voltage control devices such as static var compensators (SVCs). With increased penetration of renewable energy resources, there are also efforts to utilize distributed generators (DG units) for oscillation damping as well as voltage stability in network. DG units of lower capacity do not have to meet any operational commitment to support stability of a network [42-43]. Hence the smart grid PV system can enhance the stability of the grid [44].

3.7.3 Mid –term and long-term instability

The Mid-term and long-term instability problems are relatively new in the literature of power system stability. These problems are associated with the dynamic response of power systems to severe upsets or disturbances. The severe upsets result in large excursions of voltage, frequency, and power flows that thereby invoke the actions of slow processes, controls, and protections.

3.7.4 Transient Stability

It is well known that large or small-scale integration of distributed generation (DG) may have significant impact on power system stability with respect to the rotor angle, voltage and frequency stability. Reactive power compensation and voltage control is fundamental to make the grid become smarter. Without this control, the presence of distributed generation may potentially cause system collapse. Therefore, a dynamic shunt reactive power compensator such as SVC is required to mitigate these issues since it can be used to enhance transient stability margin in power system. The potential effectiveness of SVC on transient stability enhancement can be examined through the following discussion. As depicted in Fig. 3.8, assume that a single power generation machine with interconnecting lossless lines have a reactance (*X*). Denoting the terminal voltages of generator machine and the infinite bus by $V_1\angle\delta$ and $V_2\angle 0$, power angle δ and the transmitted power as *P*, then without the SVC installed in the line, the value of the power transfer can be expressed by,

$$P = \frac{V^2}{X}\sin\delta$$

To understand the advantages of SVC, assume that an SVC is installed at the midpoint of the interconnecting line. In that case, the reactance of the SVC between the machine and infinite bus is *X*/2 ohms. Subsequently, the value of transmitted power can be calculated as

$$P = [\frac{V^2}{(X/2)}]\sin\delta = 2\frac{V^2}{X}\sin\delta$$

From Equation (2) it can be seen that the value of transmitted power is doubled *i.e.*, from $\frac{V^2}{X}$ it goes to $2(\frac{V^2}{X})$. Accordingly, the transient stability level is also increased. This fact can also be validated by the transient stability equal area criterion with SVC and without SVC, as shown in Fig. 3.8. Consider that Fig. 3.9(a) is system without SVC and Fig. 3.9(b) is system with SVC.

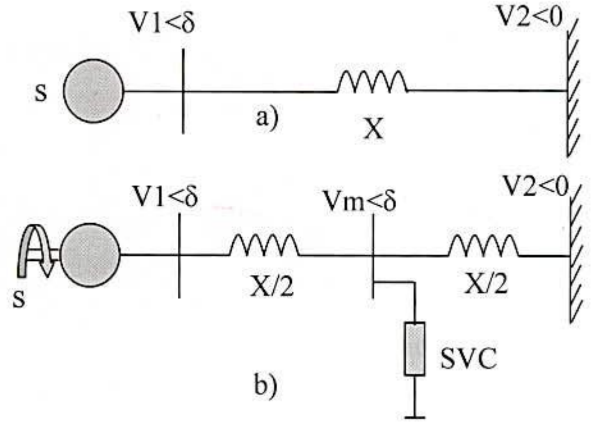


Fig.3.8 Simplified power systems (a) without SVC and (b) with SVC

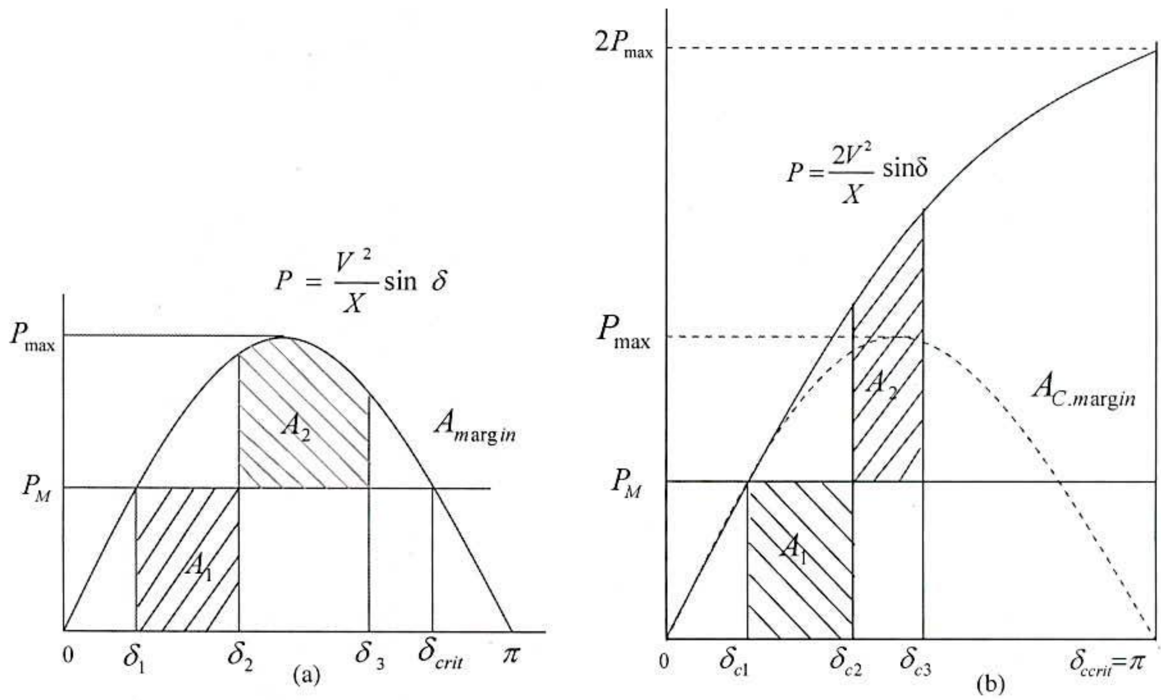


Fig. 3.9 Equal area illustration for transient stability without SVC (a) and with SVC (b)

After fault clearing, the transmitted power exceeds the mechanical input power and the generator starts to decelerate. Nevertheless, their angle increases due to the kinetic energy stored in the rotors. At δ_3 and δ_{c3} the maximum rotor angle are reached when the decelerating energies that represented by areas 'A_2'and 'A_{c2}' become equal to the accelerating energies defined by areas 'A_1' and 'A_{c1}'. The maximum of transient stability limits is achieved at δ_3 and δ_{Crit}. The areas of A_{margin} and $A_{C.margin}$ represent the transient stability margin of the system. From above description, it is evident that SVC is able to enhance transient stability limit. In addition, it is obvious that the transient stability is determined by power P against power angle δ.

3.8 Conclusion

A detail discussion on design and analysis of smart grid PV system is present in this chapter. Three models of PV power generation system and their P-Q characteristics equation has been solved. Solar radiation and temperature data and conversion of solar energy into electricity has been calculated. Cost analysis and financial feasibility study of smart grid PV system are analyzed. The dynamics of the PV system is completely different from that of the conventional generator, though both of them have almost identical P-Q characteristics. For this reason transient stability analysis of smart grid PV system are discussed with equal area criterion.

CHAPTER IV

Hardware Implementation for Smart Grid PV System

4.1 Introduction

This chapter deals with the hardware implementation of smart grid PV system. It is composed of hardware and software combination. The PV generation system includes photovoltaic array, MPPT charge controller (DC/DC converter), Grid connected inverter and their controllers. The system efficiency directly depends on the conversion efficiency of converter, inverter and their controllers. The procedure to design the improved quality components of PV system are described clearly one by one. Finally, the implemented circuit configurations are described and discussed.

4.2 Design of the Charge Controller

In general PV systems operate in one mode only that means it charges the battery first and turns supply power to the load. In this mode of operation, the life cycle time of the battery may be reduced due to continuous charging and discharging. The proposed PV charge controller shows the procedure that describes the operation in two modes (Fig. 4.1). Charge controller supplies PV energy directly to the load and when the radiation goes down or produced PV energy is not enough to meet the demand, then battery turns supply power to the load. On the other hand when the radiation is sufficient or minimum load demand then the system will charge the battery as well as supply the load. To manage these modes of operation, comparator IC LM324, flip flop IC 74LS279, transistor BC547 and control circuits are used to control above conditions.

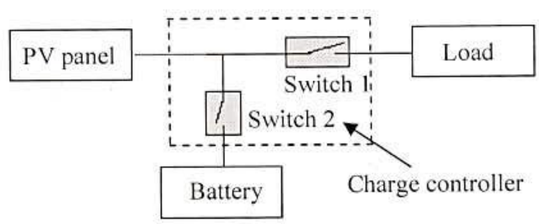


Fig.4.1 Block diagram of charge controller

4.2.1 Description of Charge Controller Circuit

The charge controller continuously senses the battery terminal voltage and compares with four reference voltages by four comparators LM324 used to serve this purpose. The comparator operates 74HC279 flip flop which operates Q1 and Q2 that simultaneously operate Electro magnetic relay RL1 and RL2.

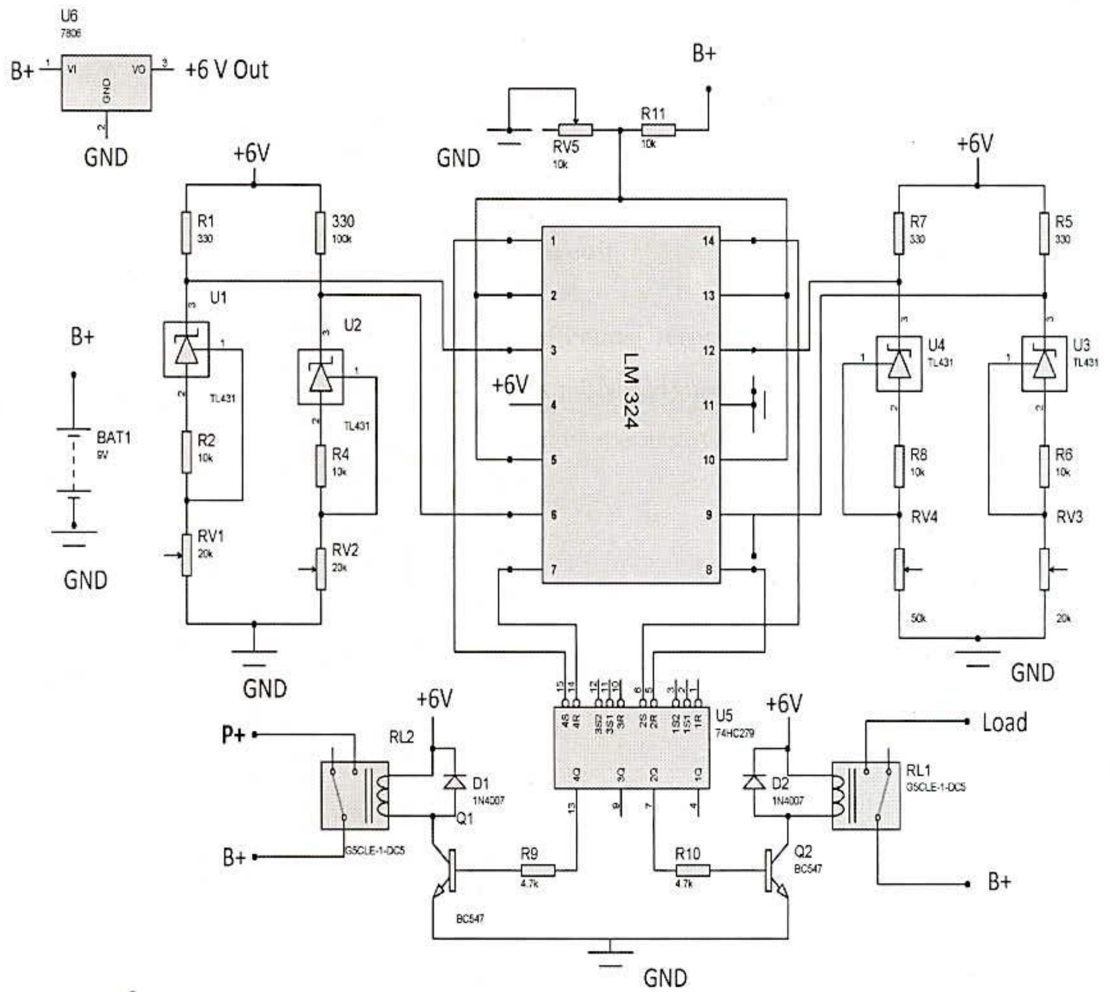


Fig.4.2 Circuit diagram of charge controller.

4.2.2 Charge Controller Circuit Operation

When battery terminal voltage becomes greater than a preset value (called voltage regulation set point (VR) =14.4 Volt for 12volt lead acid battery) then the out put of comparator 2 will be low (zero), it reset the flip flop 1 and give zero signal to the base of transistor Q1; it disconnects the PV panel from the battery by relay RL2. So the battery will be protected from over charging.

When the battery terminal voltage falls below another preset level (Array Reconnect Voltage Set Point (ARV) = 13.0Volt) then the out put of comparator 1 will be low (zero), it set the flip flop 1 and give 1 (+5v) signal to the base of transistor Q1; it reconnect the PV panel to the battery by relay RL2. The difference in these two set points is called Voltage Regulation Hysteresis (VRH). Hysteresis protects the frequent ON/OFF of the Switch RL1.

Similarly when the terminal voltage becomes less than another preset value (called Low Voltage Load Disconnect (LVD) set point=10.8Volt for 12volt lead acid battery) the output of Comparator 3 becomes low (zero) it reset the flip flop 2 and give zero signal to the base of transistor Q2; it disconnects the load from the battery and PV panel by relay RL1. So the battery will be saved from over discharging.

When the battery terminal voltage increase up to another preset level (Load Reconnect Voltage set point (LRV)=12.5volt) then the out put of comparator 4 will be low (zero), it set the flip flop 2 and give 1 (+5v) signal to the base of transistor Q2; it reconnect the load to the battery by relay RL1. The difference between these two set points is called Voltage Load Disconnect Hysteresis (LVDH).

4.2.3 MPPT Algorithm

There are various algorithms to achieve maximum power point in PV system operation. The most popular methods are constant voltage method, perturb and observe method, Incremental conductance method and parasitic capacitance method. Out of all the available methods constant voltage method is the most recognized because of its simplicity in design. A simple MPPT algorithm is developed as shown in figure 4.3. It continuously observes the load voltage, PV panel voltages and current. Depending on these observations, the controller will generate a suitable duty cycle and operate boost converter to keep rated voltage on load terminal for achieving maximum output power.

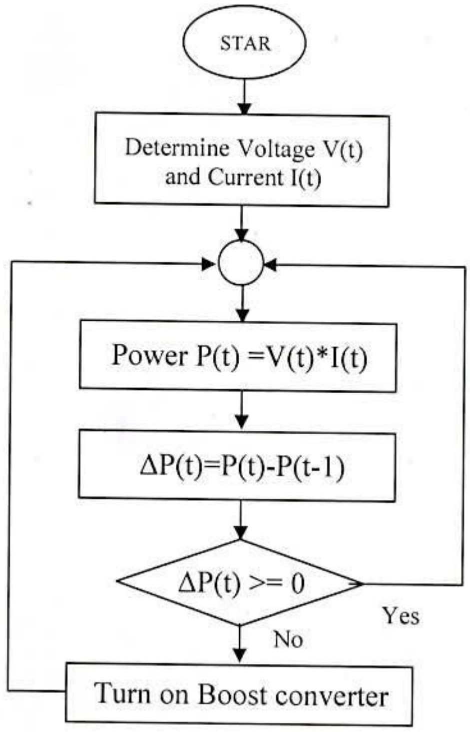


Fig.4.3 Flowchart of Maximum Power Point tracking algorithm

4.2.4 Boost Converter Design

The power converter with an output DC voltage greater than its input DC voltage is known as boost converter. It is a switching-mode power supply containing at least two semiconductor switches and at least one energy storage element. The boost converter activate when the panel voltage decreased to a preset value. A voltage comparator is used to determine the preset level and activate boost converter. Filters made of capacitors in combination with inductors are normally added to the output of the converter to reduce output voltage ripple.

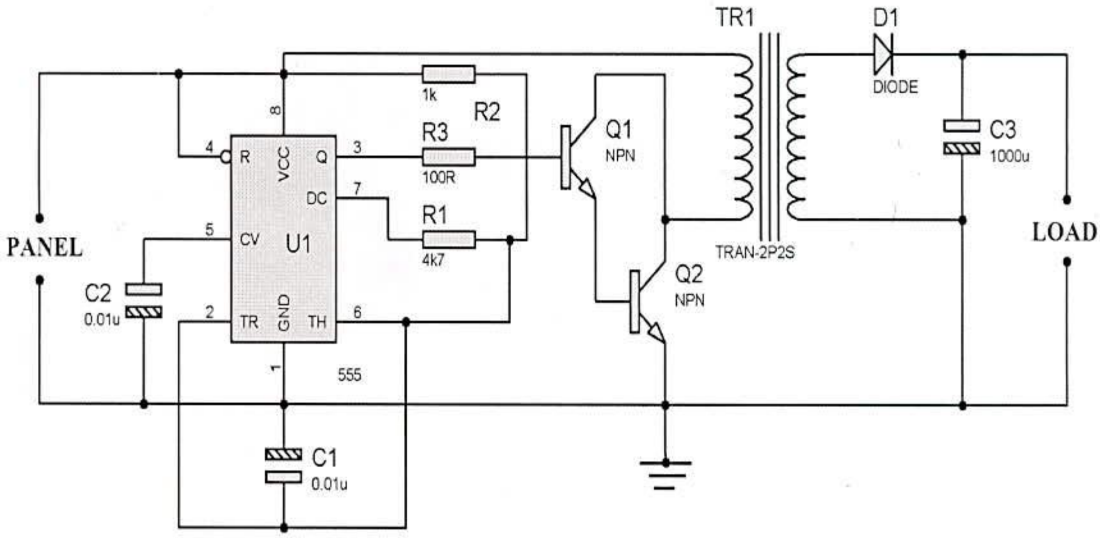


Fig.4.4 Circuit diagram of Boost converter

4.3 Inverter

Inverter is an electrical power converter that changes direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. There are three major types of inverter based on waveform, square wave (SW), modified sine wave (MSW), and pure sine wave (PSW). The first type, square wave, is not suitable for marine use because it has no voltage control. This means that the input voltage is proportional to the output [45]. This type of inverter is the simplest and least expensive on the market. However, reliability and output voltage regulation of these inverters are poor. Eventually, it can damage sensitive equipment. Another shortcoming of SW inverter is its lack of surge power which can result in an inability to power motorized equipment [46].

In order to overcome this problem and maintains the output voltage over a large input voltage range, the second type is used. This is called the step square wave, rectangular wave, or modified sine wave. The MSW inverters operate in line frequency switching; as a result audio frequency interference does not occur. The main advantages of this inverter are low cost; high performance and it can run 95% of general equipment. This makes it the most popular inverter in the market [46-47].

4.3.1 Design of the Inverter

The configuration of the grid connected PV system consists of a dc-bus filter, DC-DC converter, a half-bridge DC-AC converter, an output filter and system controller. The half-bridge inverter contains two active switches and two dc voltage that can process real power bidirectionally. That is, the inverter either transfers PV power to ac side or draws power from utility. In addition, the inverter performs current harmonics elimination to improve power quality. The dc bus filter suppresses dc-link voltage fluctuations and filters out ac components on the dc side for maximum power point tracking, while the output filter serves as an interface between inverter and the grid.

4.3.2 Flowchart

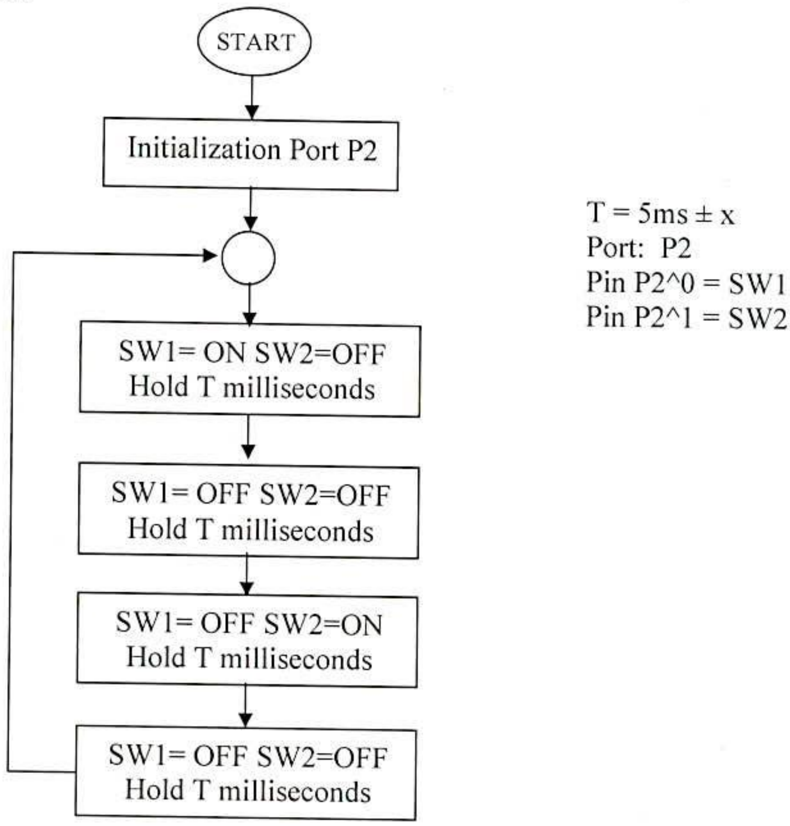


Fig.4.5 Flowchart of inverter frequency matching circuit

4.3.3 Description of the Inverter

The microcontroller AT89C51 programmed in such a way that it can generate suitable get pulse that can operate MOSFET STP55NF06L.The source terminals of two MOSFET are connected to the low voltage terminal of center tap transformer as shown in Fig.4.6, center of that transformer are connected to the battery positive terminal, gets and drain terminals are connected to the microcontroller and battery negative terminal respectively. According to the microcontroller get signal MOSFET turns on and off. The operating sequences of MOSFET are shown in Table 4.1. The microcontroller generates get pulse adding some operating delay to match the grid frequency voltage and phase. The frequency of the designed inverter can be calculated by the following equation.

$$f = \frac{1}{T}, f = \frac{1}{20\ ms} = \frac{1}{0.02\ s} = 50\ Hz$$

The operating delay time can be calculated by following ways. Let microcontroller delay = x, from Fig.5.10 one frequency = 4x, from 50Hz frequency system one cycle = 0.02 second = 4x, one second require = 4x / 0.02 =200x, microcontroller delay = microcontroller clock frequency / system frequency; 200x = 12000000/50, x=1200.

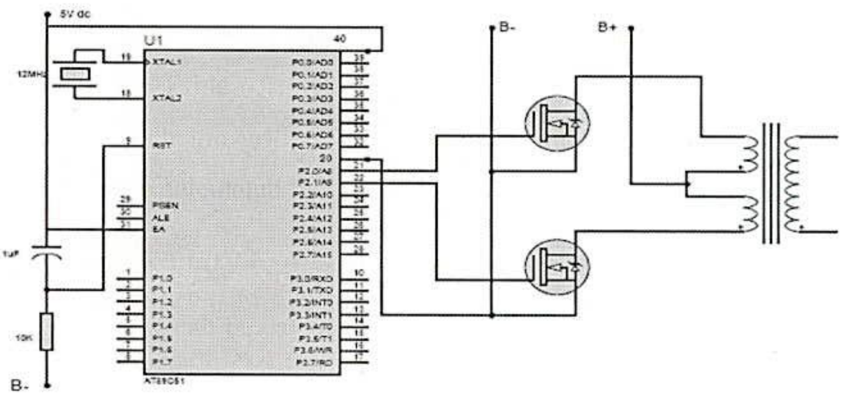


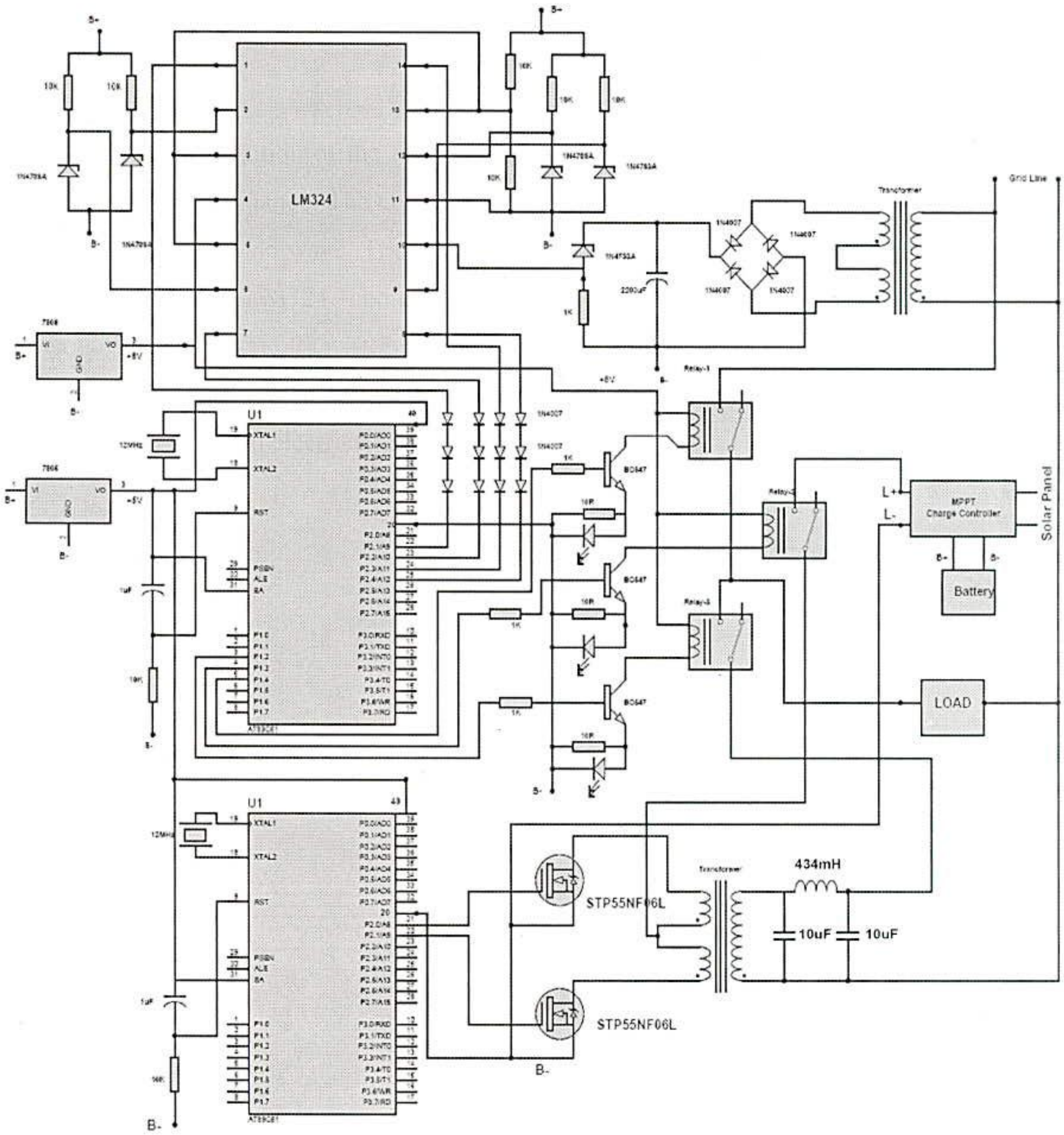
Fig.4.6 working principle of grid connected PV system

Table.4.1 MOSFET Switching Sequences

Step	MOSFET 1	MOSFET 2
1	ON	OFF
2	OFF	OFF
3	OFF	ON
4	OFF	OFF

4.3.4 Hardware Design

The circuit diagram of the proposed grid connected single phase sine wave inverter is shown in Fig. 4.7. It is composed of a half bridge dc-ac converter. One Atmel89C51 microcontroller used for MOSFET operating signal for inverter and another used for control and synchronization of the inverter. The switching MOSFET STP55NF06L used for its excellent performance. The combination of to MOSFET and microcontroller signal generates a modified sine wave. Transformer and filter circuit makes it sine wave shape. The comparator IC LM324 compares different voltages and send signal to the microcontroller to operate transistor BC547 so that switching relays can operate properly. Different voltage sources are designed to need for utilization and control scheme for both photo voltaic system and electrical grid.



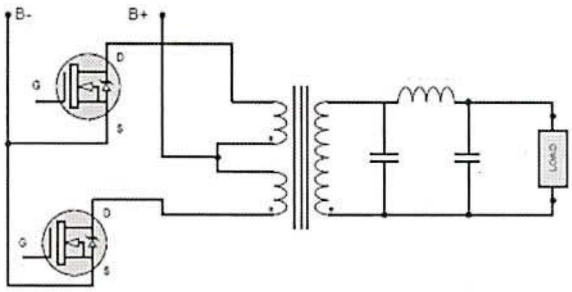
4.7 Circuit diagram of grid connected inverter

4.3.5 Filter design

The filter used over here is an L-C passive π filter, consisting of an iron core inductor and a capacitor. The capacitance of the capacitor is 20μF non-polar and the inductor inductance 434mH approximately. The resonant frequency of the combination can be determined from the equation,

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

$$f_c = \frac{1}{2\pi\sqrt{(0.434 \times 20 \times 10^{-6})}} = 54.05\,Hz$$



4.8 Filter circuit of the inverter

4.3.6 Control circuit and synchronization

The control circuit continuously senses the inverter output voltage, grid voltage; PV panel (battery) terminal voltage and compares with four reference voltages by comparator. The output signals of comparator are processed by microcontroller that was initially programmed. If the battery and PV panel voltage will be in the range of 14.4V to 10.8V then only relay 2 will operate and inverter can convert dc power to ac beyond this range relay disconnect the PV panel from inverter due to over voltage and under voltage respectively. As soon as reaching the array reconnect voltage level the system automatically connects the PV panel to the system. The control circuit checks the voltage level and phase. If the conditions of synchronization satisfy relay3 and relay1 connect PV system to the grid simultaneously. If the synchronism does not achieved feedback system change the parameters and try to synchronization. If synchronization does not achieve PV and backup battery will drive the load at that condition relay1 disconnect the grid from load. If PV system is not capable to drive the load then load will automatically transfer to the grid by relay 1. In this condition PV system charges the storage battery.

4.4 Conclusion

This chapter represents the procedure to design of an effective and efficient PV charge controller by incorporating MPPT algorithm and grid connected inverter with auto synchronization and control mechanism. The designed charge controller and inverter is simple and low cost with better performance that improves the quality of PV system. Grid connected inverter and control circuits established a contributory two way power flow between electrical grid and PV system to drive the load.

CHAPTER V

Result and Discussion

5.1 Introduction

This chapter deals with the simulation and experimental results of different building block of smart grid PV system. Circuit simulations are done by Proteus software and implementation is performed in laboratory. The performances of different components of PV system such as MPPT charge controller, on grid inverter and control circuit of the inverter are discussed below. Moreover, a feasibility study and cost analysis of smart grid PV has been performed by RETScreen software. Finally, a comparison between different types of PV systems and their challenge are described.

5.2 Performance Evaluation of Charge Controller

5.2.1 Charge Controller Set Points

The charge controller different set points are tested in laboratory with a stand-alone PV system and lead acid battery to protect the battery from overcharge and over discharge. The IV Characteristic of Solar panel is shown in Fig. 5.1.

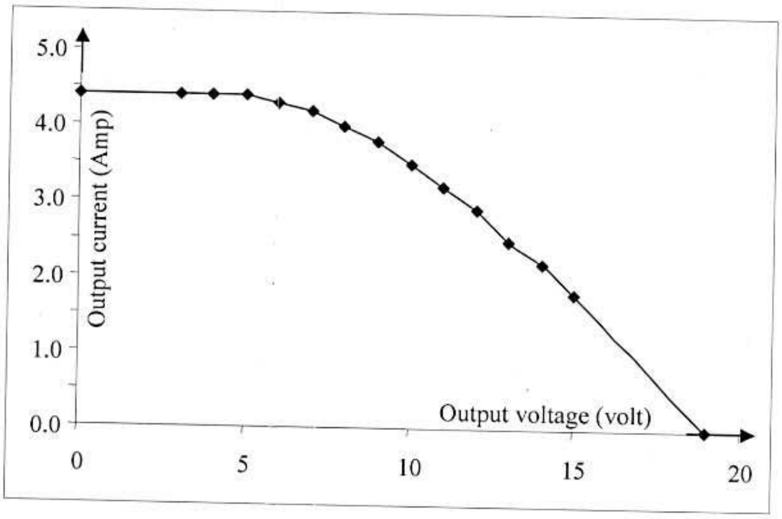


Fig.5.1 VI Characteristic of Solar panel

The implemented charge controller achieve the Voltage Regulation set point (VR): 14.4V Array Reconnect Voltage set point (ARV): 13.0V, Load Reconnect Voltage set-point (LRV): 12.5V and Low Voltage load Disconnect (LVD): 10.8V. There are two Hysteresis (VRH and LVDH) protect the frequent ON/OFF of the Switching relays.

5.2.2 Power Curves at Different Condition

The output power of PV array depends on temperature and irradiation condition. The different I-V characteristic curve at different temperature and irradiation values are shown in Fig.5.2 and Fig 5.3. It shows that output power increase with irradiation increase but with the increase of temperature output power decreases. The high performance MPPT charge controller removes this problem operating all the time at maximum power points are shown in fig.5.4.

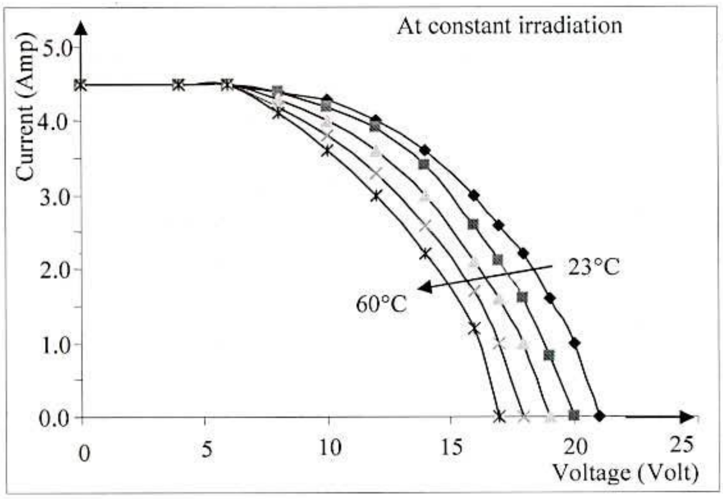


Fig.5.2 I-V curves at different temperature (23°C, 35°C, 43°C, 54°C and 60°C)

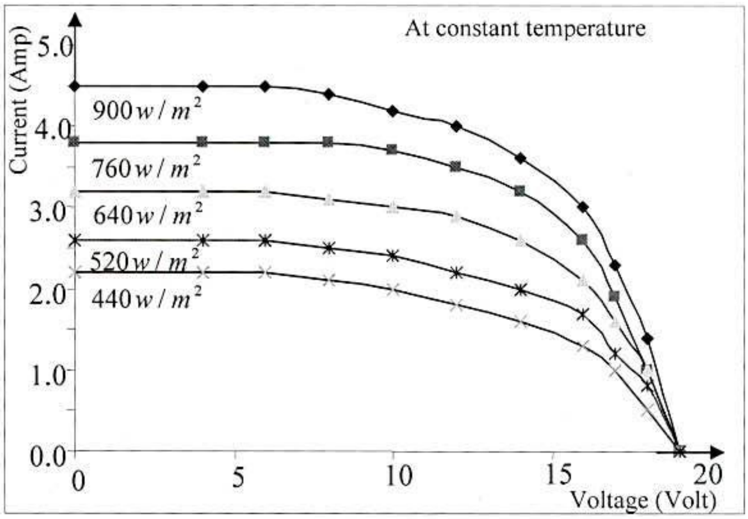


Fig.5.3 V-I curves at different radiation

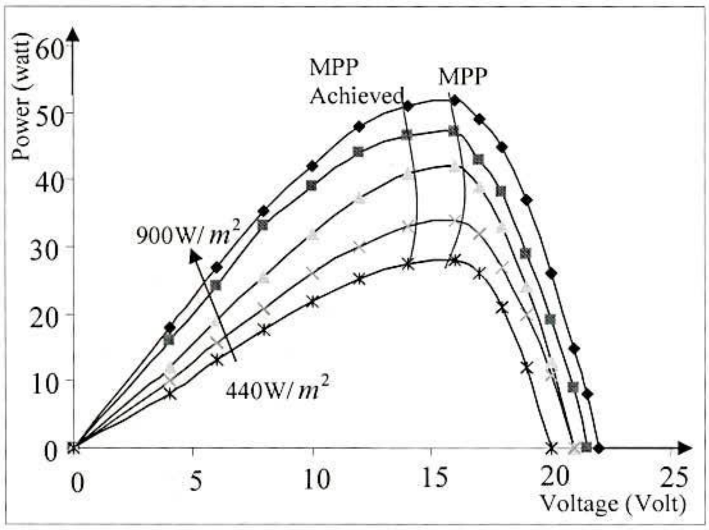


Fig.5.4 P-V curve with respect to MPP

5.2.3 Charging Current and Voltage Curves

The initial charging current provided by the PV module depends on its operating point. During the charge cycle, the PV module current decreases and its voltage moves towards the area where it behaves like a voltage source (Fig.5.5). The initial charging current (Fig.5.6) is high keeping almost the same value as long as the charging voltage is far from the set point (14.4 Volts). The battery terminal voltage rises, effectively reducing the magnitude of the charging current. When the battery voltage approaches the set point, the charging current decreases quickly allow keeping the charging voltage at a value close to the set point.

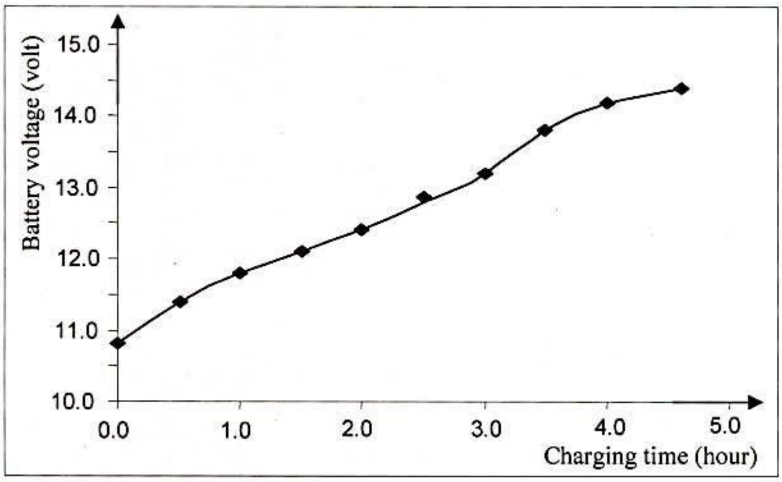


Fig.5.5 Battery charging Voltage

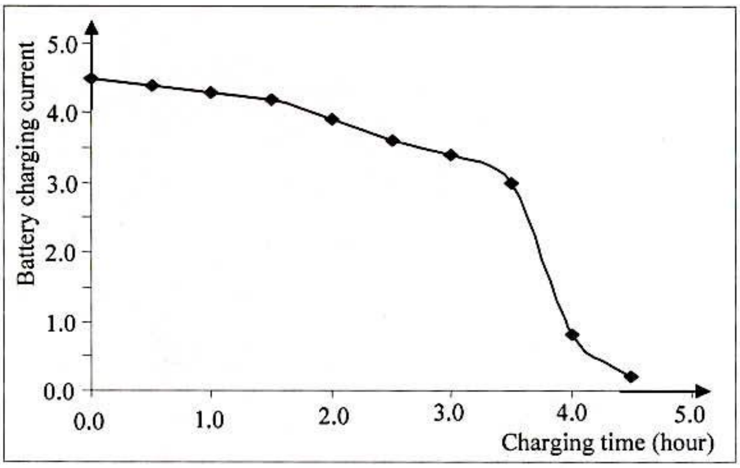


Fig.5.6 Battery charging current

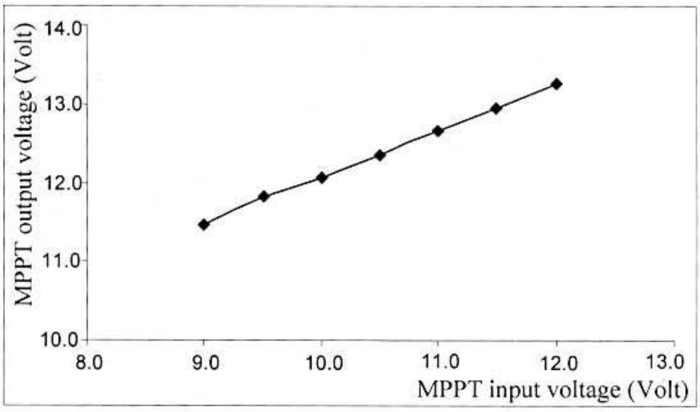


Fig.5.7 MPPT Charge controller output voltage – input voltage curve

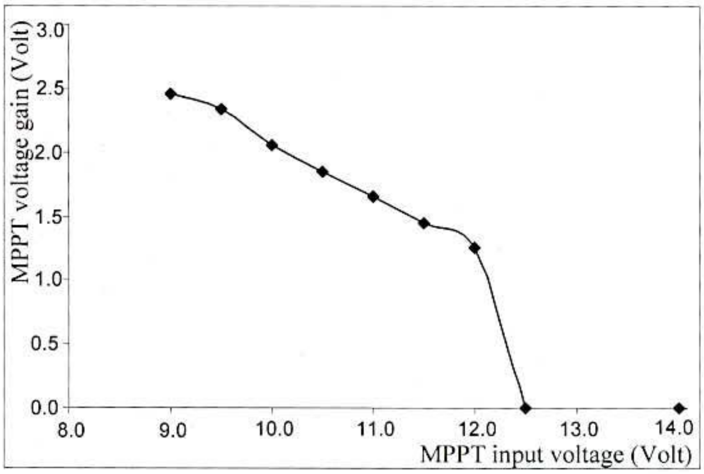


Fig.5.8 MPPT Charge controller voltage gain – input voltage curve

5.2.4 Performance of the Charge Controller

Table 5.1 Performance table of charge controller with respect to input output power

Sl.No	Input			Output			Efficiency %
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	
1	14.40	2.20	31.68	14.35	2.05	29.42	92.86
2	13.60	4.86	66.10	13.57	4.60	62.42	94.44
3	12.76	6.85	87.41	12.70	6.55	83.19	95.17
4	11.80	9.35	110.33	11.73	8.99	105.45	95.58
5	11.20	12.40	138.88	11.60	11.49	133.28	95.97
6	10.80	15.25	164.70	10.80	14.67	158.44	96.20
7	10.80	15.76	170.21	10.80	15.17	163.84	96.26

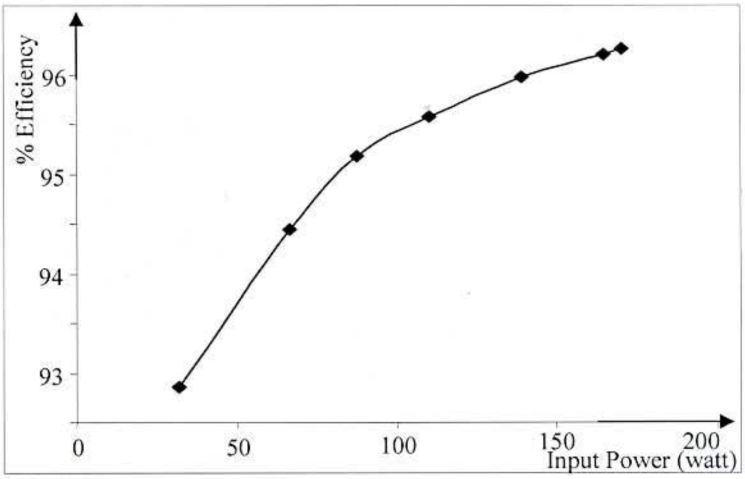


Fig.5.9 Charge controller input power - efficiency curve

5.2.5 Evaluation of Charge Controller

Different MPPT algorithms have different procedure and their implementation is different. The several performances are perturb and observe method 96.5%, incremental conductance method 96.7% and constant voltage method 93.1% efficiency [48]. The charge controller has been implemented in constant voltage method. It achieves 96.26% efficiency. Moreover, the implemented charge controller is simple and cost effective with better performance that improves the system quality.

5.3 Performance Evaluation of Grid Connected Inverter

5.3.1 Gate Controlling Signal of the Inverter

The input output signal and set points are tested in laboratory with electrical grid, PV system and lead acid battery to protect the inverter, load and the systems. The MOSFET operating gate pulse automatically generated by microcontroller are shown in fig.5.10 and 5.11. The switching sequences MOSFET generate modified sine wave and it feeds to the low voltage terminal of the center tap transformer (Fig.4.6) and it will generate almost sine wave with slide distortion (Fig 5.12).

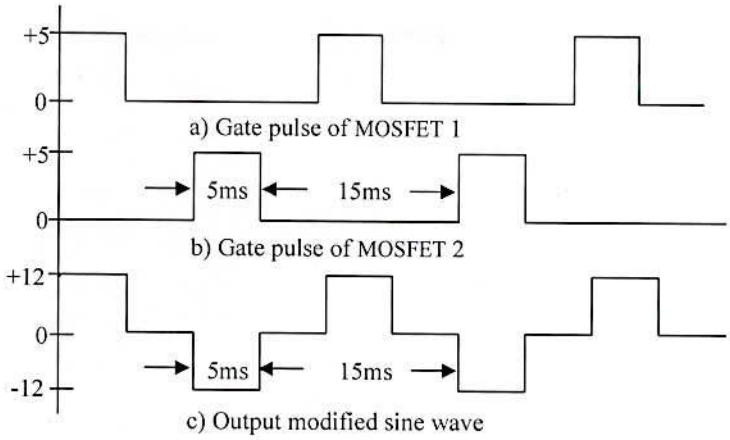


Fig.5.10 Get pulse and MOSFET output sequences

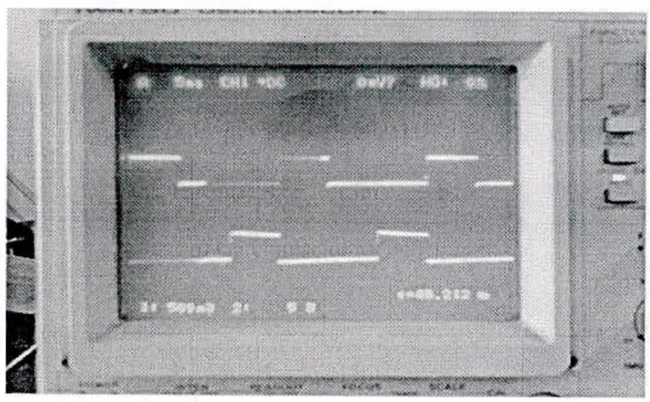


Fig.5.11 The get operating signal

5.3.2 Different output wave shape of the inverter

The distortion occurs during chopping of DC voltage and high frequency switching of MOSFET. After filtering pure sine wave shapes appear are shown in Fig.5.14 and 5.15. Table 5.2 and Fig. 5.16 show the efficiency of the inverter at different load condition. It shows that near rated capacity efficiency is better due to less conversion losses.

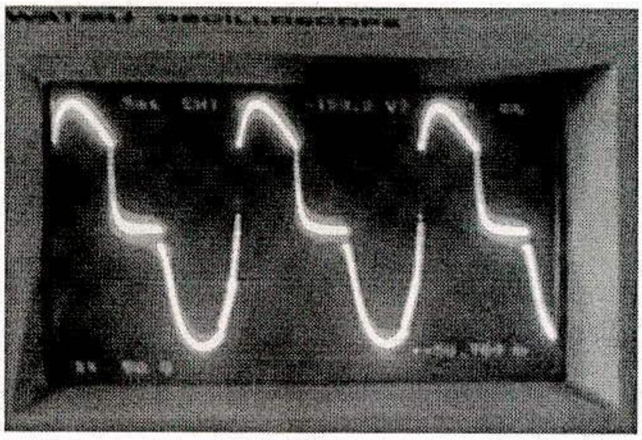


Fig.5.12 The output sine wave before filtering

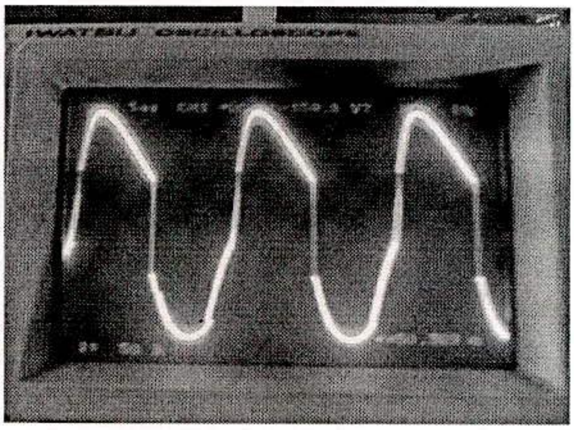


Fig.5.13 The output wave shape before filtering

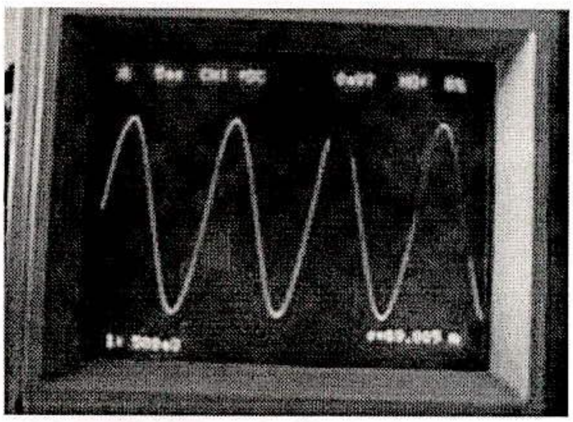


Fig.5.14 The output filtered wave shape in analog oscilloscope

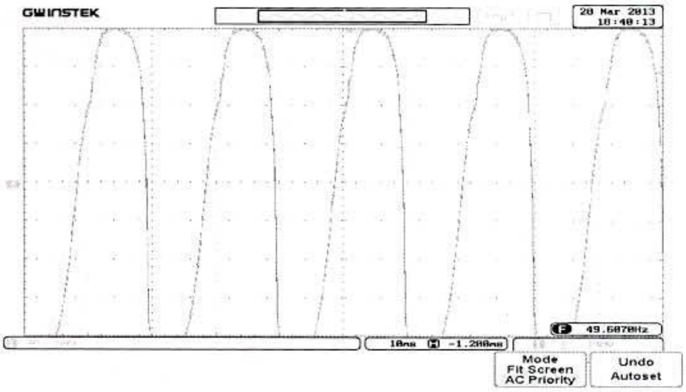


Fig.5.15 The output filtered wave shape in digital oscilloscope

5.3.3 Performance of the Inverter

Table 5.2 Performance table of inverter with respect to input output power

Sl. No	Input (DC)			Output (AC)			Efficiency %
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	
2	12	7.9	94.8	226	0.31	70.06	73.90
3	12	12.4	148.8	224	0.52	116.48	78.28
4	12	15.2	182.4	223	0.66	147.18	80.69
5	12	18.6	223.2	221	0.85	187.85	84.16
6	12	23.7	284.4	220	1.12	246.40	86.64
7	12	26.8	321.6	220	1.28	281.60	87.56
8	12	29.6	355.2	219	1.44	313.17	88.16

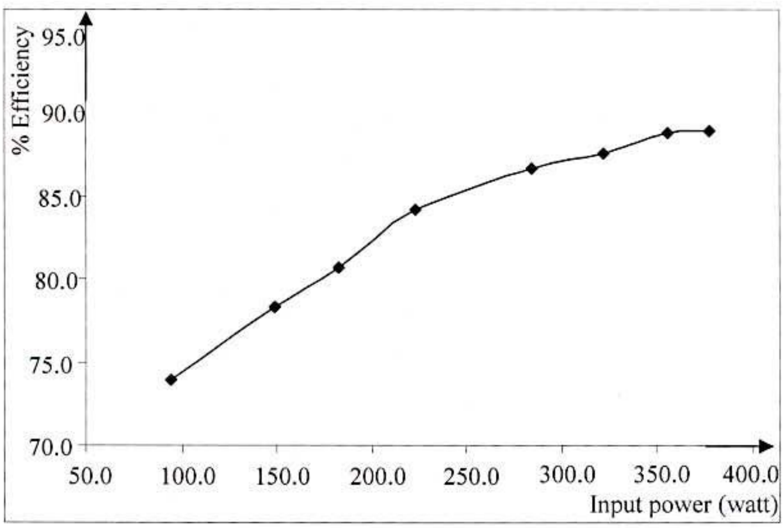


Fig.5.16 Efficiency VS input power curve

5.4 Synchronization

The implemented charge controller, inverter and control circuits are connected with the grid. From table 5.3 it is observed that before synchronization load is taking power from PV system. When synchronization achieve grid and PV system share the load. Load is increasing as well as grid current is increasing to the load. After reducing load PV system export energy to the grid. When the PV generation fall grid drives the load alone and PV system charges the storage battery. Here (-) negative sign means grid is taking power from PV system and (+) positive sign means grid is contributing current to the load.

Table: 5.3 Load sharing table of PV system and grid in different condition

Sl. No.	PV system contribution		Grid Contribution		Load		Comments
	Voltage (V)	Current (I)	Voltage (V)	Current (I)	Voltage (V)	Current (I)	
1	226	1.15	220	0.00	226	1.15	Not Synchronized
2	223	1.24	223	+0.62	223	1.86	Synchronized
3	221	1.30	221	+1.04	221	2.34	Synchronized
4	220	1.35	220	- 0.72	220	0.63	Synchronized
5	218	1.70	218	- 1.25	218	0.45	Synchronized
6	180	0.00	219	+1.56	219	1.56	Not Synchronized

5.5 Feasibility Study

5.5.1 Comparative Study Between on Grid and off Grid System

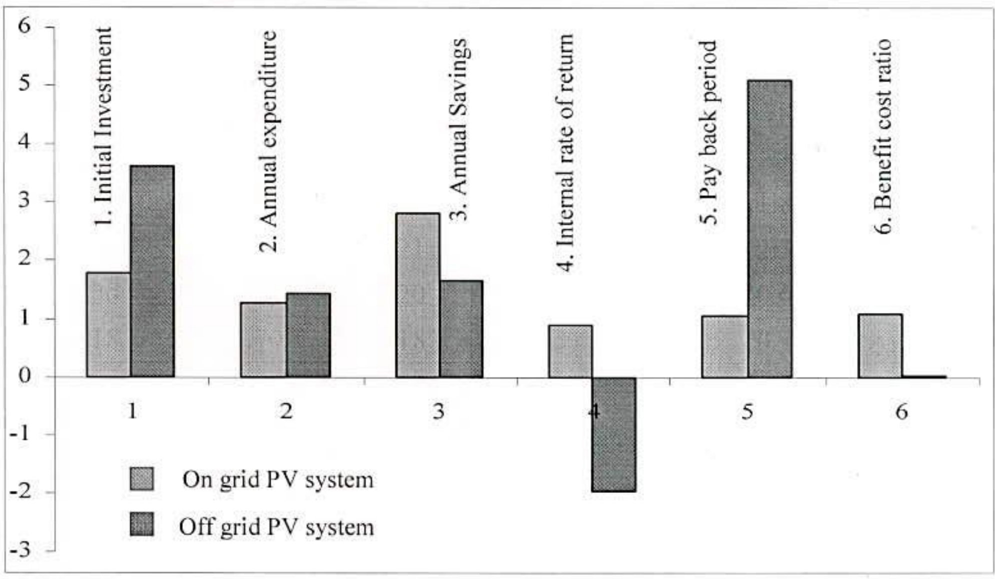


Fig.5.17 Comparative study of on & off grid PV system

5.5.2 Cash flow statement

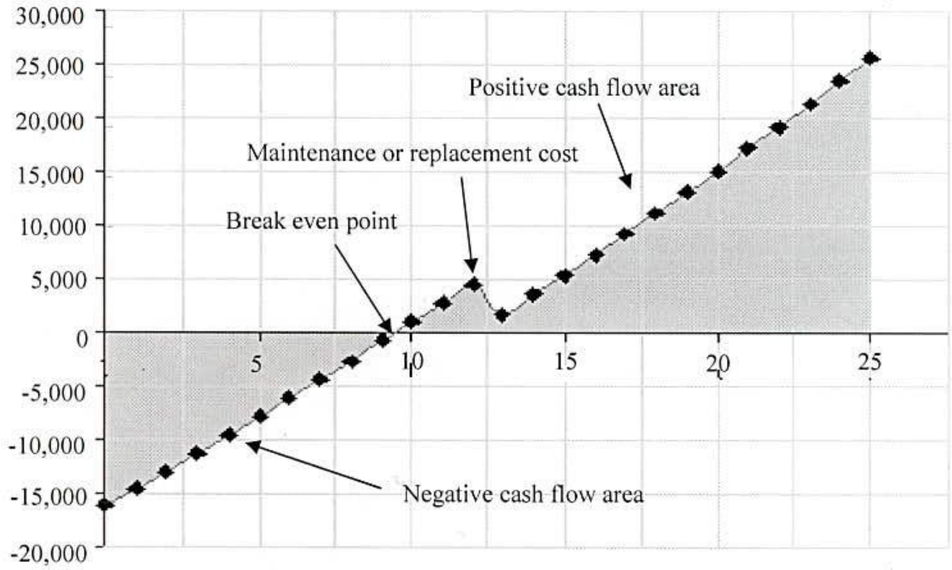


Fig.5.18 Cash flow statement of grid connected PV system

5.5.3 Evaluation of Feasibility Study

A comparison has been performed in different application type of PV system, their tilt angle annual energy generation, annual savings, installation cost and pay back period are shown in Table 5.4. From the observation it is clear that the described PV system shows better performance than others.

Table 5.4 comparison between different PV models

Array tilt (Deg)	PV system capacity (KW)	Annual output (KWh/year)	Annual cost saving ($/year)	System cost with incentives($)	Pay back period (year)	Reference
Crystalline silicon (Fixed tilt) off grid configuration						
38.4	27600	31408800	$3862654	$96600000	27	[49]
Crystalline silicon (Single axis tracking) off grid configuration						
0	22600	29380000	$3613152	$94920000	30	[49]
Thin film (Fixed Tilt) off grid configuration						
38.4	11550	13143900	$1616437	$35574000	23	[49]
Mono silicon solar cell (Fixed Tilt) Grid connected configuration						
30	10	14463	$2822	$17966	11	Present work

5.6 Conclusion

The above simulation and experimental result shows that the performance of the smart grid PV system is satisfactory. The inverter and Charge controller is more economical than any other topologies. The efficiency of the designed hardware is satisfactory. It is stable with power system and also enhances the stability limit of grid. The feasibility study report shows smart grid PV system is financially viable. The above achievement indicates that the potentiality of grid connected PV system can provide efficient and stable solution for future energy demand.

CHAPTER VI

Conclusion

6.1 Conclusion

The importance of PV energy is increasing day by day due to energy security and environmental safety. There are technological issues to utilize PV energy in smart grid system. The off grid system has several difficulties, to overcome these problems, development of grid connected configuration are urgently required to meet the future energy demand. The goal of this thesis work was to overcome the technological issue and design improved quality charge controller, inverter and their controllers.

There are various techniques to design MPPT charge controller but we develop a simple and effective MPPT algorithm that makes the circuit easy and cost effective. Switching is operated by logic circuit that is capable of eliminating flickering noise and time delay. It shows better performance than the conventional charge controller which is about 96.26% efficiency.

One of the main challenges to utilize PV energy in grid connected configuration is implementation of suitable synchronized inverter. To fulfill the necessity we design a microcontroller based grid connected inverter and control circuits. The inverter circuit takes feedback from grid. After processing the signal in microcontroller it generate different controlling signals and operation mode. The implemented inverter has some special feature like it is capable of dealing power with minimum number of active switches that simplifies the system configuration and its cost is lower significantly. It does not make interference with nearby audio signal or communication networks due to low frequency switching. The system synchronization, switching and control circuits of this inverter enhance by using microcontroller based programming that improves its quality. The efficiency of the inverter is about 88.16%. It is apparent that our achievements are better than some reports and are comparable to the others.

To utilize PV system in smart grid system it requires to integrate PV panel, charge controller, inverter and associated equipment with grid. The experimental result of implemented system work rightly. It established a contributory two way power flow from PV system and grid. The protective devices protect the smart grid system from faulty operation condition successfully.

Finally, cost analysis has been performed to implement the grid connected PV system. To justify the economic viability the feasibility study has been performed with 10kWp grid connected PV system for commercial building. Both simulation and calculated result of this system is found financially viable. The main parameters are follows: the internal rate of return (IRR) is 8.8%, payback period 11 years and benefit cost ratio of the system is found 1.07. In addition a comparative study has been done for on grid and off grid system. It is apparent that on grid PV system shows better performance than off grid PV system. The transient stability has also been performed and the results demonstrate that the PV system increases grid stability level. The above achievement indicates that the potentiality of smart grid PV system may be the key solution to meet future energy demand and pollution free environment.

6.2 Proposal for Future Research

The thesis paper represents the smart grid PV system and its challenge and benefits clearly. Smart grids are complex systems that incorporate a number of technologies, consumer interactions and decision points. This complexity makes it difficult to define detailed development and deployment scenarios. Smart grid technologies are being developed worldwide, so development and demonstration can be discussed in a global context. But deployment needs to be discussed at the regional level, where important factors such as the age of infrastructure, demand growth, generation make-up, regulatory and market structures vary significantly. The system efficiency depends on charge controller, inverter and their controller efficiency so any improvement of those components improves system quality. Also it can be utilized in three phase system to get better performance. Sun tracking system may improve the energy generation by utilizing more solar radiation and improve system efficiency. Moreover, to utilize smart grid PV system commercially it takes renovation of existing grid system. The Demand response, smart metering and automation of grid system makes smart grid popular in future.

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Appendix

Control circuits and synchronization

```
#include<reg51.h>
sbit a=P2^1;
sbit b=P2^2;
sbit c=P2^3;
sbit d=P2^4;

sbit battery=P1^2;
sbit load=P1^3;
sbit grid=P1^4;

void main()
 {

  a=b=c=d=0;
  battery=0;
  load=0;
  grid=0;
  while(1)
{

if(a==1&b==1&c==0&&d==1)
{
load=1;
battery=1;
grid=1;
}
if(a==1&b==1&c==0&d==0)
{
load=1;
battery=1;
grid=0;
}
if(a==0&b==1&c==0&d==1)
{
load=0;
battery=1;
grid=1;
}
if(a==1&b==1&c==1&d==1)
```

```
{
load=1;
battery=0;
grid=1;
}
if(a==1&b==1&c==1&d==0)
{
load=1;
battery=0;
grid=0;
}
if(a==0&c==0&b==1&d==0)
 {
 load=0;
battery=1;
grid=0;

 }
 if(a==0&b==0&c==0&d==1)
 {
 load=0;
battery=0;
grid=1;
 }

  }

 }
```

On Grid Inverter

```
#include<reg51.h>
sbit a=P2^0;
sbit b=P2^1;
void Delay_ms(unsigned int itime)
{
unsigned int i,j;
for (i=0;i<itime;i++)
for (j=0;j<1200;j++);
}
void main()
{
P2=0x00;
while(1)
 {
a=1;
b=0;
Delay_ms(1);
a=0;
b=0;
Delay_ms(1);
b=1;
a=0;
Delay_ms(1);
b=0;
a=0;
Delay_ms(1);
}

}
```

List of publications

International conference papers:

1 Md. Jahangir Hossain, Md. Rafiqul Islam, "Design and Feasibility Study of Smart Grid System for PV Power Generation" Published in the *"International Conference on Electrical, Computer and Telecommunication Engineering (ICECTE-2012)"* RUET, Bangladesh. pp 69-72.

2 Md. Jahangir Hossain, Md. Asadur Rahman, Md. Mamunur Rahman, Nezam Uddin, Md. Rafiqul Islam, " Design and implementation of high performance MPPT charge controller for photo voltaic system", Published in the *"International Conference on Mechanical, Industrial and Energy Engineering (ICMIE)"* KUET, Bangladesh, 2012.

3 Md. Jahangir Hossain, Md.Raqibull Hasan, Monowar Hossain and Md. Rafiqul Islam, "Design and Implementation of a Grid Connected Single Phase Inverter for Photovoltaic System", published in the *"3rd International Conference on the Developments in Renewable Energy Technology (ICDRET)"* UIU, Dhaka Bangladesh, 2014