DEVELOPMENT OF OPTIMAL MPPT TECHNIQUE FOR GRID CONNECTED PV SYSTEM

ग्रिड से जुड़ा पी.वी. प्रणाली के लिए इष्टतम एमपीपीटी तकनीक का विकास

by

KRITIKA SINGHVI

THESIS

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Dated: 26/04/13

CERTIFICATE-I

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CERTIFICATE-II

This is to certify that thesis entitled "**Development of Optimal MPPT Technique for Grid connected PV system**" submitted for the degree of **Master of Technology** in the subject of **Power Electronics** embodies bonafide research work carried out by **Ms. KRITIKA SINGHVI** under my guidance and supervision and that no part of the thesis has been submitted for any other degree. The assistance and help received during the course of investigation has been fully acknowledged. The draft of the thesis was also approved by the advisory committee on 07/09/13.

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ABSTRACT

Photovoltaic is one of the important renewable energy sources. Compared to other renewal energy sources photovoltaic energy is clean and abundantly available. Solar power is considered a very promising source for electric power generation. The abundance of sunlight over a large area of the earth surface gives rise to several applications of photovoltaic systems. Electricity can be generated from sunlight either directly by employing the photovoltaic effect, or by using energy from the sun to heat up a working fluid that can be used to power up electricity generators. These two technologies are widely used today to provide power to either standalone loads or for connection to the power system grid. A standalone solar photovoltaic system cannot provide a continuous supply of energy due to seasonal and periodic variations. Therefore, in order to satisfy the load demand, grid connected energy systems are now being implemented that combine solar and conventional conversion units. Grid connected PV systems have become very popular because of their applications in distributed generation and for effectively using the PV array power.

Low efficiency of the solar PV module leads to research and improvement about control technology of different sub-modules of grid connected photovoltaic system. Maximum power point tracking (MPPT) is a very important consideration that is taken into account when building a new photovoltaic power system. This is needed in order to extract maximum power output from a PV array under varying atmospheric conditions to maximize the return on initial investments.

This thesis deals with the development of a simple but efficient Grid connected photovoltaic system. The system employs the maximum power point tracker (MPPT). The investigation includes discussion of various MPPT algorithms and control methods. The MPPT control is verified by simulations in PSIM while overall system is modelled using MATLAB/Simulink. MATLAB and PSIM simulations verify the overall PV system and functionality of MPPT.

In this work, 'P & O' type and 'INC' type MPPT are developed in PSIM software. Both MPPT's are validated and compared under different Input/ Output conditions like different irradiance, step change in load, under fault condition etc. The major

contribution is to develop hardware prototype of P & O based 200W PV system. This prototype have been tested and investigated under different condition. Experimental and simulation result proves that energy captured was more when 'P & O' type MPPT is used.

सारांश

फोटोवोल्टिक महत्वपूर्ण अक्षय ऊर्जा स्रोतों में से एक है. अन्य नवीकरण ऊर्जा स्रोतों की तुलना में फोटोवोल्टिक ऊर्जा स्वच्छ और प्रचुर मात्रा में उपलब्ध है. सौर ऊर्जा विद्युत उत्पादन के लिए एक बहुत ही होनहार स्रोत माना जाता है. पृथ्वी की सतह के एक बड़े क्षेत्र में सूरज की रोशनी की बहुतायत फोटोवोल्टिक प्रणालियों के कई आवेदनों को जन्म देता है. बिजली सीधे फोटोवोल्टिक प्रभाव को रोजगार से , या सत्ता तक बिजली जनरेटर के लिए इस्तेमाल किया जा सकता है कि एक काम तरल पदार्थ को गर्म करने के लिए सूर्य से ऊर्जा का उपयोग करके या तो सूरज की रोशनी से उत्पन्न किया जा सकता है . इन दोनों तकनीकों का व्यापक रूप से स्टैंडअलोन भार या तो या बिजली व्यवस्था ग्रिड कनेक्शन के लिए बिजली उपलब्ध कराने के लिए आज का उपयोग किया जाता है. एक स्टैंडअलोन सौर फोटोवोल्टिक प्रणाली के कारण मौसमी और आवधिक बदलाव करने के लिए ऊर्जा के एक निरंतर आपूर्ति प्रदान नहीं कर सकते. इसलिए, लोड मांग को पूरा करने के क्रम में, ग्रिड से जुड़ा ऊर्जा प्रणालियों अब सौर और पारंपरिक रूपांतरण इकाइयों कि गठबंधन चलाई जा रही हैं. ग्रिड से जुड़े PV प्रणाली क्योंकि वितरित पीढ़ी में और प्रभावी ढंग से पी.वी. सरणी शक्ति का उपयोग करने के लिए अपने आवेदन में बहुत लोकप्रिय हो गए हैं.

सौर पीवी मॉड्यूल की कम क्षमता अनुसंधान और ग्रिड के विभिन्न उप मॉड्यूल फोटोवोल्टिक प्रणाली से जुड़ा के नियंत्रण तकनीक के बारे में सुधार की ओर जाता है. अधिकतम पावर प्वाइंट ट्रैकिंग (MPPT) एक नई फोटोवोल्टिक ऊर्जा प्रणाली का निर्माण करते समय ध्यान में रखा है कि एक बहुत महत्वपूर्ण विचार है. यह प्रारंभिक निवेश पर प्रतिफल को अधिकतम करने के लिए वातावरण की स्थिति बदलती के तहत एक पी.वी. सरणी से अधिकतम बिजली उत्पादन निकालने के क्रम में की जरूरत है.

इस थीसिस फोटोवोल्टिक प्रणाली से जुड़ा एक सरल लेकिन कुशल ग्रिड के विकास से संबंधित है. प्रणाली अधिकतम पावर प्वाइंट ट्रैकर (MPPT) कार्यरत हैं. जांच विभिन्न MPPT एल्गोरिदम और नियंत्रण के तरीकों की चर्चा भी शामिल है. समग्र प्रणाली में MATLAB / Simulink मॉडलिंग का उपयोग कर रहा है, जबकि एमपीपीटी नियंत्रण PSIM में सिमुलेशन द्वारा सत्यापित है. MATLAB और PSIM सिमुलेशन समग्र PV प्रणाली और MPPT की कार्यक्षमता को सत्यापित. इस काम में, ' P & O ' प्रकार और 'INC' प्रकार MPPT PSIM सॉफ्टवेयर में विकसित कर रहे हैं. दोनों एमपीपीटी की गलती शर्त के तहत विभिन्न विकिरण, भार में कदम परिवर्तन, जैसे विभिन्न इनपुट / आउटपुट शर्तों के तहत मान्य है और तुलना कर रहे हैं आदि प्रमुख योगदान 'P & O' आधारित 200W पी.वी. सिस्टम के हार्डवेयर प्रोटोटाइप विकसित करने के लिए है. इस प्रोटोटाइप विभिन्न शर्त के

तहत जांच की और जांच की गई है. प्रायोगिक और सिमुलेशन परिणाम पर कब्जा कर लिया है कि ऊर्जा और अधिक जब 'P & O' प्रकार MPPT प्रयोग किया जाता था साबित होता है.

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List of Abbreviations:

RES	Renewable Energy Sources
PV	Photovoltaic
kWh	Kilo Watt Hour
kVAR	Kilo Volt-Ampere Reactive
FLC	Fuzzy Logic Controller
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
DSP	Digital Signal Processor
IGBT	Insulated Gate Bipolar Transistor
VSI	Voltage Source Inverter
CSI	Current Source Inverter
SPWM	Sinusoidal Pulse Width Modulation
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PLL	Phase Lock Loop

CHAPTER 1

INTRODUCTION

Recent years have shown unprecedented growth of renewable energy scenario, where despite the global financial crisis the sector has managed to hold its own. The resilience of the sector against all odds showcases that renewable energy is indeed the future and will play a major role in providing a clean, secure and sustainable energy economy. The potential is unquestionably large and the rapidly growing economies are determined to transform the economic crisis into an opportunity for greener growth. However, for the sector to grow significantly to meet world energy demands, it is imperative for the governments to provide support in making renewables cost competitive as compared with other energy sources and technologies.

The world's energy supply is largely based on fossil fuels. It is estimated that by 2030, 80% of primary energy mix will be dominated by fossil fuels, where in oil will remain the dominant fuel and demand for coal will rise more than that of any other fuel in absolute terms. In such a scenario, the realisation that these sources of energy will not last forever and are also contributing to environmental problems is what has made renewables a lucrative and sustainable option. This has also led the governments around the globe, along with industries, thinking seriously about alternative sources of energy, the need for which was further affirmed by the 1973 oil embargo and oil price shock of 2008, coupled with the ever increasing oil prices.

Recent studies underscore that current global trends in energy supply and consumption are patently unsustainable – environmentally, economically and socially. It also went on to add that the situation can be changed if the supply of reliable and affordable energy is secured and a rapid transformation is made to a low-carbon, efficient and environmentally benign system of energy supply.

Now, more than ever, countries all over the world fully recognize the need to promote wide spread adoption of renewable energy into their country's energy sources, with the intention of promoting sustained economic growth, social development and environmental stewardship. It is also presumed that with increasing scope, scale, research and development, the cost of renewable energy technologies will come down; making them affordable and able to make a major contribution to electricity generation, heating, cooling and transport. Estimates highlight that renewable energy could contribute at least half of all the electric power in each of the large economies by 2050; even in countries where electricity demand is significantly high. What's more, renewable energy not only has the capacity to provide millions of people with access to electricity; renewable energy equipment manufacturing and installation is highly labour intensive, thus contributing not only to improved living conditions, but also leading to reduced poverty. Renewables Global Status Report (2009 update) by REN21 also reiterates that the renewable energy sector offers an essential path for growth that can stimulate economic recovery and job creation without the burden of increasing carbon emissions.

In recent years, there has been an increasing awareness about the global warming and the harmful effects that the emissions of carbon have. This created a higher demand for clean and sustainable energy sources like: wind, sea, sun, biomass etc. The wind energy has experienced the biggest growth in the past 10 years. This is because wind energy is a pollution-free resource, has an inexhaustible potential and also because of its increasingly competitive cost.

1.1 Renewable Energy Scenario in India

India is endowed with abundant primary energy sources; fossil, renewable and unconventional. Coal dominates the country's energy mix with a robust 52% share in primary energy consumption, followed by oil at 30% and gas at 10%. Other sources include 2%hydroelectricity and less than a percent nuclear energy. The consumption profile in terms of primary sources is not matched by indigenous production profile, creating concerns about energy security. Import dependence of oil consumption is currently about 75%, which is projected to increase to 80% by 2016-17. Import component of gas is currently ruling at 19%, slated to increase to 28% by 2016-17. Similarly, coal import is expected to rise from about 90 million tons at present to over 200 million tons in 2016-17. As per present estimate, 85% of electric power generation is dependent on oil, natural gas and coal. Even though India has abundant quantities of coal, it is constrained to regional locations, high ash content, affecting the thermal efficiency of power plants, and also there are environmental concerns.

Renewable Energy in India is a sector that is still undeveloped. India was probably the first country in the world to set up a separate ministry of non-conventional energy resources in early 1980s. However the results have been very mixed and in recent years it has lagged far behind other developed nations in using renewable energy (RE). RE contribution to energy sector is less than 1% of India's total energy needs.

India is one of the largest and fastest growing economies in the world with an expansive populace of above 1.1 billion people. There is a very high demand for energy, which is currently satisfied mainly by coal, foreign oil and petroleum, which apart from being a non-renewable, and therefore non-permanent solution to the energy crisis, it is also detrimental to the environment. The price of crude oil has risen sharply over the last few years, and there are no signs of a change in this trend. Thus, it is imperative that India obtains energy security without affecting the booming economy, which would mean that alternative energy sources must be developed. This would mean that the country must switch from the non-renewable energy (crude oil and coal) to renewable energy.

Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, bio fuels and hydrogen derived from renewable resources.

Fig.1.1 gives an account of installed power capacity of various power generation systems. India is determined to become one of the world’s leading clean energy producers. The Government of India has already made several provisions, and established many agencies that will help it achieve its goal.

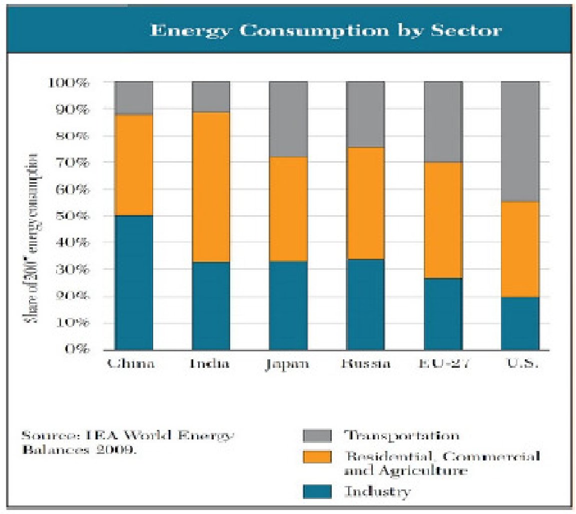


Figure 3.1 Percentage of installed Power capacity in India

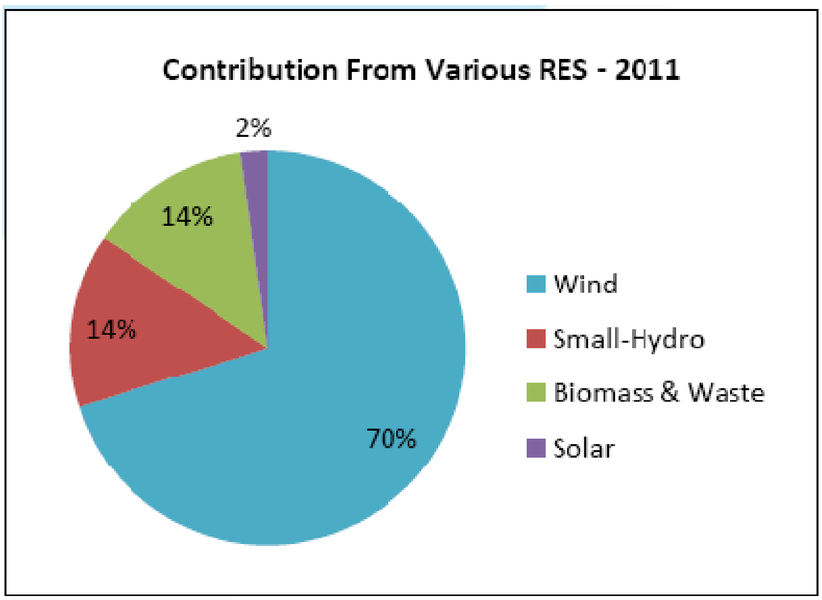


Figure 1.4 Contribution from various Renewable Energy Sources

Coal based generation contributes major part of the installed capacity and contributes to about 68.6% of the total energy generation (year 2008-09). In addition to above, the installed capacity of captive power plants of 1MW and above is of the order of 24,986 MW at the end of 2007-08.The energy generated from captive power plants during the year 2007-08 was 90477 GWh. Renewable Energy, excluding large hydro projects already accounts for 11% of the total installed energy capacity, equivalent to 20,162.24 MW.

By 2030, the total energy requirement for the country would increase to 400,000 MWs from the existing 185,000 MWs. Ideally India has to plan for 215,000 MWs of power to be realized from renewable energy resources like hydro, wind, solar, nuclear and conversion of municipal waste into energy by 2030. The country has capability to generate additional 50,000 MWs of hydro electric power by creating regional waterways. India can generate solar energy to the extent of 60,000 MWs by having large scale solar power. Gujarat State has already generated 680 MWs of solar electric power through public-private partnership program and the power is being fed to the grid. India has to generate 50,000 MWs of nuclear power, particularly using the thorium route within the next decade and has to generate 65,000 MWs of power using wind energy. If we work on these targets, we will be getting nearly 225,000 MWs of electric power. Here we have to consider the reduction in load factor in solar, wind and hydro electric power which will necessitate generation of 20 to 30% excess power beyond the 400,000 MWs. This can certainly be achieved by converting all the municipal wastes into electric energy which can easily generate over 10,000 MWs of power. Movement towards energy independence would also demand accelerated work in operationalizing the production of energy from the coal sector through integrated gasification and combined cycle route, so that the existing coal based power plant get clean coal and substantially reduce the carbon-di-oxide dumping in atmosphere.

1.2 Current Solar Energy Scenario in India

India is densely populated and has high solar insolation, an ideal combination for using solar power in India. India is already a leader in wind power generation. In the solar energy sector, some large projects have been proposed, and a 35,000 km^2 area of the Thar Desert has been set aside for solar power projects, sufficient to generate 700 GW to 2,100 GW. Also India's Ministry of New and Renewable Energy has released the JNNSM Phase 2 Draft Policy, by which the Government aims to install 10GW of Solar Power and of this 10 GW target, 4 GW would fall under the central scheme and the remaining 6 GW under various State specific schemes.

In July 2009, India unveiled a US$19 billion plan to produce 20 GW of solar power by 2020. Under the plan, the use of solar-powered equipment and applications would be made compulsory in all government buildings, as well as hospitals and hotels. On 18 November 2009, it was reported that India was ready to launch its National Solar Mission under the National Action Plan on Climate Change, with plans to generate 1,000 MW of power by 2013. From August 2011 to July 2012, India went from 2.5 MW of grid connected photovoltaics to over 1,000 MW.

According to a 2011 report by BRIDGE TO INDIA and GTM Research, India is facing a perfect storm of factors that will drive solar photovoltaic (PV) adoption at a "furious pace over the next five years and beyond". The falling prices of PV panels, mostly from China but also from the U.S., has coincided with the growing cost of grid power in India. Government support and ample solar resources have also helped to increase solar adoption, but perhaps the biggest factor has been need. India, "as a growing economy with a surging middle class, is now facing a severe electricity deficit that often runs between 10 and 13 percent of daily need".

With about 300 clear, sunny days in a year, India's theoretical solar power reception, on only its land area, is about 5000 Petawatt-hours per year (PWh/yr) (i.e. 5000 trillion kWh/yr or about 600 TW). The daily average solar energy incident over India varies from 4 to 7 kWh/m2 with about 1500–2000 sunshine hours per year (depending upon location), which is far more than current total energy consumption. For example, assuming the efficiency of PV modules were as low as 10%, this would still be a thousand times greater than the domestic electricity demand projected for 2015.

1.2.1 Installed Capacity

The amount of solar energy produced in India in 2007 was less than 1% of the total energy demand. The grid-interactive solar power as of December 2010 was merely 10 MW. Government-funded solar energy in India only accounted for approximately 6.4 MW-yr of power as of 2005. However, India is ranked number one in terms of solar energy production per watt installed, with an insolation of 1,700 to 1,900 kilowatt hours per kilowatt peak (kWh/KWp). 25.1 MW was added in 2010 and 468.3 MW in 2011. By the end of March 2013 the installed grid connected photovoltaics had increased to 1686.44 MW, and India expects to install an additional 10,000 MW by 2017, and a total of 20,000 MW by 2022.

Table 2.1: State Wise Installation

State	MWp	%
Andhra Pradesh	21.8	2.2
Chhattisgarh	4	0.4
Delhi	2.5	0.3
Gujarat	654.8	66.9
Haryana	7.8	0.8
Jharkhand	4	0.4
Karnataka	9	0.9
Madhya Pradesh	2	0.2
Maharashtra	20	2
Orissa	13	1.3
Punjab	9	0.9
Rajasthan	510.25	20.2
Tamil Nadu	15	1.5
Uttar Pradesh	12	1.2
Uttarakhand	5	0.5
West Bengal	2	0.2
Total	**1686.44**	**100**

1.2.2 Challenges and opportunities

The amount of solar energy produced in India in 2007 was less than 1% of the total energy demand. The grid-interactive solar power as of December 2010 was merely 10 MW. Government-funded solar energy in India only accounted for approximately 6.4 MW-yr of power as of 2005. However, India is ranked number one in terms of solar energy production per watt installed, with an insolation of 1,700 to 1,900 kilowatt hours per kilowatt peak (kWh/KWp). 25.1 MW was added in 2010 and 468.3 MW in 2011. By the end of March 2013 the installed grid connected photovoltaics had increased to 1686.44 MW, and India expects to install an additional 10,000 MW by 2017, and a total of 20,000 MW by 2022.

1.3 Proposed System

In this work, two types of MPPT algorithm for Grid connected PV system are developed and compared under different input/output conditions i.e. under different irradiance, fault, islanding etc. Also a laboratory prototype of 200W 'P & O' type PV system is developed and investigated under different condition.

Details of various components of developed system is as follows:

1.3.1 Solar Module

Solar module consists of PV cells which generate electric power when illuminated by sunlight or artificial light. Solar PV module considered for evaluation of proposed system is Sunpower-305.

1.3.2 Boost Converter

The main role of the Boost DC-DC converter is to insure Impedance adaptation between the PV module and the grid, Set the PV operating point (V_{PV}, I_{PV}) to MPP and efficiently step up the PV Module voltage (V_{PV}) to a higher DC voltage V_{DC} of 500V.

1.3.3 Inverter

Inverter efficiently generates AC output in phase with the AC grid voltage and balances the average power delivery from the PV module to utility grid. It converts the DC voltage of 500V to three phase AC voltage of 260Vac.

As per scope of thesis the proposed system model will be developed using MATLAB/Simulink. Different system components will be modelled and tested in Simulink to validate the system operation. The objectives which are explained below will be validated based on the simulation results.

A reference 200W laboratory prototype will be developed for investigation purpose. The prototype system will be microcontroller based PV system which will be implemented using MPPT techniques analyzed in the thesis. The MPPT techniques will be selected based on the criteria that it should efficient in operation and also it should be easier from implementation point of view. The power level strategy of proto system is to be kept similar to one analyzed in the thesis.

1.4 Objectives of Thesis

The various objectives of the thesis are:

1. To develop grid connected PV system using MATLAB/Simulink.
2. To implement Maximum Power Point Tracking (MPPT) technique algorithms for maximizing energy yield using MATLAB/Simulink or PSIM.
3. To investigate the performance of the grid connected PV system under MPPT technique for different input/output conditions.

1.5 Organization of Thesis

The present thesis is divided into the following chapters.

Chapter 2 provides a detailed literature survey. The studied literature is divided into sub-sections as per various power conversion stages of the PV system. In Chapter 3, overall Grid Connected PV system is described in details. This chapter provides the working principles of different power conversion stages, PV generator and various MPPT techniques. A more detailed explanation of modeling and design of Grid Connected PV system is provided in Chapter 4. Here Simulink model of each component of PV system is explained and also MPPT control algorithms implementation in PSIM is explained. This chapter further provides the details of laboratory prototype. Simulation results for various input and output scenarios based on real environmental conditions of developed PV system model and the laboratory prototype are explained in Chapter 5. It also investigates the performance of system under different condition through simulation and experimentation results. Finally Chapter 6 concludes the thesis work and explores future scope based on the present scope of the thesis.

CHAPTER 2

LITERATURE REVIEW

With the quick development of society, the rapid trend of industrialization of nations and increased interest in environmental issues has recently to consideration of the use of renewable forms such as solar energy. Photovoltaic (PV) generation is becoming increasingly important as a renewable source since it offers many advantages such as incurring no fuel costs, not being polluting, requiring little maintenance (lifetime > 20years) and no noise (Jiang *et al*., 2005; kuo *et al*., 2001).

The PV generator exhibits a nonlinear V-I characteristic and the energy extracted from a solar panel is strongly limited by the physical constraints of photovoltaic cells (Esram, 2007). The approximate power density of the insolation on a sunny day is around 1000W/m2. In combination with solar cell efficiencies between 15% and 17% (Mol, 93), this yields a maximum possible power output between 150W/m2 and 170W/m^2. There are two ways to increase the power coming from a photovoltaic array i.e. by adding more panels to the array, and allowing the existing arrays to work at its highest possible efficiency by using MPPT Technique.

MPPT is a power electronic device interconnecting a PV power source and a load, maximizes the power output from a PV module or array with varying operating conditions, and therefore maximizes the system efficiency, it is necessary to match the PV generator to the load such that the equilibrium operating point coincides with the MP point of the PV source. However, since the MP point varies with insolation and seasons, it is difficult to maintain MP operation at all solar insolations. To overcome this problem, use of an intermediate dc-dc converter is proposed, which continuously adjusts the voltage, current levels and matches the PV source to the load.

2.1 DC-DC Converter for PV System

Chen *et al.,* (2013) proposed a three-port dc-dc converter integrating PV and battery power for high step-up applications. The topology includes five power switches, two coupled inductors and two active-clamp circuits. The coupled inductors are used to achieve high step-up voltage gain and to reduce the voltage stress of input side switches. Two sets of active-clamp circuits are used to recycle the energy stored in the leakage inductors and to improve the system efficiency. The operation mode does not need to be changed when a transition between charging and discharging occur. Moreover, tracking maximum power point of the PV source and regulating the output voltage can be operated simultaneously during charging/discharging transitions. As long as the sun irradiation level is not too low, the maximum power point tracking (MPPT) algorithm will be disabled only when the battery charging voltage is too high. Therefore, the control scheme of the proposed converter provides maximum utilization of PV power most of the time.

Olalla *et al*., (2013) had presented and simulated photovoltaic (PV) module architectures with parallel-connected submodule-integrated dc–dc converters (subMICs) that improve efficiency of energy capture in the presence of partial shading or other mismatch conditions. The subMICs are bidirectional isolated dc–dc converters capable of injecting or subtracting currents to balance the module substring voltages. When no mismatches are present, the subMICs are simply shut down, resulting in zero insertion losses.

Liang *et al.,* (2011) compared the parallel connected dc module-integrated converter (MIC) structure with its counterpart, the series connected MIC architecture. The future renewable electric energy delivery and management (FREEDM) system provides a dc interface for alternative energy sources. As a result, photovoltaic (PV) energy can be easily delivered through a dc/dc converter to the FREEDM system's dc bus. From the presented analysis, the parallel connected architecture was shown to have more advantages. A high-efficiency dual mode resonant converter topology is proposed for parallel connected dc MICs. This new resonant converter can maintain a high efficiency for a wide input range at different output power levels.

Jung *et al.,* (2011) proposed interleaved soft switching boost converter (ISSBC) for a photovoltaic (PV) power-generation system. This topology raised the efficiency of dc/dc converter of the PV power conditioning system (PVPCS), and it minimizes switching losses by adopting a resonant soft-switching method. The overall Chen *et* efficiency of proposed topology is increased by about 1.5% compared with the conventional hard switching interleaved boost converter.

al., (2011) was designed and analyzed the cascade controller for a boost converter. The fast inner current loop uses sliding mode control and the slow outer voltage loop uses the proportional-integral (PI) control. Stability analysis and selection of PI gains are based on the nonlinear closed-loop error dynamics. The controller is validated by a simulation circuit with nonideal circuit parameters, and various maximum switching frequencies.

Hasaneen and Mohammed (2008) presented design and simulation of DC/DC boost converter. This system has a nonlinear dynamic behavior, as it work in switch-mode. Moreover, it is exposed to significant variations which may take this system away from nominal conditions, due to changes on the load or on the line voltage at the input. The input usually is obtained by PV array and therefore the design and simulation covers the whole range of radiations and temperature. This work is applied to photovoltaic system for tracking the point of maximum power.

Subiyanto *et al.*, (2011) presented high performance boost converter for maximum power point tracking (MPPT) of photovoltaic (PV) systems. The proposed boost converter uses a new active snubber to minimize losses in the switching and improve efficiency of the converter. For traking the maximum power point of a PV array, a closed loop fuzzy logic based MPPT controller has been developed. The proposed boost converter was designed using the Orcad PSpice software whereas the MPPT controller is modeled in the Matlab Simulink program.

ChittiBabu *et al.*, (2011) presents the use of smart PV energy system for portable applications; especially to charge the batteries used in mobile phones. A dc-dc synchronous buck converter is introduced between PV system and load to meet the dynamic energy requirement of the load in an efficient way. The synchronous buck converter largely increases the system efficiency by reducing the switching losses through soft switching techniques.

Luo et al., (2009) proposed Buck boost converter to obtain the maximum power point tracking of the grid-connected PV generation system. The buck boost is a simple converter with good response speed and the controlling method is flexible. And the efficiency of photovoltaic power generation is improved apparently with the method in grid-connected photovoltaic system.

Dhople *et. al.,* (2010) proposed a buck-boost converter to find the MPP of the photovoltaic array. The buck-boost stage tracks the maximum power by matching the output load to the optimal photovoltaic impedance. The two power stages worked independently, solving the problem of ineffectiveness, and transfer efficiency. The buck-boost tracks the maximum power in continuous conduction mode and the boost minimizes the PV current ripple. The duty cycle of the boost can be set to control the dc bus voltage. The dual stage has a better efficiency but increase the cost by introducing additional stage to the converter.

WU *et al*., (1999) analyzed and designed Single-stage converters (SSCs) which is the integration of buck-boost charger/discharger and a class-D series resonant parallel loaded inverter. SSCs can fulfil maximum power point tracking (MPPT), battery charging, discharging, and lamp ballasting features. Both pulsewidth modulation (PWM) and variable-frequency controls are used to govern the system operation. The proposed system has a simple configuration, as well as a zero voltage switching (ZVS) feature. These result in the inherent merits of lower cost, more compact size and possibly achieving higher reliability over conventional systems.

2.2 PV Inverter for PV system

Alajmi *et al.,* (2013) proposed a single-phase, single-stage current source inverter-based photovoltaic system for grid connection. The system utilizes transformer-less single-stage conversion for tracking the maximum power point and interfacing the photovoltaic array to the grid. The maximum power point is maintained with a fuzzy logic controller. A proportional-resonant controller is used to control the current injected into the grid. To improve the power quality and system efficiency, a double-tuned parallel resonant circuit is proposed to attenuate the second- and fourth- order harmonics at the inverter dc side. A modified carrierbased modulation technique for the current source inverter is proposed to magnetize the dc-link inductor by shorting one of the bridge converter legs after every active switching cycle.

Abdalla *et al*., (2013) presented the application of multilevel dc-link inverter to overcome the problem of partial shading of individual photovoltaic (PV) sources which are connected in series. The “PV permutation algorithm,” as a new method, is developed for the control of the inverter so as to extract the maximum power form each PV source under partial shading and to deliver all that power to the load. The algorithm is based on combination of the direct pulsewidth modulation, the sequential permutation PV sources, and the output generation to control the multilevel dc-link inverter. The algorithm is applied successfully to a seven-level inverter with separate maximum power point tracking algorithm for each PV source and under nonuniform irradiance (partial shading).

Wang *et al*., (2013) had simulated and validated experimentally a high-power photovoltaic (PV) system based on dual-stage topology of boost converter plus paralleled four-leg inverter which can perform as both grid-connected inverter and active power filter. The system not only can allow a wide range of input voltage from PV arrays, but also can compensate the nonlinear and unbalanced load current.

Abu-Rub *et al*., (2013) proposed an artificial-intelligence-based solution to interface and deliver maximum power from a photovoltaic (PV) power generating system in standalone operation. The interface between the PV dc source and the load is accomplished by a quasi-Z-source inverter (qZSI). The maximum power delivery to the load is ensured by an adaptive neuro-fuzzy inference system (ANFIS) based on maximum power point tracking (MPPT). The proposed ANFIS-based MPPT offers an extremely fast dynamic response with high accuracy. The closed-loop control of the qZSI regulates the shoot through duty ratio and the modulation index to effectively control the injected power and maintain the stringent voltage, current, and frequency conditions.

Myrzlk *et al*., (2001) simulated and presented several new low-cost Inverters wlth and without HF-transformers for stand-alone as well for grld-connected appllcatlons. Photovoltaic and battery systems often operate in small stand-alone or grid-connected applications, where the generator voltage is lower than the grid voltage. To boost the voltage up to the grld level a further element, elther a DC/DC converter or 50Hz transformer, is connected in series with a PWM Inverter. To reduce the hlgh cost of such low power systems, the cost of the power electronlcs should be minimized.

Samerchur *et al*., (2011) has proposed a control strategy of vector control for the grid-connected single-phase VSI in the photovoltaic system. The objective of the grid-connected inverter control is to maintain the DC-link voltage and independent active and reactive power flow. This strategy is able to have a good dynamic responses and high accuracy to the active and reactive power control

Zhao *et al*., (2012) presented a single-phase grid-connected transformerless photovoltaic inverter for residential application. The inverter is derived from a boost-buck converter along with a line frequency unfolding circuit. High efficiency is achieved because there is only one switch operating at high frequency at a time does not have a shoot-through issue. Developed a model of boost–buck converter-based inverter and model indicates that interleaved multiple phases structure has proposed to have small equivalent inductance, the ripple can be decreased, and the inductor size can be reduced as well. A two-phase interleaved inverter is designed accordingly. The simulation and experimental results are shown to verified the concept.

Han *et al*., (2011) introduced a system scheme of the stand-alone photovoltaic inverter based on parallel charge topology for the purpose of improving the energy conversion efficiency and optimizing the battery management. The output power of the photovoltaic array is extracted to the highest degree with the proposed comprehensive strategy for maximum power point tracking.

Biao *et al*., (2011) proposed a Boost DC-AC inverter circuit for PV array which have low DC voltage output. The tasks of boost and inverter are undertaken only by one level Boost DC-AC circuits. The new topology have adjustable high voltage transfer ratio, less distortion in three-phase sinusoidal output voltage and the intermediate links between the DC source and the inverter was also eliminated.

2.3 Maximum Power Point Tracking (MPPT) system for PV System

Bianconi *et al*., (2013) proposed a novel Current-Based MPPT Technique Employing Sliding Mode Control. The largest part of the MPPT approaches presented in the literature are based on the sensing of the PV generator voltage. On the contrary, a current-based technique includes sensing of the current in the capacitor placed in parallel with the PV source. A dual control technique based on

an inner current loop plus an outer voltage loop allows to take profit of the fast current tracking capability of the inner current loop while the voltage loop benefits from the logarithmic dependency of the PV voltage on the irradiation level.
Latham *et al*., (2013) analyzed the effect of noise on several maximum power point tracking (MPPT) algorithms for photovoltaic systems. Noise is an essential consideration for optimization of MPPT algorithms. The effect of noise and other parameters on tracking performance is quantified, leading to an optimization of the system parameters to provide the best tracking accuracy for a specified tracking speed.

Alajmi *et al*., (2013) had simulated and validated experimentally, a modified fuzzy-logic controller for maximum power point (MPP) to increase photovoltaic (PV) system performance during partially shaded conditions. Instead of perturbing and observing the PV system MPP, the controller scans and stores the maximum power during the perturbing and observing procedures. The controller offers accurate convergence to the global maximum operating point under different partial shadowing conditions.

Chang *et al*., (2013) developed the operational control of two maximum power point trackers (MPPTs) for two-string photovoltaic (PV) panels in dc distribution systems. This dc distribution system is connected to ac grid via a bidirectional inverter. Two PV strings and two MPPTs are implemented in this system. The proposed MPPT topology consists of buck and boost converters to deal with wide output voltage range of PV panels. The perturbation and observation method are applied for maximum power point tracking. Moreover, the current balancing of two MPPT modules in parallel is achieved.

Nedumgatt *et al*., (2011) validated an algorithm for Maximum Power Point Tracking using Perturb and Observe technique. The algorithm starts by setting the computed maximum power PMAX to an initial value (usually zero). Next the actual PV voltage and current are measured at specific intervals and the instantaneous value of PV power, PACT is computed. PMAX and PACT are compared. PMAX and PACT are compared. If PACT is greater than PMAX, it is set as the new value of PMAX. At every instant the PACT is calculated, and the comparison is continuously executed. Hence the final value of PMAX will be the point at which maximum power can be delivered to the load. For maximum power transfer across the load, the input impedance should be equal to the load impedance. Based on the mechanism of load matching the duty cycle of the converter is varied so that the output power will almost be equal to the input in practical systems.

Reddy *et al*., (2011) proposed to control duty cycle of boost converter by PWM signal from microcontroller implementing Incremental Conductance algorithm. The scheme utilizes PWM techniques to regulate the output power of boost converter at its maximum possible value and simultaneously controls the charging process of battery.

Subudhi et al., (2012) provides a classification of available MPPT techniques based on the number of control variables involved, types of control strategies, circuitry, and cost of applications, which is possibly useful for selecting an MPPT technique for a particular application. It also gives an idea about grid-tied or standalone mode of operations, types of preferable converters for each MPPT technique and the efficiency calculation procedure of the developed MPPTs.

Yang et al., (2012) proposed a compact-size analog maximum power point tracking (AMPPT) technique for high power efficiency in the photovoltaic (PV) system. A wide-range current multiplier, which tracks the maximum power point (MPP) in the solar power system, has been implemented to detect the power slope condition of the solar panel. Experimental results showed that the proposed technique can rapidly track the MPP with a high tracking accuracy of 97.3%. The proposed system can connect to the grid-connected inverter to supply ac power.

Lokanadham et al., (2012) presented an Incremental Conductance based maximum power point tracking (MPPT) for photovoltaic system. Maximum power point tracking (MPPT) is used in photovoltaic (PV) systems to maximize the photovoltaic array output power, irrespective of the temperature and radiation conditions and of the load electrical characteristics the PV array output power is used to directly control the dc-dc converter, thus reducing the complexity of the system. The method is based on use of a Incremental Conductance of the PV to determine an optimum operating current for the maximum output power.

Petrone et al., (2011) presented a novel MPPT algorithm based on the perturb-and-observe (P&O) technique. The novelty of the approach was represented by the perturbation of more control variables, rather than just one. This allows the increase of the power extracted from the photovoltaic (PV) field as compared to the case of perturbation of a single control variable. The proposed technique overcomes the limitations of any existing tracking technique dedicated to PV arrays exhibiting a unique maximum power point. The proposed multivariable approach was described by means of its application to a single-stage one-cycle controlled PV inverter.

Liu et al., (2008) simulated a modified variable step size INC MPPT algorithm which is able to improve the dynamic and steady state performance of the PV system simultaneously. At the start process of the MPPT, the PV system may exhibit comparable large step change in the output voltage and current due to the large step size. A simple CVT start program is introduced to the MPPT algorithm, which enables the smooth start process. Both fixed step size and the proposed variable size INC MPPT methods implemented with MATLAB-SIMULINK and with DSP for the hardware experiment. The simulation and experimental results verified the feasibility and effectiveness of the proposed method.

Yu et al., (2009) simulated a photovoltaic system with maximum power point tracking (MPPT) function using Matlab/Simulink to evaluate and predict the behaviors of the real photovoltaic system. The characteristics of the established solar module model were simulated and compared with those of the original field test data under different temperature and irradiance conditions. A model of a photovoltaic system with maximum power point tracker, which was developed using DC-DC buck-boost converter with the perturbation and observation method, was then established and simulated. According to comparisons of the simulation results, the I-V curves of the established solar module model could closely match those of the original field test data, and the model of the photovoltaic system that was built can track the maximum power point of the system successfully and accurately under arbitrary temperature and irradiance conditions.

Zhang et al., (2011) proposed a new topology of an MPPT controller for solar microgrid applications that incorporates a variable inductance. It has the advantage of reducing the overall size of the inductor by up to 75% and increases the operating range of the tracker to recover solar energy at low solar levels.

Luigi et al., (2011) presented evaluations of most MPPT techniques, with respect to the amount of energy extracted from the photovoltaic panel, Tracking Factor, PV voltage ripple, dynamic response and use of sensors. Beta technique has high quality tracking factor, reduced and smaller ripple voltage in steady state, good transient performance and medium complexity of implementation; however, it is dependent of the PV characteristics. It was observed that modified IC, modified P&O, IC Based on PI and P&O Based on PI, has also outstanding performance and they are independent of the type of the PV panel.

Elgendy et al., (2012) presented comprehensive analysis and evaluation of the reference voltage perturbation and direct duty ratio perturbation techniques for implementing the P&O MPPT algorithm. With reference voltage perturbation, the system has a faster response to irradiance and temperature transients. However, it loses stability if operated at a high perturbation rate or if low pass filters are used for noise rejection from the array current and voltage feedback signals. Direct duty ratio control offers better energy utilization and better stability characteristics at a slower transient response and worse performance at rapidly changing irradiance. System stability is not affected by using low-pass feedback filters. In addition, direct duty ratio perturbation allows the use of high perturbation rates up to the PWM rate without losing the global stability of the system.

Yuan et al., (2011) proposed a dc voltage sensorless control scheme for two stage three-phase grid-tied PV inverter. It does not assume voltage sensors at dc side without downgrading MPP tracking accuracy and output waveform quality. The MPPT function is realized by using the inherent operational principle of boost converter and the traditional P&O mechanism. The rear-end inverter controls the dc-link voltage indirectly without measuring the dc-link voltage but gets the same performance as direct dc-link control by regulating the modulation depth.

Al-Diab et al., (2010) proposed, theoretical analysis and the design principle of modified variable step size P&O MPPT algorithm. Among all the MPPT strategies, The P&O MPPT algorithm is mostly used, due to its ease of implementation. On the other hand, its main drawbacks are the waste of energy in steady state conditions, when the working point moves across the MPP and the poor dynamic performances exhibited when a step change in solar irradiance or in temperature occurs. In modified variable step size P&O MPPT algorithm, the step size is automatically tuned according to the operating point. Compared with the conventional fixed step size method, the proposed approach can effectively improve the MPPT speed and efficiency simultaneously.

Islam et al., (2010) developed a complete generalized model of PV array along with fuzzy logic based MPPT controller in Matlab/Simulink. The specialty of this Fuzzy logic controller (FLC) is that the rule base is very simple which increases the speed of computation of the processor. It can successfully track the MPP accurately and quicker than conventional perturb and observe based controller when environment changes abruptly.

Safari et al., (2011) presented an incremental conductance (IncCond) MPPT used in solar array power systems with direct control method. The main difference of the proposed system to existing MPPT systems includes elimination of the proportional–integral control loop and investigation of the effect of simplifying the control circuit. The resultant system is capable of tracking MPPs accurately and rapidly without steady-state oscillation, and also, its dynamic performance was satisfactory. The IncCond algorithm is used to track MPPs because it performs precise control under rapidly changing atmospheric conditions.

Abdelsalam et al., (2011) presented modified P&O MPPT technique for PV-based microgrids to maximize the harvested. Perturb and observe (P&O) techniques, still suffer from several disadvantages, such as sustained oscillation around the MPP, fast tracking versus oscillation tradeoffs, and user predefined constants. The proposed technique achieves: first, adaptive tracking; second, no steady-state oscillations around the MPP; and lastly, no need for predefined system-dependent constants, hence provides a generic design core. Practical results for the implemented setup at different irradiance levels are illustrated to validate the proposed technique.

NianCHun et al., (2011) presented that output characteristics of a PV array are influenced by the environment factors, and the conversion efficiency of PV arrays is very low. So real-time simulation of the PV array was done for Grid-connected PV system in MATLAB/Simulink. On the basis of P&O method and the simulation model of PV cell, a simulation model of the PV cell under MPPT control was established. Characteristics of photovoltaic arrays based on MATLAB simulation were analyzed.

Hussein K.H. et al., (1995) developed a new MPPT algorithm based on the fact that the MPOP (maximum peak operating point) of a PV generator can be tracked accurately by comparing the incremental and instantaneous conductance of the PV array. The work was carried out by both simulation and experiment, with results showing that the developed incremental conductance (InCond) algorithm has successfully tracked the MPOP, even in cases of rapidly changing atmospheric conditions, and has higher efficiency than ordinary algorithms in terms of total PV energy transferred to the load.

Mahendran et al., (2011) proposed an advanced cascaded multilevel inverter which varies from the conventional one from the number of input dc sources used. The research on multilevel inverter in these days goes on rapidly due to its efficient operation, for various applications. The proposed nine level multilevel inverter configurations utilize a single dc source i.e., photo voltaic panel, whereas in the conventional multilevel inverter it varies based on the number of levels. The single phase transformer is replaced by the three phase linear transformer to reduce the transformer number.

2.4 Grid Connected PV System

Cai et al., (2011) developed a grid-connected photovoltaic simulation system with maximum power point tracking (MPPT) function using MATLAB software to predict the behaviors of the real photovoltaic system. An engineering model of the photovoltaic (PV) cell is first established and then combined with an MPPT algorithm, as well as models of an MPPT controller and a DC-DC converter, in order to verify the correctness of MPPT controller. A DC-AC inverter using double closed loop control system is used to track the characteristics of the grid. The outer DC voltage control loop is to keep the input DC voltage stable, and the inner grid current control loop is to ensure that the output current has the same frequency and phase angle as the grid voltage. PLL technique used in the control circuit of the inverter ensures the tracking accuracy of the output current. The simulated results shows that the system not only achieves the maximum power point tracking function but also makes the outputs of the inverter as sine waveforms and have less ripple, and also the power factor is close to 1. Therefore the outputs of the inverter satisfy the demands of the grid-connected photovoltaic system.

Sanchis et al., (2005) has been developed and simulated a control strategy for the Boost inverter. In a single stage system Boost dc–ac inverter naturally generates an ac voltage whose peak value can be lower or greater than the dc input voltage. The main drawback of this structure deals with its control. Boost inverter consists of Boost dc–dc converters that have to be controlled in a variable-operation point condition. In the proposed control strategy, each Boost is controlled by means of a double-loop regulation scheme that consists of a new inductor current control inner loop and an also new output voltage control outer loop. These loops include compensations in order to cope with the Boost variable operation point condition and to achieve a high robustness to both input voltage and output current disturbances. The proposed control strategy achieves a very high reliable performance, even in difficult transient situations such as nonlinear loads, abrupt load changes, short circuits, etc., which sliding mode control cannot cope with.

Han et al., (2011) presented a system scheme of the stand-alone photovoltaic inverter based on parallel charge topology for the purpose of improving the energy conversion efficiency and optimizing the battery management. The low loss circuit topology with the soft switching property effectively reduces the switching loss of the DC-AC inverter. The output power of the photovoltaic array is extracted to the highest degree with the Constant Voltage Tracking (CVT) algorithm and the modified adaptive Perturbation and Observation (P&O) algorithm for maximum power point tracking. The total system efficiency is improved and the battery management is optimized with the proposed system scheme. The proposed system scheme is valuable for the stand-alone photovoltaic generation system.

Karimi-Davijani et al., (2011) presented a photovoltaic (PV) system and a battery bank as energy sources, which with the aid of converters, provide electric power to three-phase balanced stand-alone loads. Such stand-alone systems include dedicated power systems for rural areas, moveable military bases and facilities requiring premium power quality. For the proper calculation and control operation of stand-alone systems, the dynamics of the power sources and the loads must be properly accounted for thorough adequate system modeling. With the aid of DC-DC converters, source output powers and the DC link voltage are controlled. A three phase DC-AC inverter converts the input DC voltage to AC and controls the frequency and magnitude of the load voltage. The modeling and steady state operation of the system are set forth under various operating conditions while accounting for the nonlinearity of the PV source and load type. Besides, the maximum power point tracking algorithm of the solar system is added. The controller design and structures are explained in details and the dynamic behavior of the whole system is studied by computer simulations.

CHAPTER 3

THEORY OF GRID CONNECTED PV SYSTEM

A grid-connected photovoltaic (PV) system transfers the solar energy efficiently which is previously converted into electrical energy from to the utility grid. From the functional point of view a PV system can be subdivided into two parts, the solar energy collectors and the power conversion system. The solar energy collectors consist of a number of PV modules that capture the solar irradiance and transform it into electrical energy; this part of PV systems can be referred as 'photovoltaic generator'. The objective of the power conversion system is to guarantee the maximum extraction of energy from the PV generator.

This chapter includes basic working principles of various components of photovoltaic system like PV generator, DC-DC converter, DC-AC inverter. In this chapter MPPT technique algorithms for extraction of maximum energy from the PV generator are also discussed in detail.

3.1 Photovoltaic (PV) Cell

PV cells are the basic components of photovoltaic modules or arrays. PV cells are mainly made from silicon along with other materials. PV cells take advantage of the photoelectric effect which is the ability of some semiconductor materials to convert electromagnetic radiation directly into electrical current as explained further. The charged particles generated by the incident photons in the solar radiation are separated conveniently to create an electrical current by an appropriate design of the structure of the PV cell. The PV cells are crystalline silicon (c-Si) based on the p-n junction photovoltaic device developed in Bell Labs in 1954 by Chapin, Fuller, and Person (D. Chapin *et. al.*, 1954).

3.1.1 Photovoltaic Generator Working Principle

When there is no solar radiation on the PV cell its behaviour can be approximated simply as p-n junction diode. Now once the cell is illuminated by solar radiation, electron-hole pairs are produced by the interaction of the incident photons with the atom of the cell. The electric field created by the cell junction causes the photon-generated electron-hole pair to separate, with electrons drifting to the n-region of the cell and the holes drifting into the p-region. This movement of charged particles causes a photocurrent which depends mainly on the intensity and wavelength of the incident solar radiation (R. Messenger *et. al*., 1999).

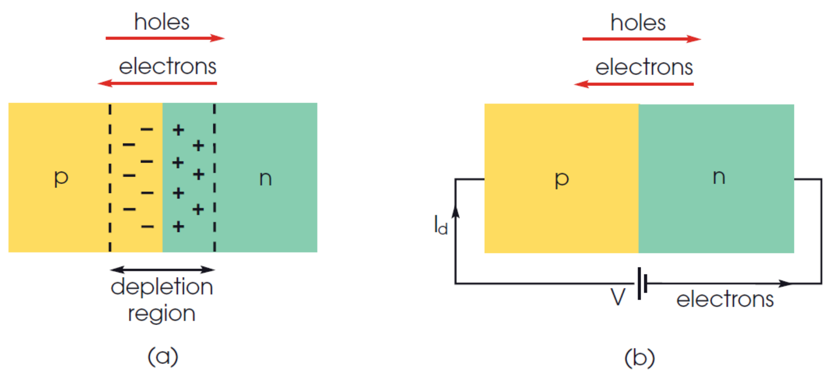


Figure 3.1 Solar Cell construction (Lynn, P. A., 2010)

A typical PV cell generates less than 2 W at approximately 0.5 V (R. Messenger *et al., 1999*) therefore in order to obtain an adequate output voltage for practical applications several cells are connected in series to form a PV panel. Commercially available PV panels have peak output power ranging from a few watts to more than 300 W at panel voltages from 12 V to 48 V. Grid-connected PV applications often requires higher voltages and currents than the ones available in a PV panel. In this case, PV panels must be connected into arrays. Series connections of PV panels result in higher voltages, while parallel connections result in higher currents. In the present document it is assumed that the PV generator is formed of several PV panels and considering it as single PV module.

3.1.2 Photovoltaic Cell Model

As explained earlier when PV cell is not illuminated it is not an active device; it works as a diode, i.e. a p-n junction. In this state cell do not produces a current or a voltage. However, when cell is connected to an external sufficiently large supply than the cell voltage it generates a current I_D, this current is called diode current or dark current.

A PV cell is generally represented by an electrical equivalent one-diode model, as shown Fig. 3.2 below.

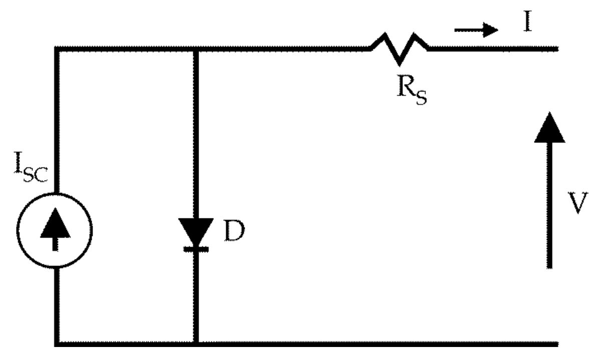


Figure 3.2 Equivalent circuit of PV cell

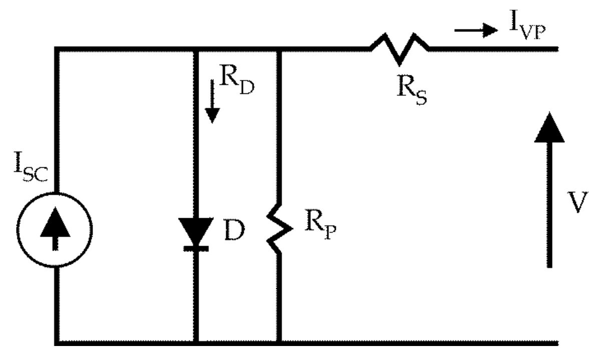


Figure 3.3 Equivalent circuit of Solar cell with Rs and Rp

A PV cell model can be considered as a current source and an inverted diode connected in parallel to it. The model has its own series and parallel resistance. Series resistance (Rs) is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance (Rp) is taken into consideration because of cell leakage current. By considering the practical scenario, the value of Rp is very large and that of Rs is very small, hence these resistances cab be neglected to simplify the analysis.

The different parameters of the PV cells along with those shown in Fig. 3.2 and Fig. 3.3 are:

V is output voltage of a PV module (V)

I_{PV} is output current of a PV module (A)

I_{SC} is the light generated current in a PV module (A)

I_D is the PV module saturation current (A)

A = B is an ideality factor

k is Boltzman constant = 1.3805 × 10-23 J/K q is Electron charge = 1.6 × 10-19 C

Rs is the series resistance of a PV module

Ego is the band gap for silicon = 1.1 eV

Ns is the number of cells connected in series

Np is the number of cells connected in parallel

The ideal photovoltaic module consists of a single diode connected in parallel with a light generated current source (I_{SC}) as shown in Fig. 3.2. The equation for the output current is given by:

$$I_{PV} = I_{SC} - I_D$$

Where I_{SC} and I_D are as defined above

By Shockley equation, the diode current I_D is given by

$$I_D = I_{rs}(e^{qVoc}/_{KAT} - 1)$$

Where,

I_{rs}: reverse saturation current of diode (A),

V_{OC}: Open Circuit voltage of PV Module (V),

T: Module operating temperature in Kelvin (K)

The equation of output current by replacing the diode current equation is as follows:

$$I_{PV} = I_{sc} - I_{rs}\ (e^{qVoc}/_{KAT} - 1)$$

The light current depends on both irradiance and temperature. It is measured at some reference conditions.

Thus,

$$I_{SC} = [I_{\ SCr} + K_i\ (T - T_{ref})] * \frac{\lambda}{1000}$$

Where,

ISCr: PV module short-circuit current at 25oC and 1000W/m2

Ki: short-circuit current temperature co-efficient at ISCr

Tr: reference temperature (K)

T: module operating temperature (K)

λ: PV module illumination (W/m2) = 1000W/m2

The Module reverse saturation current can be given as

$$I_{rs} = \frac{I_{SCr}}{\left[e^{\frac{qV_{OC}}{N_S KAT}} - 1\right]}$$

The thermal voltage (V_t) of the module with Ns cells connected in series is defined by

$$V_t = \frac{N_S KAT}{q}$$

The module saturation current I_D varies with the cell temperature, which is given by

$$I_D = I_{rs}\left[\frac{T}{T_r}\right]^3 e^{\left[\frac{qEgo}{Bk\{\frac{1}{T_r} - \frac{1}{T}\}}\right]}$$

The output current of PV module is

$$I_{pv} = N_p * I_{sc} - N_p * I_o\left[e^{\left\{\frac{q*(V + I_{pv} R_S))}{N_S KAT}\right\}} - 1\right]$$

3.1.3 PV Cell Maximum Power Point

Typical PV cell current-voltage characteristic curves are shown in Fig. 3.4. As can be seen from the figure when PV cell voltage is equal to Voc or cell current is equal to Isc the power generated is zero. Voc is the PV cell voltage when the output current of the cell is zero, i.e. Ipv = 0 and the shunt resistance Rp is neglected. The short circuit current ISC is the current at V = 0 and is given above equations.

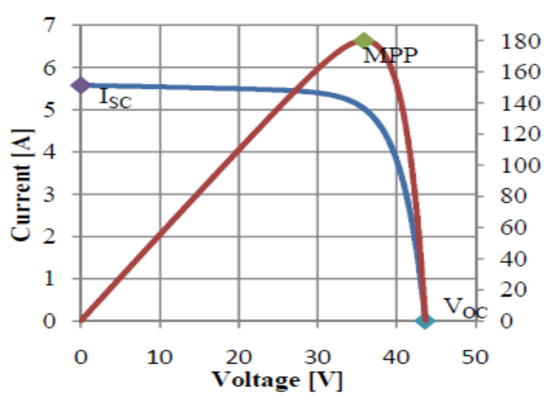


Figure 3.4 Important Points in the characteristic curves of a solar panel

Also as can be seen the Fig. 3.4 when the VI products of cell is maximum, the maximum power is generated by the PV cell. This point is known as the MPP.

3.1.4 Fill Factor of PV Cell

The fill factor (FF) can be defined as:

$$FF = \frac{I_{MPP} V_{MPP}}{I_{SC}\, V_{OC}}$$

Here IMPP and VMMP are the PV cell output current and voltage at MPP. Fill factor is a widely used measure of the solar cell overall quality (Lynn, P. A., 2010). It is the ratio of the actual maximum power (IMPP VMPP) to the theoretical one (ISC VOC). As the MPP voltage and current are always below the open circuit voltage and the short circuit current respectively, the theoretical power is practically not achievable. This is because of the series and shunt resistances and the diode as shown in Fig. 3.3. The typical fill factor for commercially available solar cells is usually over 0.70.

3.1.5 Effect of Temperature and Irradiance on PV cell characteristics

Solar module characteristics are mainly affected by the temperature and solar irradiance level. As a result, the MPP varies during the day and that is the main reason why the MPP must constantly be tracked and needs to be ensured that the maximum available power is obtained from the panel.

The effect of the irradiance on the voltage-current (V-I) and voltage-power (V-P) characteristics is shown in Fig. 3.5, where the curves are shown in per unit, i.e. the voltage and current are normalized using the VOC and the ISC respectively. This is in order to illustrate effects of the irradiance on the V-I and V-P curves in better way. As the photo-generated current is directly proportional to the irradiance level, an increment in the irradiation leads to a higher photo-generated current. Moreover, the short circuit current is directly proportional to the photo-generated current; therefore it is directly proportional to the irradiance. When the operating point is not the short circuit, in which no power is generated, the photo-generated current is also the main factor in the PV current, as is expressed by equations in section 3.1.2 of this chapter. For this reason the voltage-current characteristic varies with the irradiation. In contrast, the effect in the open circuit voltage is relatively small, as the dependence of the light generated current is logarithmic.

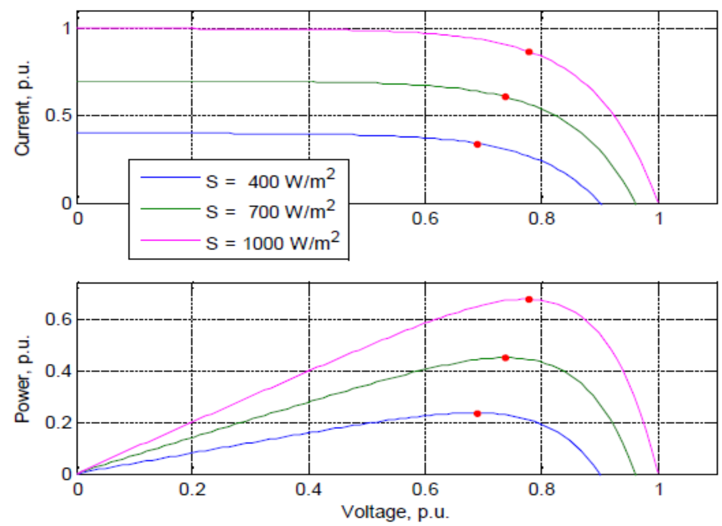


Figure 3.5 V-I and V-P curves at constant temperature (25°C) and three different insolation values

It can be seen from the characteristics that the change in the current is greater than that in the voltage. In practice, the voltage dependency on the irradiation is often neglected. As both the current and voltage increases when the irradiation rises, the effect on the power is also the same. So from the above explanation it is clear that more power is generated as irradiation level increases.

The change in the temperature affects the voltage. The open circuit voltage is linearly proportional to the cell temperature. When the temperature rises, the voltage decreases. The current increases with the temperature but very little that is why the power also decreases as rise in current does not compensate the decrease in the voltage caused by a given temperature rise. As the effect of the temperature on the current is really small, it is usually neglected.

Fig. 3.6 shows how the voltage-current and the voltage-power characteristics change with temperature. The curves are again in per unit, as in the previous case. As mentioned before, the temperature and the irradiation depend on the atmospheric conditions, which are not constant during a year and not even during a single day these conditions can vary rapidly due to fast changing conditions such as clouds. This causes the MPP to move constantly, depending on the irradiation and temperature conditions. If the operating point is not close to the MPP, great power

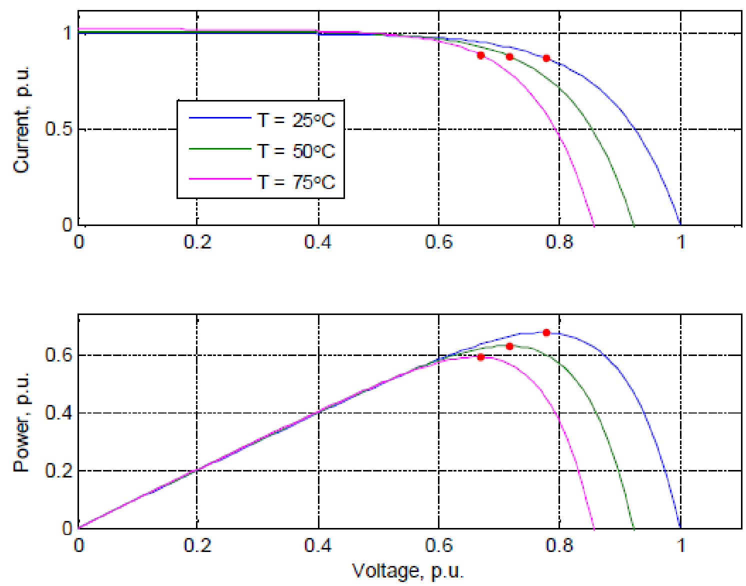


Figure 3.6 V-I and V-P curves at constant irradiation (1 kW/m2) and three different temperatures

losses occur. Hence it is essential to track the MPP in any conditions to assure that the maximum available power is obtained from the PV panel. The operation of PV system at maximum power point is achieved by using various MPPT algorithms as explained in next section.

3.2 Maximum Power Point Tracking Techniques

As explained in the previous section, the efficient operation of a PV system is possible if the system operates at Maximum Power Point on V-I, V-P characteristics. V-I characteristics of a PV cell or array varies with temperature and irradiance conditions. Also the change in MPP can be rapid, so the PV system needs to implement the control techniques which ensure the maximum efficiency. Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity of the method. A complete review of 19 different MPPT algorithms can be found in (Esram, T. *et al.*, 2007).

Among these techniques, the 'Perturb and Observe (P&O)' and the 'Incremental Conductance (InCond)' algorithms are most common. These techniques have the advantage of an easy implementation but they also have drawbacks compared to other techniques. Other techniques based on different principles are fuzzy logic control, neural network, fractional open circuit voltage or short circuit current, current sweep etc. Most of these methods yield a local maximum and some, like the fractional open circuit voltage or short circuit current, give an approximated MPP, not the exact one. In normal conditions the V-P curve has only one maximum, so it is not a problem. However, if the PV array is partially shaded, there are multiple maxima in these curves. In order to relieve this problem, some algorithms have been implemented as in (Nguyen, T.L. et al., 2010).

3.2.1 Hill-climbing techniques

Both P&O and InCond algorithms are based on the "hill-climbing" principle, which consists of moving the operation point of the PV array in the direction in which power increases. Hill-climbing techniques are the most popular MPPT methods due to their ease of implementation and good performance when the irradiation is constant (Sera, D. et al., 2006). The advantages of both methods are the simplicity and low computational power they need. The shortcomings are also well-known: oscillations around the MPP and they can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions (Femia, N. et al., 2004).

3.2.1.1 Perturb and Observe

The P&O algorithm is also called "hill-climbing", but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter (Esram, T. et al., 2007). In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique.

In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. As can be seen in Fig. 3.7, on the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power.

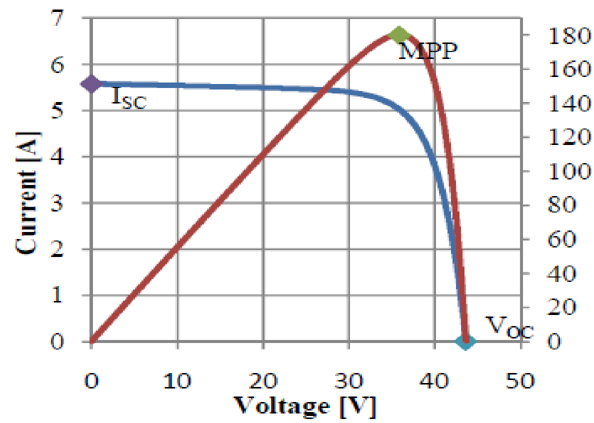


Figure 3.7 PV Panel Characteristic Curves

The flow chart of the P&O algorithm is shown in Fig. 3.8. The "perturb and observe" algorithm starts by sensing the PV array current and voltage. The power is then calculated and compared with its previous value stored in memory. In case it has remained the same, the array voltage should remain as it is, but in case it has increased and the array voltage has increased, then the array voltage must increase further by "v" to check if the new power is higher than the previous one. The operating point is thus on the left side of the MPP and the operating point is moving upwards. If the power has increased but the voltage has decreased, then the array voltage should be decreased by "v" where the operating point is on the right side of the MPP with the point moving upwards.

In case the power has decreased and the voltage has increased, then the operating point is on the right of the MPP and moving downwards, thus the array voltage should be decreased by "v". Finally, if both power and voltage have decreased, then the operating point is on the left side of the MPP and moving downwards, thus the array voltage must be increased by "v". "v" is a step voltage that is either added or subtracted from the array voltage to reach the MPP. The size of the step "v" could be decreased to a small value so that the MPP is best approximated.

On the other hand, decreasing the size of "v" will make the convergence speed slower and thus more time is needed to reach the MPP.

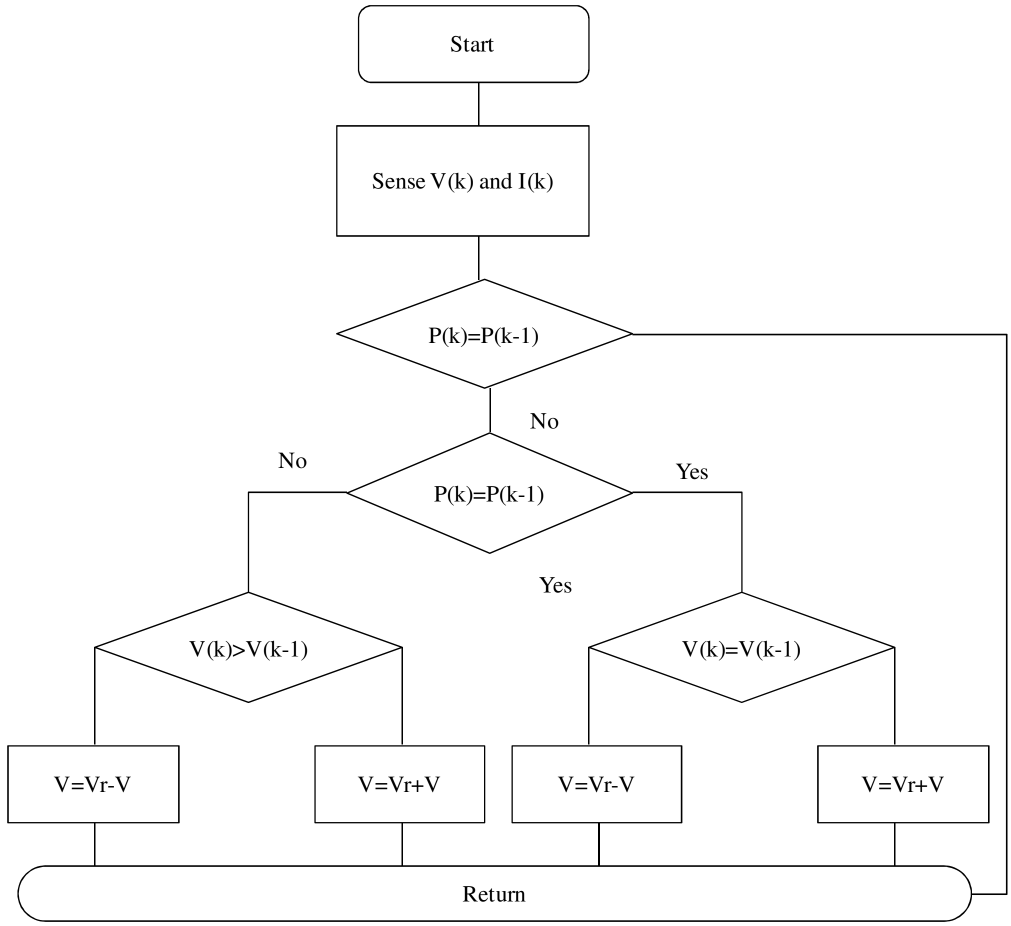


Figure 3.8 Flowchart of the P&O Algorithm

3.2.1.2 Incremental Conductance

Incremental conductance (incCond) algorithm was proposed by Hussein, Muta, Hoshino, and Osakada of Saga University, Japan, in 1992. The main focus of this algorithm was to solve the problem of the P&O algorithm under rapidly changing atmospheric conditions (Hussein, K. H. et al., 1995).

The slope of the curve power vs. voltage (current) of the PV module is zero at the MPP, positive (negative) on the left of it and negative (positive) on the right, as can be seen in Fig. 3.7:

- $\Delta V/\Delta P = 0$ ($\Delta I/\Delta P = 0$) at the MPP
- $\Delta V/\Delta P > 0$ ($\Delta I/\Delta P < 0$) on the left of MPP
- $\Delta V/\Delta P < 0$ ($\Delta I/\Delta P > 0$) on the right of MPP

In this algorithm the change in the MPP voltage can be determined by comparing the increment of the power vs. the increment of the voltage (current) between two consecutives samples. Fig. 3.9 shows the Incremental Conductance algorithm (Jain, S. et al., 2007)

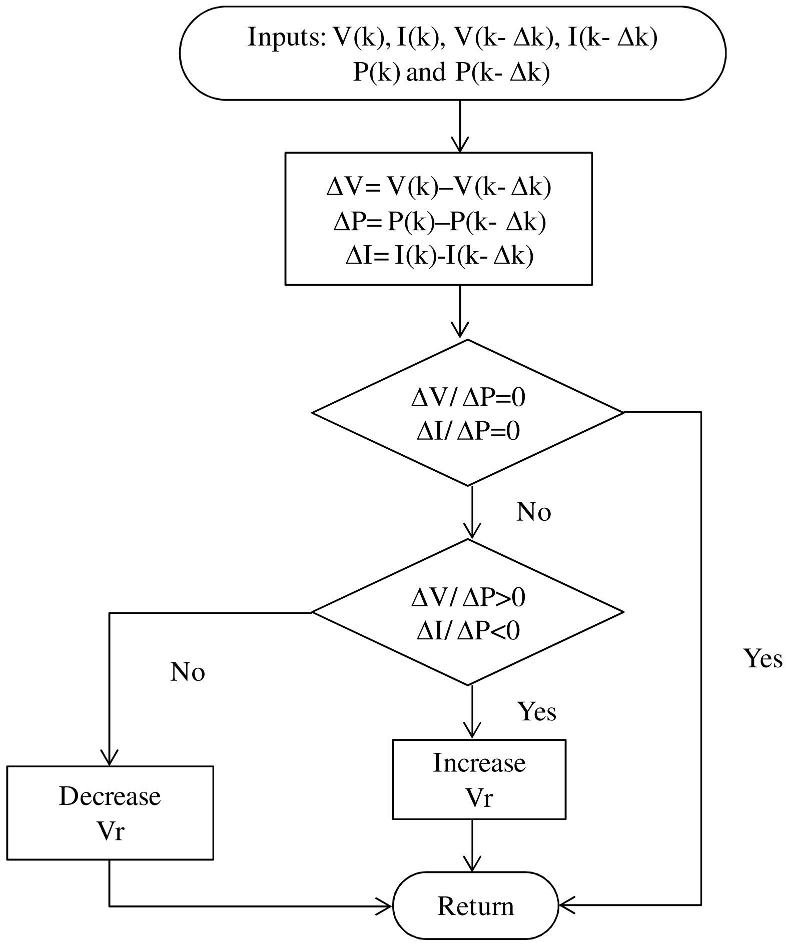


Figure 3.9 Flowchart of Incremental Conductance Algorithm

In case of above explained Hill Climbing techniques namely P&O and InCond, the size of increment in reference voltage decides how fast the MPP is reached. If this increment step size is larger MPP will be reached faster. But with larger step size the output power oscillates to much extent.

There are mainly two drawbacks of these techniques. The first and main one is that they can easily lose track of the MPP if the irradiation changes rapidly. In case of step changes as the change is instantaneous and the curve does not keep on changing these techniques track the MPP very well. However, when the irradiation changes following a slope, the curve in which the algorithms are based changes continuously with the irradiation, so the changes in the voltage and current are not only due to the perturbation of the voltage. Because of above reasons it is not possible for the algorithms to determine whether the change in the power is due to its own voltage increment or due to the change in the irradiation.

The other disadvantage of both methods is the oscillations of the voltage and current around the MPP in the steady state (Zhang, C. et al., 2009) and (Xiao, W. et al., 2004) as mentioned above. This is due to the fact that the control is discrete and the voltage and current are not constantly at the MPP but oscillating around it. The size of the oscillations depends on the size of the rate of change of the reference voltage. The larger the step size, the larger is the amplitude of the oscillations. However, how fast the MPP is reached also depends on this rate of change and this dependence is inversely proportional to the size of the voltage increments. So there is a trade off between the system response time to achieve the maximum efficiency condition and the system stability.

3.2.1.3 Other 'hill climbing' techniques

There are other three techniques revised in (Esram, T. et al., 2007) that can be grouped with the hill climbing algorithms: ripple correlation control (RCC), dP/dV or dP/dI Feedback control and slide control.

In RCC technique, ripple imposed by the power converter on the PV array is observed to track the MPP. It correlates dp/dt with di/dt or dv/dt, to drive the power gradient to zero, which happens when the MPP is reached. '(dp/dt) (di/dt)' or '(dp/dt) (dv/dt)' are positive to the left of the MPP, negative to the right and zero at the MPP this similar criteria is used in InCond technique also, so this technique also suffer the same problems. In fact, it has been only tested with irradiation steps, which are not appropriate to test the dynamic performance. Besides, it needs low switching frequencies to have enough ripple so the correct decisions can be made and it is an analog technique. On the contrary, inverters are nowadays controlled digitally with DSPs, so this method does not show any advantage to the P&O or InCond. dP/dV or dP/dI Feedback control is a technique which computes the slope of the P-V or P-I characteristic curve and feeds it back to the controller in order to drive it to zero, as they are zero at the MPP. Again this is another implementation of the InCond algorithm, so it has the same advantages and disadvantages. Finally, in the slide control, the switching function used is again dP/dV, thus the same problems as with the InCond algorithm can be expected under changing irradiation.

To summarise, all hill-climbing MPPT methods depend on the PV array's V-P or I-P characteristics, which vary with temperature and irradiation, therefore these MPPT methods can be confused when the irradiation or temperature are changing, as it is explained in (Sera, D. et al., 2006). Also the other hill-climbing MPPT methods do not offer any improvement to the original P&O and InCond algorithms.

3.2.2 Fuzzy Logic Control

The use of fuzzy logic control has become popular over the last decade because it can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity. Microcontrollers have also helped in the popularization of fuzzy logic control Fuzzy logic control has the advantage to be robust and relatively simple to design as it do not require the knowledge of the exact model. They do require in the other hand the complete knowledge of the operation of the PV system by the designer.

The fuzzy logic control can be categorized in three stages namely fuzzification, inference system and defuzzification. Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. Membership functions, as shown in Fig. 13 are used to associate a grade to each linguistic term. The number of membership functions used depends on the accuracy of the controller, but it usually varies between 5 and 7. In Fig. 3.10 seven fuzzy levels are used: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big).

The values a, b and c are based on the range values of the numerical variable. The inputs of the fuzzy controller are usually an error, E, and the change in the error, ΔE. The error can be chosen by the designer, but usually it is chosen as ΔP/ΔV because it is zero at the MPP. Then E and ΔE are defined as follows:

$$E = \frac{P(k) - P(k-1)}{V(k) - V(k-1)}$$

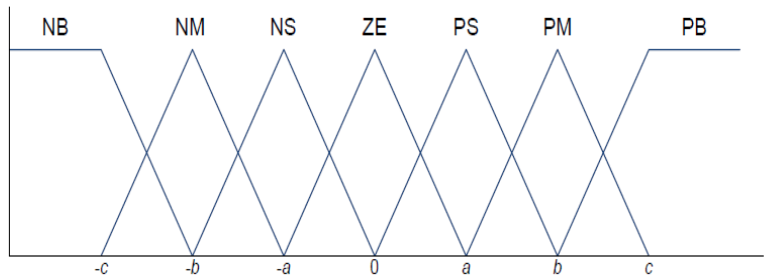


Figure 5.10 Membership Function

$$\Delta E = E(k) - E(k-1)$$

In other cases ΔP/ΔI is used as error or other inputs are considered, as in (Li, J. et al., 2009), where ΔU and ΔP are used.

The output of the fuzzy logic converter is usually a change in the duty ratio of the power converter, ΔD, or a change in the reference voltage of the DC-link, ΔV. The rule base, also known as rule base lookup table or fuzzy rule algorithm, associates the fuzzy output to the fuzzy inputs based on the power converter used and on the knowledge of the user. Table 3.1 shows the rules for a three phase inverter, where the inputs are E and ΔE, as defined in (Femia, N. et al., 2004) and (Esram, T. et al., 2007) and the output is a change in the DC-link voltage, ΔV. For example, if the operating point is far to the right of the MPP, E is NB, and ΔE is zero, then to reach the MPP the reference voltage should decrease, so ΔV should be NB (Negative) to move the operating point towards the MPP.

The last stage of the fuzzy logic control is the defuzzification. In this stage the output is converted from a linguistic variable to a numerical crisp once again using membership functions as those in Fig. 3.10. There are different methods to transform the linguistic variables into crisp values. It can be said that the most popular is the center of gravity method. However the analysis of these methods is beyond the scope of this thesis.

The advantages of these controllers, besides dealing with imprecise inputs, not needing an accurate mathematical model and handling nonlinearity, are fast convergence and minimal oscillations around the MPP. Furthermore, they have been shown to perform well under step changes in the irradiation. However, no evidence was found that they perform well under irradiation ramps. Therefore, their performance under the conditions specified for testing the dynamic MPPT efficiency

Table 3.1 Rule Base

E/dE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

is unknown. Another disadvantage is that their effectiveness depends a lot on the skills of the designer; not only on choosing the right error computation, but also in coming up with an appropriate rule base.

3.2.3 Neural Networks

Neural networks based MPPT is one of the techniques suited for implementation using microcontrollers (Midya, P et al., 1996). A neural network is composed of three layers: the input, hidden and output layers. Inputs to a network can be the array terminal voltage and the solar irradiation level or any other measurements needed by the MPPT algorithm. Each node in the network is referred to as a neuron; these neurons are connected together through lines that are associated with certain weighted sums wij. The effectiveness of this MPPT technique is mainly determined by the hidden layer and the amount of training the network received. The training process might span several months or years where the network is subjected to various measurements obtained from the PV system. Using this information, the weights between the neurons are tuned to generate the required output which could be a command to change a DC converter duty cycle. A disadvantage of this technique is the lengthy training process it needs before the neural network can accurately track the maximum power point, in addition to its dependency on the characteristics of the PV array to which it is connected.

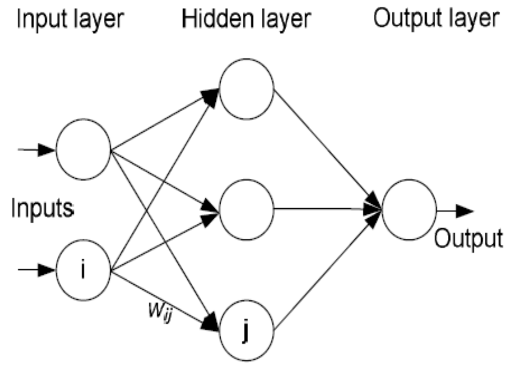


Figure 3.11 Neural Network

The performance of the NN depends on the functions used by the hidden layer and how well the neural network has been trained. The links between the nodes are all weighted. In Fig. 3.11 the weight between the nodes i and j is labelled as wij. The weights are adjusted in the training process. To execute this training process, data of the patterns between inputs and outputs of the neural network are recorded over a lengthy period of time, so that the MPP can be tracked accurately. The main disadvantage of this MPPT technique is the fact that the data needed for the training process has to be specifically acquired for every PV array and location, as the characteristics of the PV array vary depending on the model and the atmospheric conditions depend on the location. These characteristics also change with time, so the neural network has to be periodically trained.

3.2.4 Fractional open circuit voltage

This method uses the approximately linear relationship between the MPP voltage (VMPP) and the open circuit voltage (VOC), which varies with the irradiance and temperature (Esram, T. et al., 2007).

$$VMPP \approx K1\ VOC$$

Where k1 is a constant depending on the characteristics of the PV array and it has to be determined beforehand by determining the VMPP and VOC for different levels of irradiation and different temperatures. According to (Esram, T. et al., 2007) the constant k1 has been reported to be between 0.71 and 0.78. Once the constant of proportionality, k1, is known, the MPP voltage VMPP can be determined periodically by measuring VOC. To measure VOC the power converter has to be shut down momentarily so in each measurement a loss of power occurs. Another problem of this method is that it is incapable of tracking the MPP under irradiation slopes, because the determination of V_{MPP} is not continuous. One more disadvantage is that the MPP reached is not the real one because the relationship is only an approximation. To overcome these drawbacks, some solutions have been proposed. For example, pilot cells can be used to obtain V_{OC}. They are solar cells that represent the PV array's cells and which are not used to produce electricity but to obtain characteristics parameters such as V_{OC} without interfering with the power converters. These pilot cells have to be carefully chosen and placed to represent the PV array characteristics and the irradiation conditions. One drawback of using these pilot cells is that the cost of the system is increased.

3.2.5 Fractional short circuit current

Just like in the fractional open circuit voltage method, there is a relationship, under varying atmospheric conditions, between the short circuit current ISC and the MPP current, IMPP, as is shown by:

$$IMPP \approx K2\ ISC$$

The coefficient of proportionality k2 has to be determined according to each PV array, as in the previous method happened with k1. According to (Esram, T. et al., 2007) the constant k2 has been reported to be between 0.78 and 0.92. Measuring the short circuit current while the system is operating is a problem. It usually requires adding an additional switch to the power converter to periodically short the PV array and measure ISC. In (Noguchi, T. et al., 2002) ISC is measured by shorting the PV array with an additional field-effect transistor added between the PV array and the DC link capacitor. One other option is shown in (Yuvarajan, S. et al., 2003): a boost converter is used and the switch of the converter is used to short the PV array. Short circuiting the PV array also leads to a loss of power. One last handicap is that the real MPP is not reached because the proportional relationship is an approximation. Furthermore, k2 changes if the PV array is partially shaded, which happens due to shades or surface contamination. To overcome this problem, proposes an online tuning of k2 and a periodical sweep of the PV voltage from open circuit to short circuit to update k2 and guarantee that the real MPP is reached in the presence of multiple maxima which obviously increases the complexity of the system.

3.2.6 Current sweep

In this method the I-V characteristic curve is obtained using a sweep waveform for the PV array current. The sweep is repeated at fixed time intervals so the I-V curve is updated periodically and the MPP voltage (VMPP) can be determined from it at these same intervals. How the I-V curve is determined and the function chosen for the sweep waveform can be found in (Bodur, M. et al., 1994). With this method the real MPP is obtained. On the other hand, the sweep takes certain time during which the operating point is not the MPP, which implies some loss of available power. Strictly speaking, it is not possible to track the MPP under irradiation slopes, because the MPP varies continuously. Only if the sweep is instantaneous the global MPP could be found, but that is impossible. Furthermore, the implementation complexity is high, the convergence speed is slow and both voltage and current measurements are required. As pointed out in (Bodur, M. et al., 1994) a MPPT method is worth using only if its power consumption is lower than the increase in power it brings to the entire PV system.

Due to the drawbacks and complexity exposed above, this MPPT method is not the best option to track the MPP continuously. However, it can be used as a complement to other methods, for example when initializing the PV system in the morning, to begin the tracking in the real MPP and then change to another algorithm, or to check sometimes during the day if the system is operating at the real MPP. One more application can be checking if there are multiple maxima due to shading conditions.

3.2.7 Maximum Power Point Current and Voltage Computation

In Current and Voltage Computation technique MPP is calculated by measuring irradiance and the temperature of the PV module (Esram, T. et al, 2007). This technique needed extra measurements, which are sometimes difficult to obtain, and requires an accurate model of the PV array. On the other hand, the MPP is correctly tracked even under changing atmospheric conditions. It can be used in large plants, where the economic investment is huge and a perfect tracking is needed to obtain the maximum available power from the PV arrays.

3.2.8 State Based Maximum Power Point Tracking Technique

The state based MPP technique is based on a state-space representation of the plant and a nonlinear time-varying dynamic feedback controller. This technique is argued to be robust and tracks the MPP even under changing irradiation and in the presence of multiple maxima. However, no experimental results are given in (Solodovnik, E. V. et al., 2004), the implementation complexity is high, as the state-space representation has to be built for each PV plant, and the performance under changing irradiance has not been tested according to the standard.

3.2.9 Multiple Maxima Search

This method is used when the PV array is shaded, the P-V curve presents multiple maxima and most MPPT algorithms including P&O, InCond and fuzzy logic control, cannot determine the global maximum. Usually a local MPP is found, depending on the starting point of the algorithm. In recent years, some algorithms have been proposed to overcome this limitation but most effective is the DIRECT search technique that is based on the dividing rectangles algorithm. If this method is continuously used to track the MPP, the maximum reported efficiency is 97% (Nguyen, T.L et al., 2010). However, it can be used periodically to determine where the global maximum is and then change to a traditional algorithm whose efficiency can be over 99% (Piegari, L. et al, 2010).This could be effective as the shades move slowly during the day. In this way, the losses that occur due to convergence to a local instead of the global MPP, could be avoided.

3.2.10 Constant Voltage Method (CV)

In Constant Voltage method empirical results are used which indicates that the voltage at MPP (VMPP) is around 70% to 80% of the PV open circuit voltage (VOC), for the standard atmospheric condition. When the intensity of solar radiation changes, the voltage at the terminals of the module varies very little but it varies abruptly when there is change in temperature. So this method must be used in regions where the temperature varies very little. An advantage of CV method is that only PV voltage is necessary to be measured, and a simple control loop can reach the MPP (Khatib, T. T. N. et al, 2010).

3.3 DC-DC Boost Converter Stage

The purpose of DC-DC Switch Mode Converters in general DC power supplies is to convert unregulated DC input to regulated or controlled DC output at a desired voltage level. Also the output voltage should be regulated at a constant value from a fluctuating power source, to reduce the ripples in the output voltage or achieve multiple voltage levels from the same input voltage. In a PV system, on the other hand, the DC-DC converter is actually controlling the input by considering the unregulated output. By help of MPP Tracking which is explained in earlier section the converter adjusts its operation according to the output value to find the optimal operating voltage of the PV module.

Several topologies exist to either increase or decrease the input voltage or perform both functions together using a single circuit. The three basic topologies of DC converters are: buck (step down), boost (step up) and the buck-boost converter topologies.

As the name suggests, boost converter produces the output which is higher than the input voltage. The boost converter is widely used to pinpoint the ultimate point of power of the PV array. The boost converter circuit is shown in Fig. 3.12. The boost converter has different circuit schemes depending on the state of the switch (D1), as seen in figure. When the switch is on the output stage is isolated from the input caused by the reverse biased diode. The input will supply the inductor with a constant voltage, and the inductor current will increase accordingly. When the switch is turned off, the output will be supplied both by the input and the inductor, and the current through the inductor will decrease because of this energy transfer.

The boost converter can operate in continuous conduction mode along with discontinuous conduction mode. The mode of conduction depends of the capacity for storage of energy along with the relative timeframe of the switching. The output voltage is dependent of the duty cycle; it is adjusted by the maximum power controller. The relation of the output voltage with the input voltage as function of duty cycle is given by

$$\frac{V_o}{V_i} = \frac{T_s}{t_{off}} = \frac{1}{1-D}$$

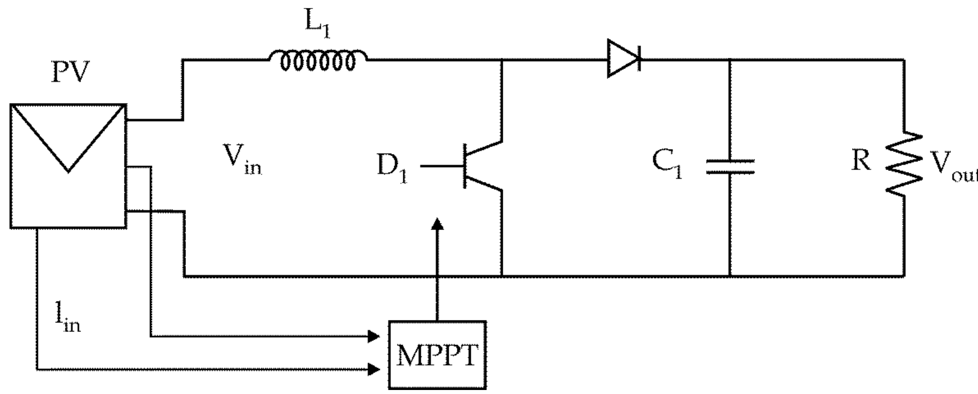


Figure 3.12 Boost converter for PV

3.3.1 Continuous Conduction Mode

For detailed explanation of Continuous conduction mode operation is subdivided into two modes as given below:

Mode 1 ($0 < t \leq t_{on}$)

Mode 1 begins when IGBT's is switched on at t = 0 and terminates at t = ton. The equivalent circuit for the Mode 1 is shown in Fig. 3.13(a). The inductor current iL(t) greater than zero and ramp up linearly. The inductor voltage is equal to input voltage Vi.

Mode 2 ($t_{on} < t \leq T_s$)

Mode 2 begins when IGBT's is switched off at t = ton and terminates at t = Ts. The equivalent circuit for the Mode 2 is shown in Fig. 3.13(b). The inductor current decrease until the IGBT's is turned on again during the next cycle. The voltage across the inductor in this period is Vi - Vo. Since in steady state time integral of the inductor voltage over one time period must be zero, following equation can be written

$$V_i . t_{on} + (V_i - V_O).t_{off} = 0$$

Where;

V_i is input voltage, V

V_o is average output voltage, V

t_{on} is switch on time of IGBT's, s

t_{off} is switch off time of IGBT's, s

Dividing both sides by Ts and rearranging items yield

$$\frac{V_o}{V_i} = \frac{T_s}{t_{off}} = \frac{1}{1-D}$$

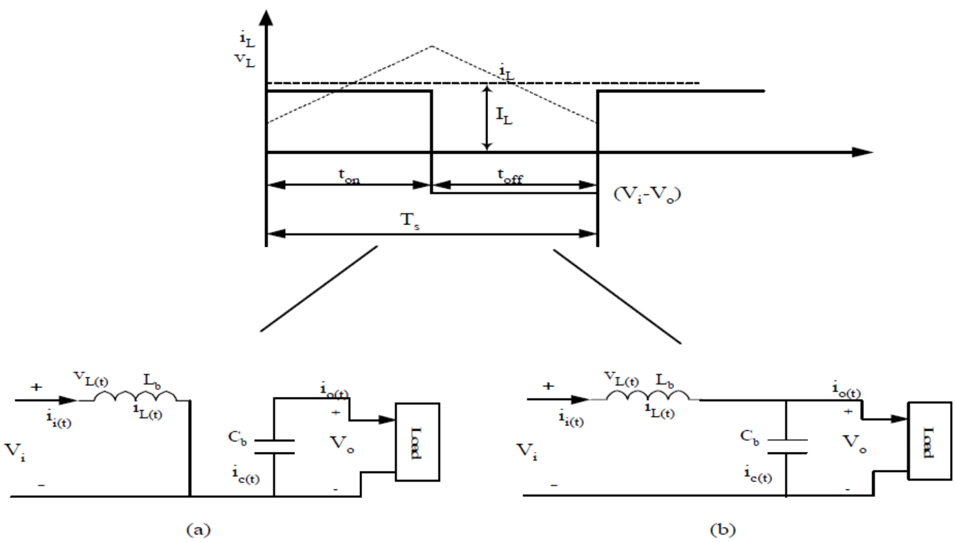


Figure 63.13 Equivalent Circuit for boost Converter in CCM (Rashid, M.H., 1993)
(a) Mode 1 (0< t ≤ton) (b) Mode 2 (ton<t ≤Ts)

Thus, Vo is inversely proportional to (1-D). It obvious that the duty cycle, D, cannot be equal to 1 otherwise there would be no energy transfer to the output. Assuming a lossless circuit, Pi=Po, then

$$I_i \,.\, V_i = I_o \,.\, V_o$$

and,

$$\frac{I_o}{I_i} = 1 - D$$

Where;

I_o is average output current, A

I_i is average input current, A

3.3.2 Discontinuous Conduction Mode

If the current following through the inductor falls to zero before the next turn-on of the switching IGBT's, then the boost converter is said to be operating in the discontinuous conduction mode. If we equate the integral of the inductor voltage as shown in Fig. 3.14 over one time period to zero.

$$V_i . D. T_s + (V_i - V_o). D. T_s = 0$$

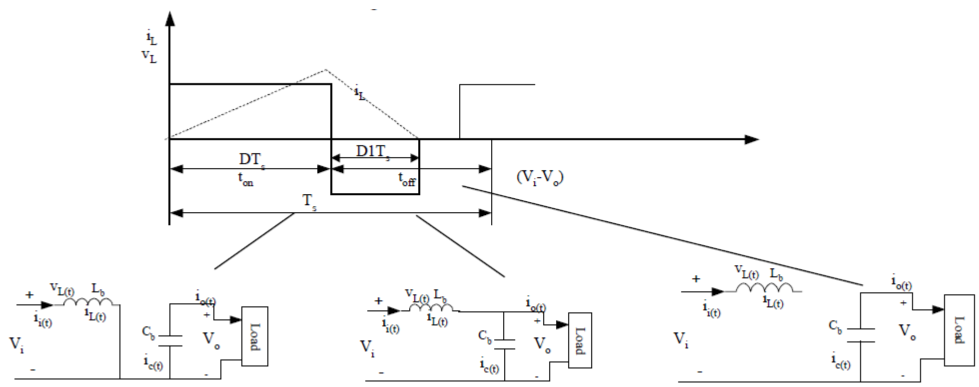


Figure 3.14 Equivalent Circuit for boost Converter in DCM (a) Mode 1 (0<t≤ton) (b) Mode 2 (ton<t ≤(D+D1)Ts (c) Mode 3 (D+D1)Ts <t ≤Ts (Rashid, M.H., 1993)

Then;

$$\frac{V_o}{V_i} = \frac{(D1 + D)}{D1}$$

As Pi=Po,

$$\frac{Io}{I_i} = \frac{D1}{(D1 + D)}$$

From Fig. 18c, the average input current, which is equal to the inductor current, is

$$I_i = \frac{V_i . D. T_s. (D1 + D)}{2L_b}$$

Using Equations in the foregoing equation yields

$$I_o = \left(\frac{V_i T_s}{2L_b}\right) D. D1$$

In practice, since Vo is held constant and D varies in response to variation in Vi, it is more useful to obtain the required duty cycle, D, as a function of load current for varies values of Vo/Vi. By using above Equations, we can determine that:

$$D = \left[\frac{4}{27}\frac{V_o}{V_i}\left(\frac{V_o}{V_i} - 1\right)\frac{I_o}{I_{o,aver,max}}\right]^{0.5}$$

3.4 DC-AC Inverter Stage

The purpose of DC-AC Switch Mode Inverters is to produce a sinusoidal AC output from a DC input through PWM. The inverter is able to control both the magnitude and the frequency of the AC. In case of grid connected PV System application the inverter output voltage frequency should track the grid voltage frequency. Inverters that have an input assumed to be a DC voltage source are referred to as Voltage Source Inverters. VSI can be divided into three categories: PWM inverters, square wave inverters and single-phase inverters with voltage cancellation. In a PV system PWM inverters are most frequently utilized and their purpose is to keep the DC-link voltage at a constant voltage level by adjusting the DC link current. The PWM in inverter circuits is more complex than for DC-DC Switch Mode Converters. To be able to produce a sinusoidal output voltage waveform with the required frequency, the control signal needs to be sinusoidal as well. And the signal it is being compared to is a triangular waveform rather than a sawtooth signal. The frequency of the waveform creates the switching frequency and is ordinarily kept constant.

Fig. 3.15 shows a schematic diagram of an IGBT based 3 phase VSI. The inverter is composed of six switches S1 through S6 with each phase output connected to the middle of each “inverter leg”. Two switches in each phase are used to construct one leg.

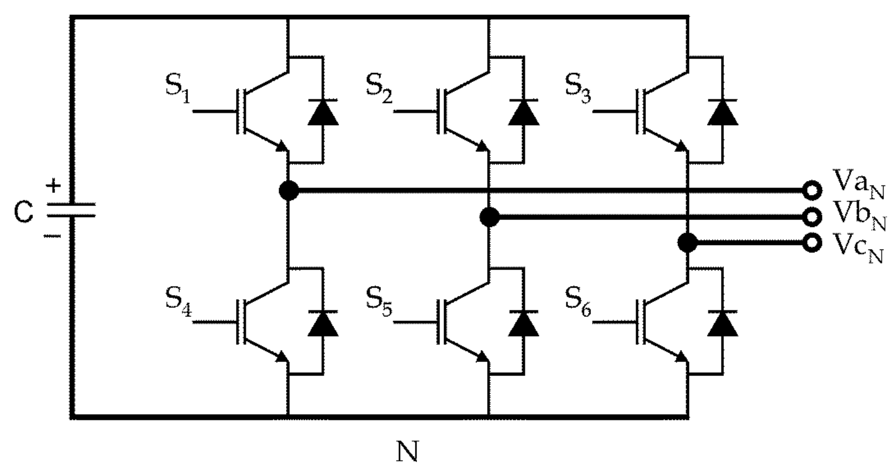


Figure 3.15 Three Phase Voltage Source Inverter (VSI)

Insulated Gate Bipolar Transistors (IGBTs) and power MOSFET devices can be used to implement the switches. Each device varies in its power ratings and switching speed. IGBTs are well suited for applications that require medium power and switching frequency (Wu, B, 2006).

In case of a Grid Connected PV system the inverter is followed by a filter stage. As the VSI as explained in this section is a PWM based, its output voltage and current has a significant amount of high frequency distortion and the ripple content. This distortion and ripple content will be passed to the grid which is not recommended. Also ripple and noise in the signals can generate distortion in the measurements and thus create errors and unstable operation in the closed loop VSI system. The noise can be removed by implementing filters, or frequency selective circuits. Depending on type of elements and placement in the circuit the filters can eliminate certain unwanted frequencies. The typical filter types are low-pass, high-pass, band-pass and band-reject filters. Noise of a typical high frequency distortion type and can be partly or totally removed by implementing a low pass filter between the input and the output of a circuit. Ideal filters will have a frequency limit where the passing of signal goes from maximum to zero, called the cutoff frequency, but in real circuits this is not possible. At frequencies higher than the cutoff frequency the signals passed through the circuit will decay with a gradient of -20n dB per decade, where n is the order of the filter. So it is hard to remove all kinds of distortion from a signal.

Filters can be divided in two types, the passive and the active filters. The passive filters incorporate utilization of passive circuit elements like resistors, inductors and capacitors, while the active filters also include operational amplifiers which are characterized as an active circuit element. In case of a Grid Connected PV system a passive low pass filter is used and it is implemented using L and C elements.

This chapter provides the basic understanding and working principles of elements of grid connected PV system. Next chapter provides detailed design and simulation modelling considerations for each element of the system.

CHAPTER 4

DEVELOPMENT OF PROPOSED MPPT BASED PV SYSTEM

This chapter provides the detailed modelling of proposed MPPT based PV system in simulating software and Laboratory hardware. First, the power circuit is developed in MATLAB/SIMULINK where control circuit in PSIM using simcoupler module. Then, hardware prototype of 200W 'P & O' based PV system is developed in the laboratory.

The prototype system is a microcontroller based PV system which uses Perturb & Observe control algorithm. The power level strategy of this system is similar to one explained in the thesis. The hardware model section of this chapter explains details of prototype system in relation with the simulation model.

4.1 Implementation of proposed MPPT based PV system in simulation environment

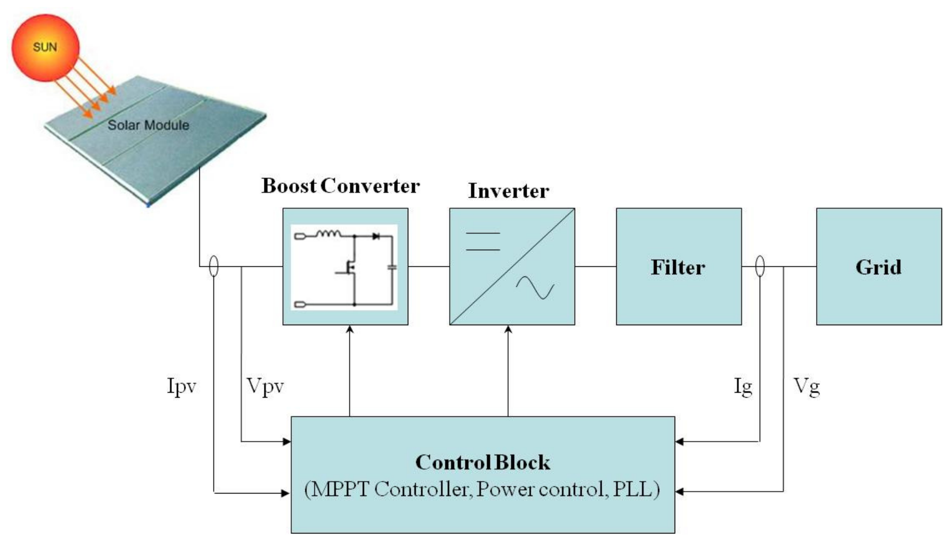


Figure 4.1 Block Diagram of Proposed MPPT based PV System

The main components of the system include the PV array model, the boost converter, Voltage Source Inverter and MPPT algorithm model. Fig. 4.2 shows the overall system Simulink model. This system is a typical Grid Connected Inverter

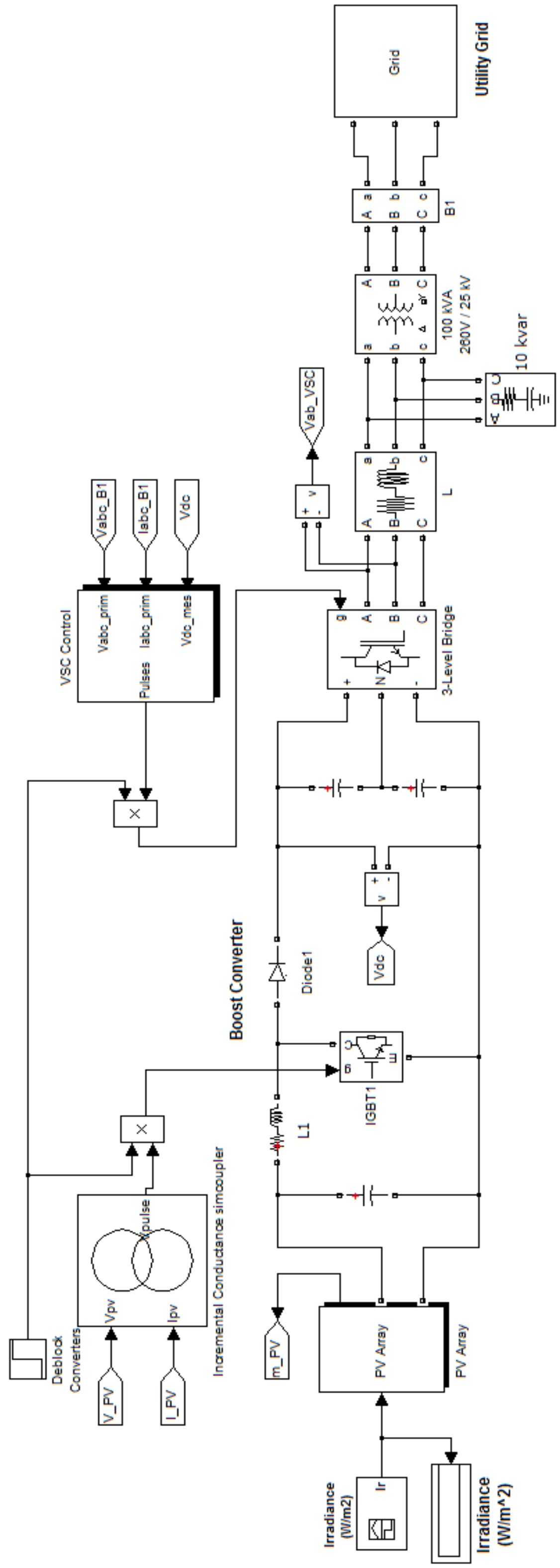


Figure 4.2 PV System Model

application using a PV array as power source. PV array feeds the boost converter, the output of the boost converter is maintained fixed at a certain dc level which feeds Voltage Source Inverter which eventually connected to Utility Grid load though a filter. The ac grid is modeled as an ac source with fixed magnitude and frequency resembling an infinite bus compared to the PV arrays. The MPPT controller based on the "Perturb and Observe" technique is implemented in PSIM using Control Library components. The Power signals from Matlab and control signals from PSIM are correlated using SimCoupler.

The conditions on the irradiance are varied to check the viability of the proposed technique under varying climate conditions. The main purpose of the system simulation is to evaluate the MPPT techniques whether it reaches the MPP during any simulated operating conditions of the PV arrays.

Overall system contains a PV module capable of delivering 100kW of maximum power. For the PV module different irradiance levels can be set. Boost converter of the system operates at 5 kHz. This stage boosts input voltage of 272Vdc which is coming from the PV module to 500Vdc level. The switching duty of boost converter is optimized by MPPT controller. Voltage Source Converter (VSC) block which is basically a 3-level 3-phase inverter as mentioned earlier operates at 1980 Hz. Inverter stage converts 500Vdc to 260Vac level power signal ensuring the unity Power Factor. The 10kVAR capacitor bank is connected to filter harmonics generated by the VSC stage. Filter stage is followed by a 100kVA 260V/25kV isolation transformer. Finally stage is the grid model created in the Simulink which contains 25kV distribution feeder and 120kV transmission system equivalent model. In further sections individual component models are explained in detail.

4.2 PV Module

Simulink model of PV module is implemented based on the equations as explained in section 3.1.2 of previous chapter. Fig. 4.3 shows the respective model.

Inputs for this model are solar irradiance level in W/m^2 and other is the module temperature in Kelvin units. PV model is basically a controlled source of electricity. The model provides the outputs in terms of Output Voltage of PV Module (V_{PV}) and Output Current of PV Module (I_{PV}).

By considering scope of this project, different specifications of PV Module are as follows:

Number of series connected cells: 96

Open-Circuit Voltage (Voc): 64.2V

Short-Circuit Current (Isc): 5.96A

Voltage and Current at Maximum Power: V_{MPP} = 54.7and I_{MPP} = 5.58A

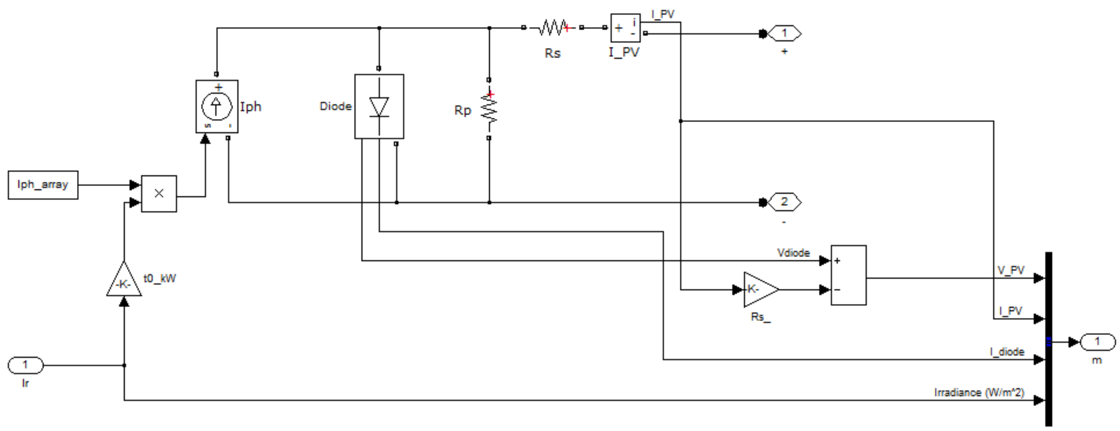


Figure 4.3 Simulink model of PV module

4.3 Development of MPPT Algorithm

Currently available solar panels are less efficient which means conversion efficiency of sunlight into electrical power is very poor. This efficiency further decreases if there is no load matching between the input side (PV array output) and the output side (grid). To maximize the power derived from the solar panel it is important to operate the panel at its maximum power point, hence an increase in output efficiency. The efficient operation of a PV system is possible if the system operates at Maximum Power Point on V-I, V-P characteristics. V-I characteristics of a PV cell or array varies with temperature and irradiance conditions. Also the change in MPP can be rapid, so the PV system needs to implement the control techniques which ensure the maximum efficiency. Among various MPPT techniques explained in Chapter 3, the ‘Perturb and Observe (P&O)’ and the ‘Incremental Conductance (InCond)’ algorithms are the most common. These techniques have the advantage of an easy implementation and good performance when the irradiation level is constant.

The advantages of both methods are the simplicity and low computational power they need though there are drawback as explained earlier.

The P&O and IncCond techniques are selected for analysis in this project for reason explained further. Firstly the selected technique should commonly used because of which its advantages and disadvantages as very well known. Secondly it should be simpler for implementation. Finally, the technique should track the track the changes in the climate conditions which are irradiance and temperature input to the simulation model with moderate response. As in both the techniques the instantaneous values of power are calculated each time and the maximum power point value is updated, these techniques are suitable selection for scope of this work.

From the complete PV system modeling point of view the MPPT controller model irrespective of the two techniques mentioned above has instantaneous PV model output voltage and current signals as inputs. These signals are PV Module Output Voltage (V_{PV}) and Output Current of PV Module (I_{PV}). Base on the instantaneous values of these signals the control algorithm decides the optimum duty for the boost converter switching device. So the output of this model is the DC-DC boost converter switching device duty signal (Vg).

The basic aim of a MPPT technique is to automatically find the voltage V_{MPP} or current I_{MPP} at which a PV array delivers maximum power under a given temperature and irradiance.

P&O Technique Algorithm which is already explained in previous chapter is shown in Fig. 4.4. In P&O method, the MPPT algorithm is based on the calculation of the PV output power and the power change by sampling both the PV Array current and voltage. The tracker operates by periodically incrementing or decrementing the solar array voltage. If a given perturbation leads to an increase (decrease) in the output power of the PV, then the subsequent perturbation is generated in the same (opposite) direction. The duty cycle of the dc chopper is varied and the process is repeated until the maximum power point has been reached. Actually, the system oscillates about the MPP. Reducing the perturbation step size can minimize the oscillation. However, small step size slows down the MPPT. For different values of irradiance and cell temperatures, the PV array would exhibit different characteristic curves. Each curve has its maximum power point.

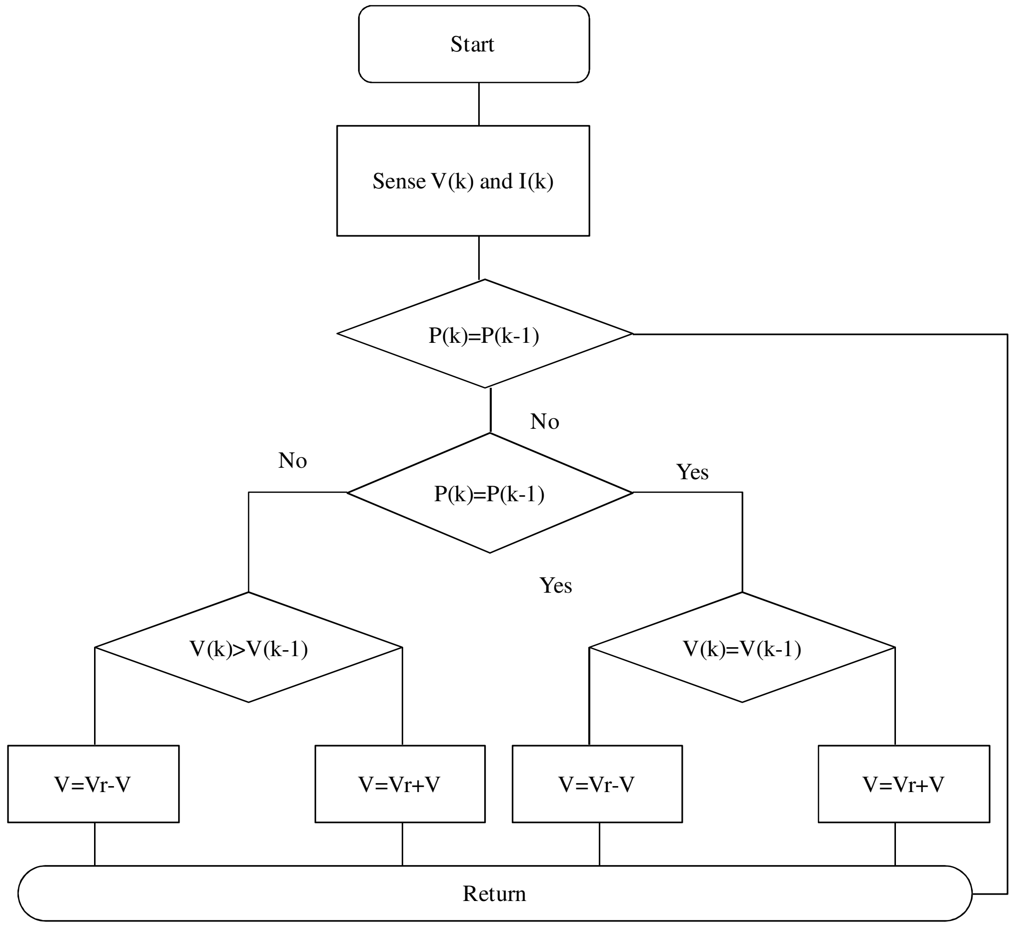


Figure 4.4 P&O Technique

The P&O MPPT technique model implemented in PSIM using control library components of PSIM as mentioned earlier is shown in the above Fig. 4.5. The algorithm starts by setting the computed maximum power (P_{max}) to an initial value which equals to zero. Next, algorithm captures instantaneous PV voltage (V_{PV}) and current (I_{PV}) at specific time intervals. This interval depends on the simulation time step while in case of actual implementation of the system the time interval depends on the sampling time of these signals. The instantaneous power (P_{inst}) is computed based on the captured instantaneous voltage and current values. P_{max} and P_{inst} are compared. If P_{inst} is greater than P_{max} then value of P_{inst} is set as the new value of P_{max}. P_{inst} is calculated at every time interval, and the comparison is done continuously. Hence the final value of P_{max} will be the point at which maximum power can be delivered to the load. If maximum power is to be transferred to be

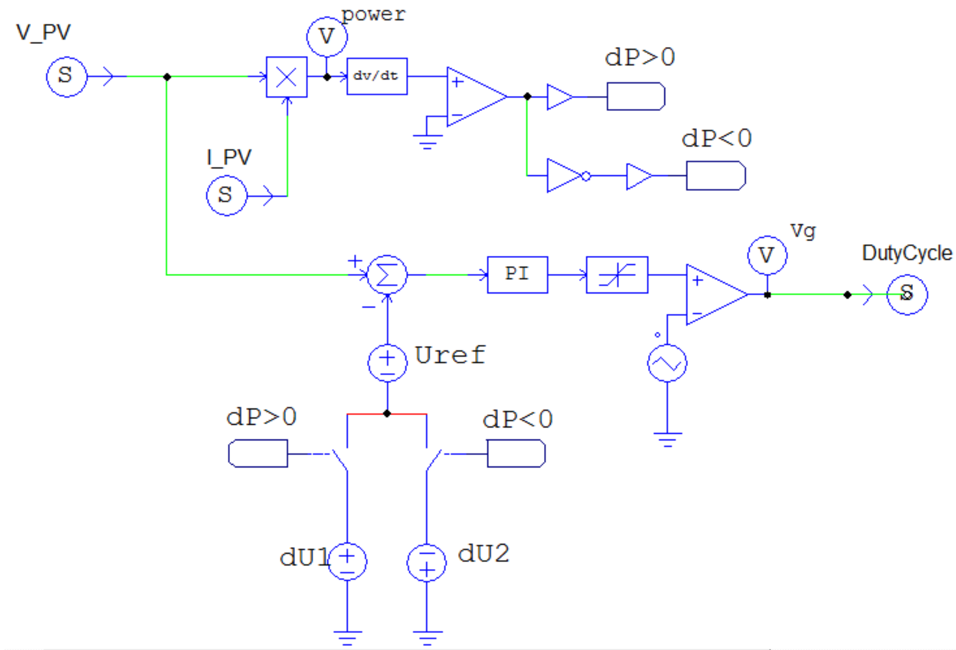


Figure 4.5 P&O Technique Model in PSIM

load, the input impedance should be equal to the load impedance. Based on the mechanism of load matching the duty cycle of the converter is varied so that the output power will almost be equal to the input in practical systems.

The IncCond MPPT technique algorithm implementation is similar to P&O algorithm. This algorithm is based on the fact that the slope of the curve power vs. voltage (current) of the PV module is zero at the MPP while positive (negative) on the left of it and negative (positive) on the right. In the PSIM model the current and voltage signals are differentiated. These signals are checked whether the signals are zero also the ratio of differentiation of voltage and current signals are checked. Fig. 4.6 shows the IncCond MPPT technique algorithm as explained in previous chapter and Fig. 4.7 shows the respective PSIM model.

As explained in the previous when maximum power is reached dP/dV ratio is zero. In this model this equation is simplified as the ratio of dI/dV will be equal to – (I/V) when maximum power is reached. So when the ratio dI/dV is larger compared to its equal to term then the reference voltage (Vr) is increased otherwise it is decreased.

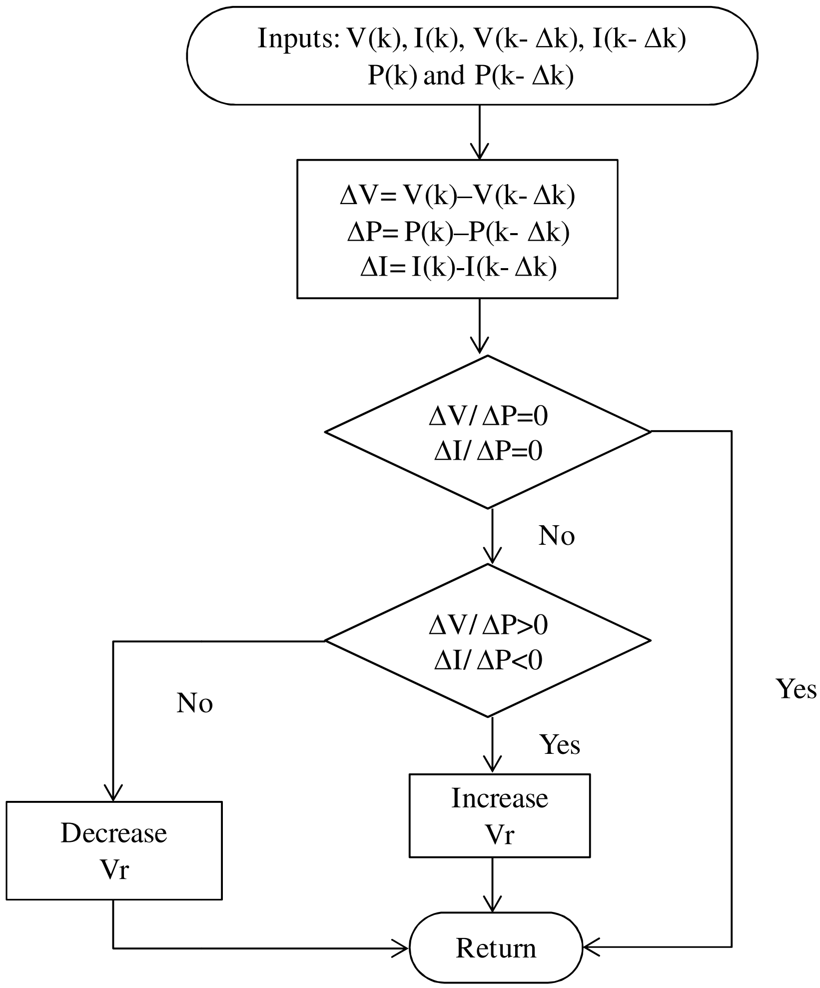


Figure 4.6 Incremental Conductance Algorithm

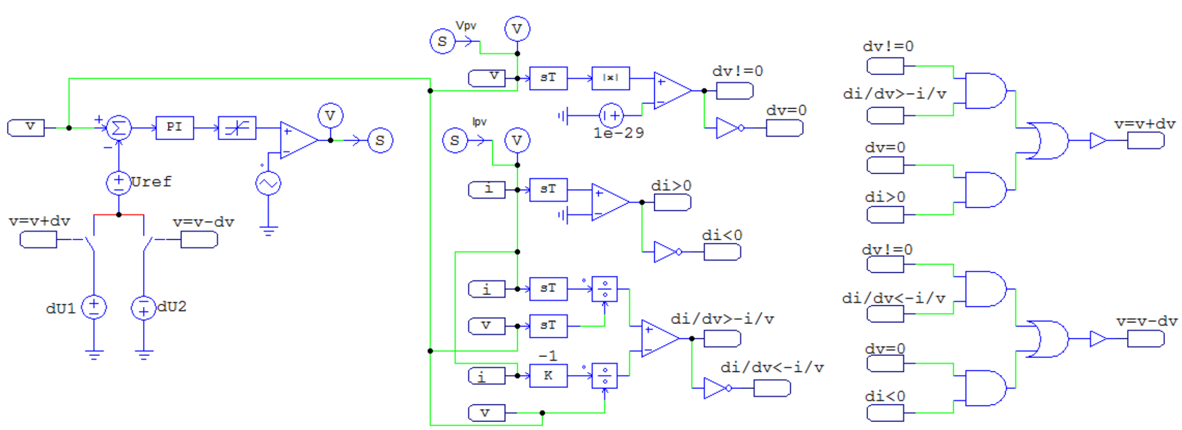


Figure 4.7 Incremental Conductance Technique in PSIM

4.4 DC-DC Boost Converter Stage Model

It consists of a simple boost circuit with a switching device, a boost inductor and a diode. The output voltage of the boost stage is kept constant at 500Vdc. The switching duty cycle is controlled by the MPPT controller to extract the maximum power from the PV module as explained in previous section. Fig. 4.8 shows Boost converter stage model.

Different specifications of boost converter stage are as follows:

Frequency of Operation: 5 kHz

Output Voltage level: 500Vdc

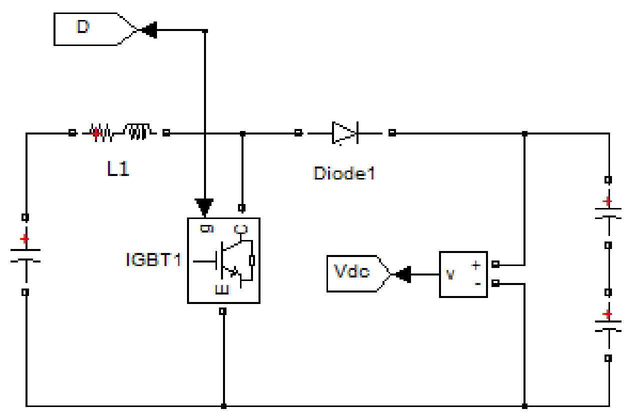


Figure 4.8 Boost Converter Model

4.5 Matlab and PSIM Interlink: SimCoupler Block

The SimCoupler Module provides the link between PSIM and Matlab/Simulink for cosimulation. This Module is straightforward and easy to use with minimum input from users. It consists of following two parts:

- Link Nodes in PSIM and
- SimCoupler Model block in Simulink

The interface is done through link nodes in PSIM, and the SimCoupler model block in Simulink. In Link Nodes receive values the signals from the Simulink, and Out Link Nodes sends the signals to Simulink.

As can be seen from Fig. 4.9, the power signals which are PV module Output Voltage (V_PV) and Output Current (I_PV) from Simulink are sent to PSIM as input to MPPT algorithm block. While switching device gate signal (g) is sent to Boost Converter block of the Simulink model.

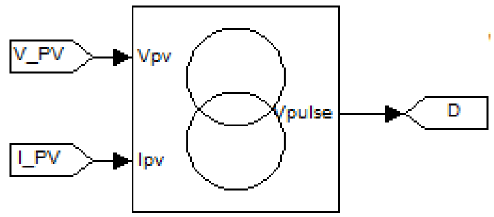


Figure 4.9 SimCoupler Block

4.6 Voltage Source Inverter Controller Model

Inverter stage is basically a voltage source converter. The VSI circuit has direct control over output voltage whereas in case of CSI directly controls output (ac) current. Also the shape of voltage waveforms output by an ideal VSI should be independent of load connected at the output. The main purpose of VSI stage is to provide a three-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable. Because of the controllability of various parameters VSI is typically suited for grid connected applications.

The standard 3-level Bridge block from Simulink is used as shown in Fig. 19. This block implements a three-level bridge of IGBTs as switching devices. Also is has the series RC snubber circuit connected in parallel with each of the switching device.

This stage converts DC voltage of 500V which is fed by Boost power stage to three phase AC voltage of 260Vac. Control input ‘g’ which is a vectorized gating signal containing pulses to control the IGBTs of the bridge, comes from the VSC control block which is explained further.

Different specifications of Voltage Source Inverter stage are as follows:

Frequency of Operation: 1980 Hz

Output Voltage level: 260Vac

Output Power Factor: Unity

VSC stage is followed by the filter stage and the isolation stage. The filter block contains a 10-kvar capacitor bank which filters the harmonics produced by the inverter. After the filter stage there is Isolation Transformer of rating 100kVA/25kV. Isolation transfer basically isolates the Grid from the PV system.

Fig. 4.10 shows the overall block diagram of VCS controller. VSC Controller consists of the different sub-systems which enable overall functionality of Inverter stage as mentioned earlier in this section. Also this control is based on space vector control method.

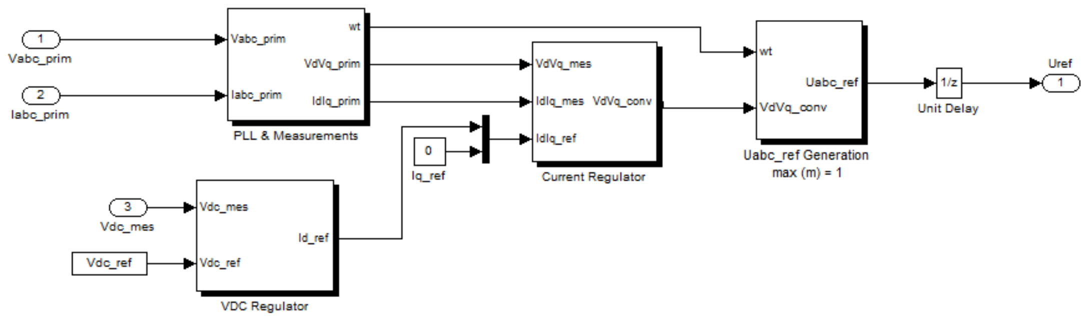


Figure 4.10 Simulink Model of Voltage Source Converter Controller

The Phase Locked Loop (PLL) system is used to synchronize on a set of variable frequency, three-phase sinusoidal signals. The input and the output of the PLL are Vector containing the normalized three-phase signals [VaVbVc], Measured frequency (Hz) = w/ (2pi), Ramp w.t varying between 0 and 2*pi, synchronized on zero crossings of the fundamental (positive-sequence) of phase A and Vector [sin (wt) cos (wt)]. Following Fig. 4.11 shows the Simulink model of PLL and measurement block.

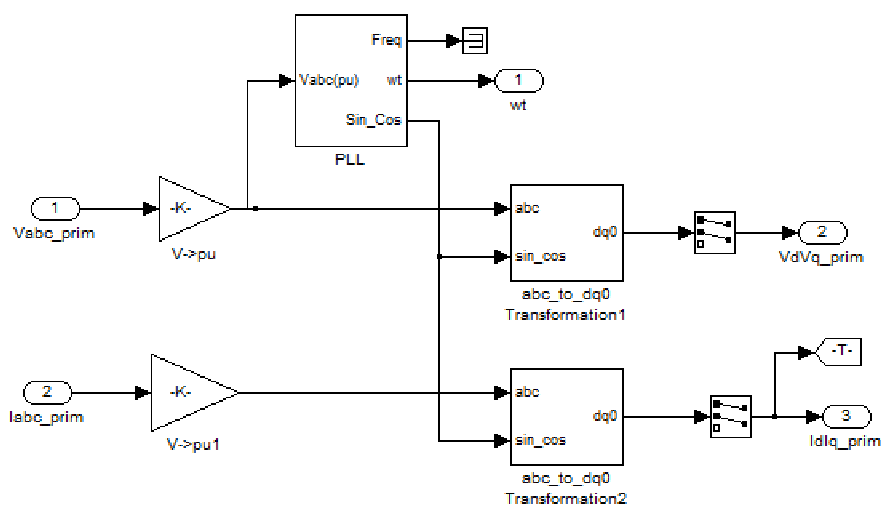


Figure 4.11 Simulink model of PLL and Measurement Block

The VDC regulator has two inputs viz. Vdc_mes and Vdc_ref, the Vdc measured signal is coming from the voltage measured at the input of the Voltage source inverter. The second signal is the reference point of DC Voltage. The output generated from this is the direct current reference signal which is further used by the current regulator. Fig. 4.12 shows the Simulink model of the VDC Regulator.

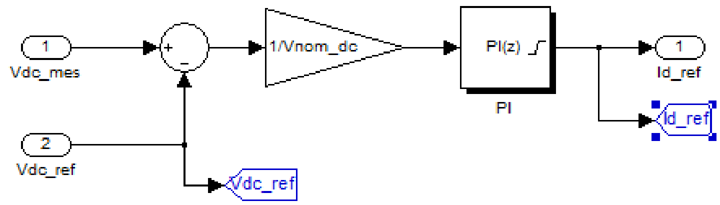


Figure 4.12 Simulink model of the VDC Regulator

.The current regulator block is used to regulate the current flowing through the converter in either direction. The assumed direction of current controller is as the current going out of the converter is called positive current. When the value of Id is positive, the converter generates active power and when value of Iq is positive the converter absorbs reactive power. Fig. 4.13 shows the Simulink model of the current regulator.

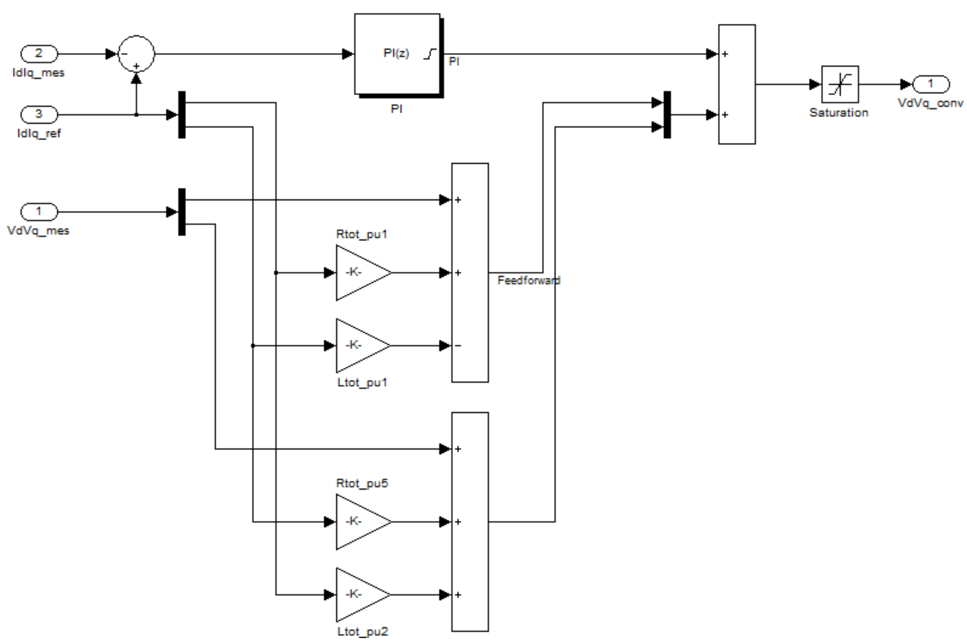


Figure 4.13 Simulink model of the Current Regulator

The Uabc_ref Generation is used to provide the gating signal or firing pulses to the voltage source inverter. Based on the output from the current regulator and PLL block the gating signals are decided. Fig. 4.14 shows the Simulink model of the Uabc_ref Generation.

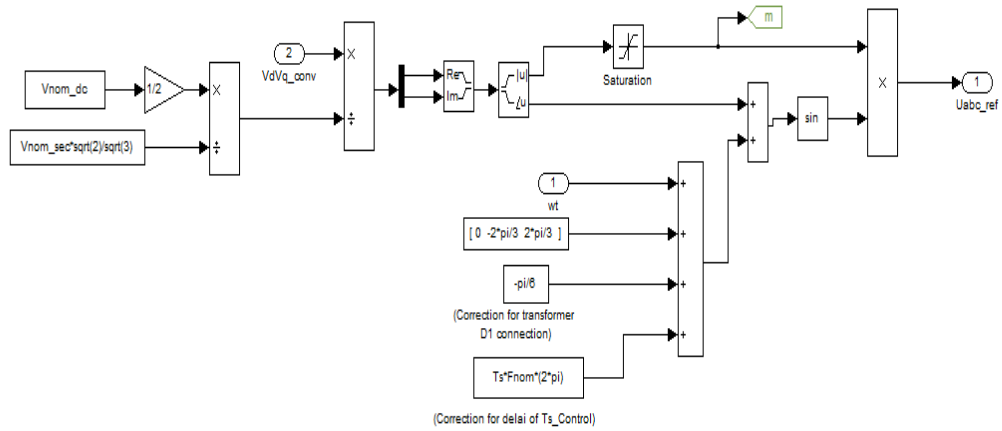


Figure 4.14 Simulink model of the Uabc_ref Generation

4.7 Development of Hardware laboratory prototype

The Hardware laboratory prototype of 200 watt PV system consist of 'P&O' type MPPT, solar panel, Buck-Boost DC-DC converter, Single phase inverter and Battery. Specifications of developed prototype of PV System is as follows:

- Meter Panel – 02 (VMP 02)
- DC – DC Buck Boost Converter (VDDCBB-01)
- Single phase inverter (PEC16HV4-PS)
- Battery (12V/40A)
- Two Solar Panel each of 100W

4.8 Solar Panel I & II

The solar panels I and II of 100W are connected in parallel to increase the output power. Specification of solar panel are given below:

Table 4.1 Solar panel specifications

Maximum Output Voltage(Vmp)	18V
Maximum Output Current(Imp)	5.56A
Open Circuit Voltage(Voc)	21.6V
Short Circuit Current(Isc)	5.85V
Maximum Power(Wp)	100W
Cell Efficiency (%)	16%

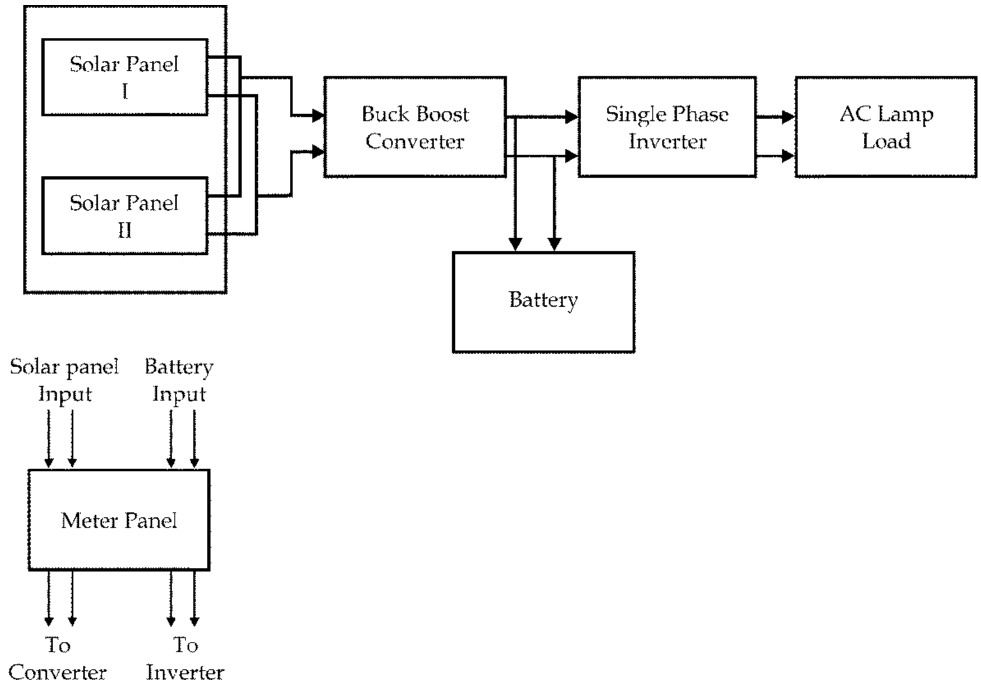


Figure 4.15 Block diagram of developed prototype

4.9 Buck Boost DC-DC Converter

When the solar panel output is below 14V, the DC-DC buck boost converter steps up the input voltage (acts as boost converter) and when the solar panel output is above 14V, the DCDC buck boost converter steps down the input voltage (acts as buck converter). A microcontroller programmed with P&O MPPT algorithm is employed in DC-DC buck boost converter to control the buck and boost operation of the converter. The converter receives its inputs from solar panels and the output of the converter is given to the battery.

4.10 P&O MPPT Algorithm

To extract the maximum power from the solar PV system, implementation of MPPT algorithm is must. Maximum Power Point tracking can be done in a few different methodologies. Here in this work, Perturb and Observe (P & O) type MPPT have been implemented to develop the hardware laboratory prototype. The basic structure and the algorithm used in realising the hardware is same as developed in PSIM as shown in Fig. 4.4 and 4.5.

In this method, the controller adjusts the voltage by a small amount from the array and measures power; if the power increases, further adjustments in that direction are tried until power no longer increases. It is referred to as a hill climbing method, because it depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point. Perturb and observe is the most commonly used MPPT method due to its ease of implementation. Perturb and observe method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted.

4.10 Single Phase Inverter:

Single phase inverter is used to convert 12V DC input as 230V AC output. Here double stage single phase inverter is used. At first stage a high frequency push pull converter which converts 12V to 400V DC is used. At second stage, H bridge inverter converts 400V DC into 230V/50Hz AC. The inverter receives its input from the battery and the input dc voltage is converted into ac voltage in two steps as described above.

4.11 Battery:

The battery is being charged up to 13.5V. In case, solar panel fails to supply power, the load will be supplied by the battery that was charged, earlier. Here 12V/42A battery is used.

CHAPTER 5
RESULTS AND DISCUSSION

This chapter investigates the robustness of the developed Grid Connected PV system under different input-output conditions *i.e.* input irradiance, islanding condition, different faults etc. Further performance of 'P&O' and 'IC' based MPPT techniques are investigated under various environmental conditions by changing the input/output parameters. It also presents the detailed experimental investigation for developed laboratory prototype of 200 watt 'P&O' based PV system.

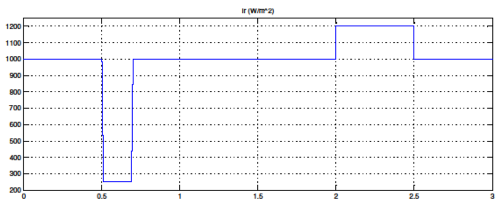
A. SIMULATION RESULTS

5.1 Operation under Step decay and rise in Irradiance

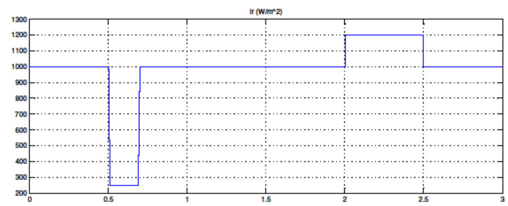
To validate the robustness of the developed PV system and its MPPT control, it is tested under step decay and rise in input irradiance as shown in Fig. 33(a). The MPPT algorithms effectively track the maximum power point when there are sudden changes in the environmental conditions. These results are also captured for both MPPT techniques *i.e.* 'P&O' and 'IC' technique.

Simulation results in Fig. 5.1 and Fig. 5.2 shows the input irradiance, PV Output Voltage, PV output current, PV output power, dc voltage, grid voltage, grid current, grid ac power under step changes in irradiance with Vref step size of 10V. Here the irradiance level is initially set to 1000W/m^2 and then a step change to input irradiance is commanded to 240W/m^2 at time t=0.5s. This low irradiance condition is kept for around 0.3 second. At time t=2 s, a step rise to input irradiance is commanded to 1200W/m^2 for a duration of 0.5s as shown in Fig. 5.1(a). For these step changes in irradiance, the MPPT tracks the maximum power point. As can be seen from the waveforms of Fig. 5.1(d) for irradiance level of 1000W/m^2 output power is near to 100kW while irradiance level of 240W/m^2 corresponds to output power of 20kW while for irradiance level of 1200W/m^2 maximum power which can be extracted from the PV module is near to 122kW. As can be seen from below results the implemented control algorithms effectively track the sudden changes in irradiance effectively.

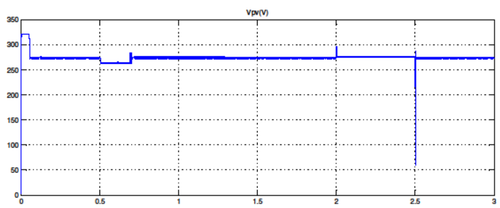
The difference in two control algorithms response is visible from PV voltage (Vpv) waveforms of Fig. 5.1(b). In case of P & O algorithm, Vpv seems to be having more oscillations or ripple during the change of input irradiance. By comparing these two waveforms it can be concluded that the Perturb and Observe algorithm has more oscillations near the MPP than that for Incremental Conductance. Fig. 5.1 shows the comparative response of IC and P &O based system for step change in irradiance.



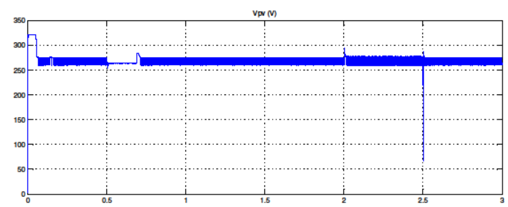
(a) Input Irradiance (IC control)



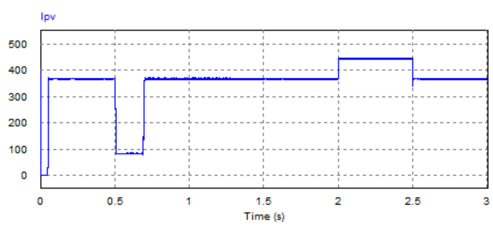
(a) Input Irradiance (P&O control)



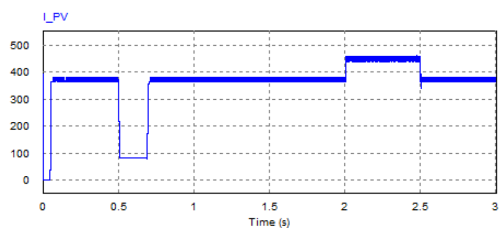
(b) PV output Voltage (IC control)



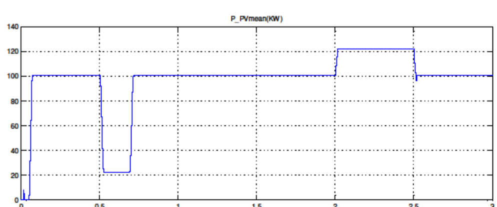
(b) PV output Voltage (P&O control)



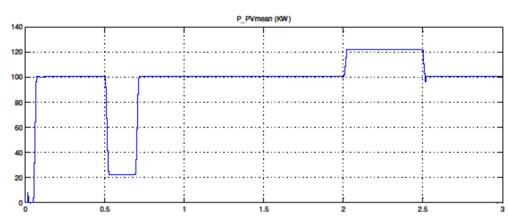
(c) PV output Current (IC control)



(c) PV output Current (P&O control)

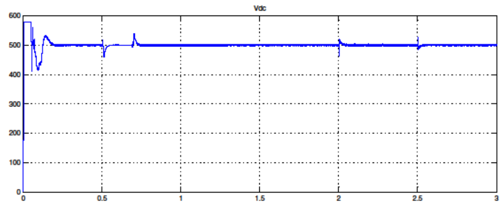


(d) PV output Power (IC control)

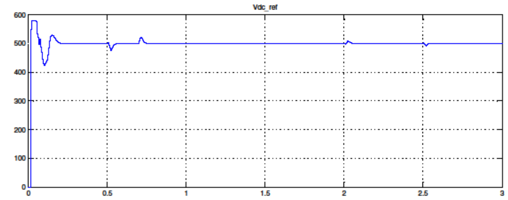


(d) (P&O control)

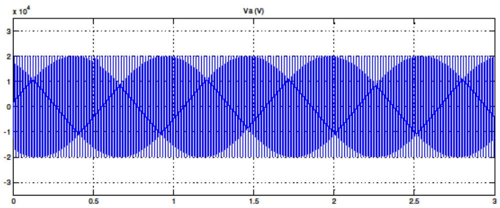
Figure 5.1 Response of IC and 'P&O' Algorithm for Step change in Irradiance



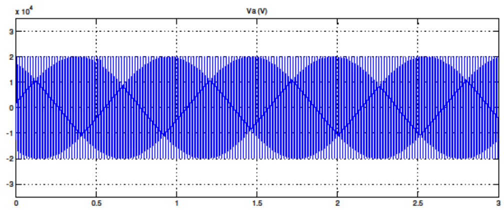
(a) dc Voltage(IC control)



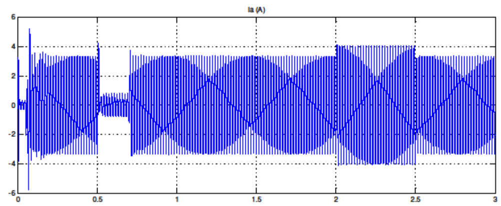
(a) dc Voltage(P&O control)



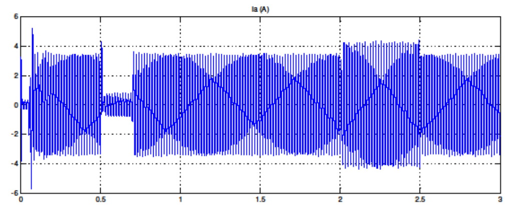
(b) Grid Voltage(IC control)



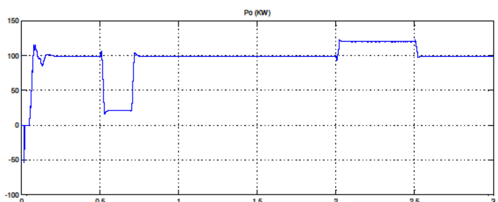
(b) Grid Voltage(P&O control)



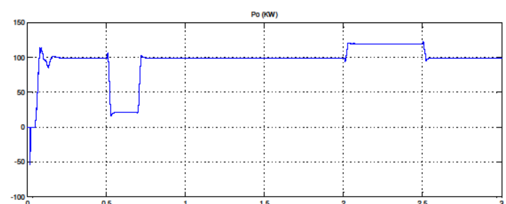
(c) Grid Current(IC control)



(c) Grid Current(P&O control)



(d) Grid Power(IC control)

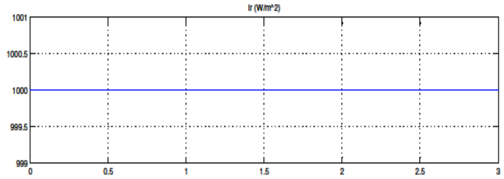


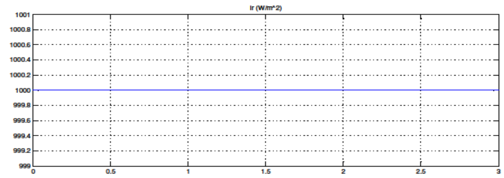
(d) Grid Power(P&O control)

Figure 5.2 Response of IC and 'P&O' Algorithm for Step change in Irradiance

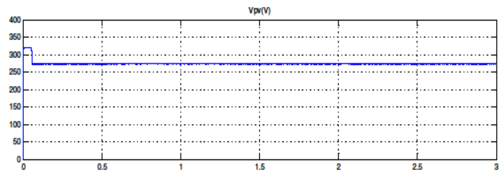
5.2 Performance under Single Phase to Ground Fault condition

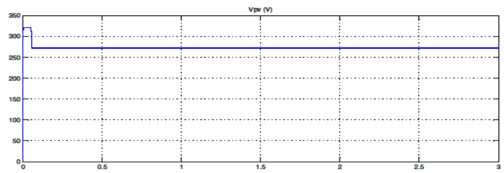
To validate the robustness of the developed system and its control, a single phase to ground fault is applied near to grid, while keeping the irradiance constant of 1000W/m^2. The fault is applied at t=1.5s for a duration of 0.5s. As can be seen from Fig. 5.3(c) and Fig. 5.3(d), that during the fault, power reduces and current increases, but both are within the safe limit, which validates the developed controls.



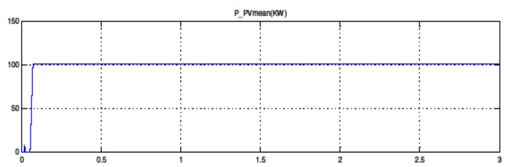


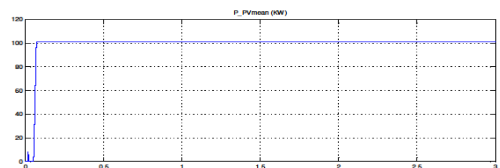
(a) Input Irradiance (IC control) (a) Input Irradiance (P&O control)



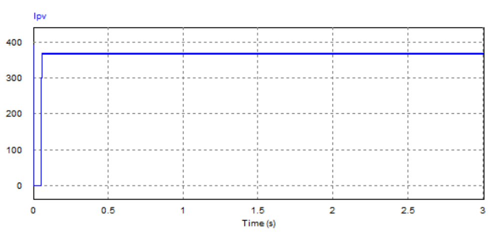


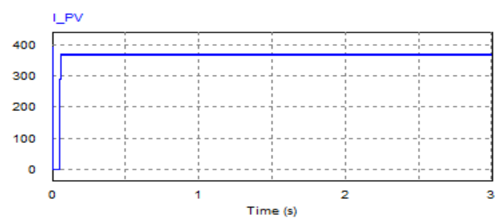
(b) PV output Voltage (IC control) (b) PV output Voltage (P&O control)



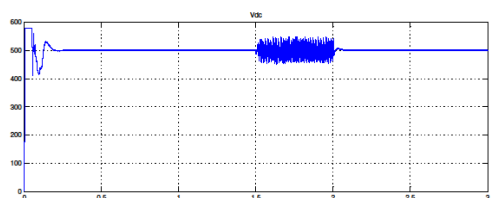


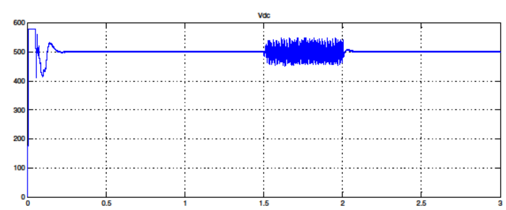
(c) PV output Power (IC control) (c) PV output Power (P&O control)



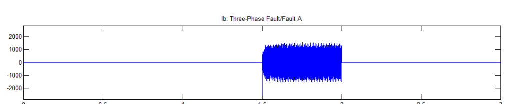


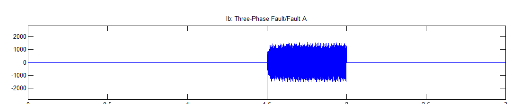
(d) PV output Current (IC control) (d) PV output Current (P&O control)





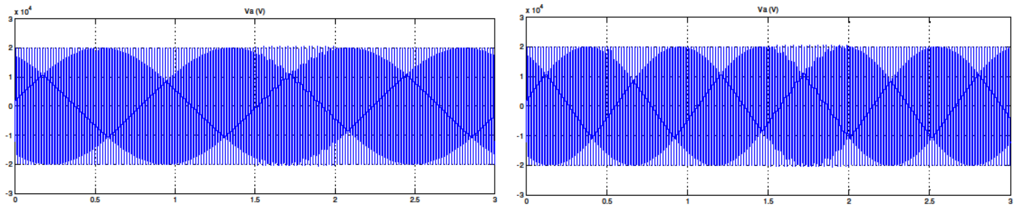
(e) dc Voltage(IC control) (e) dc Voltage(P&O control)



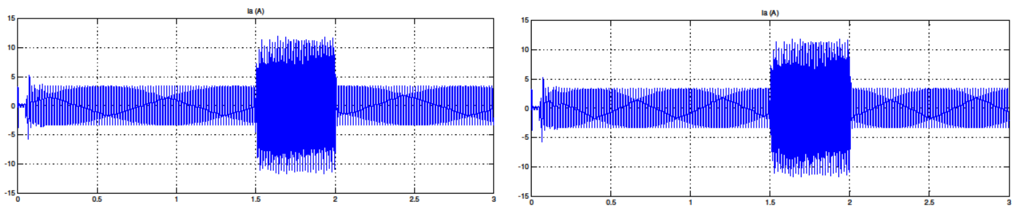


(f)Fault Current(IC control) (f) Fault Current(P&O control)

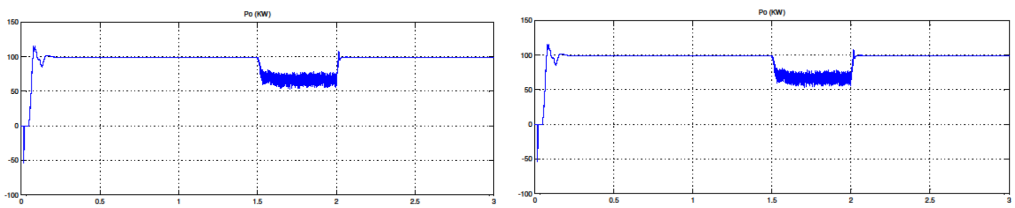
Figure 5.3 Response of IC and 'P&O' Algorithm for Single Phase to Ground Fault



(a) Grid Voltage(IC control) **(a) Grid Voltage(P&O control)**



(b) Grid Current (IC control) **(b) Grid Current (P&O control)**

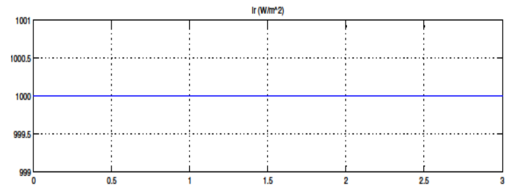


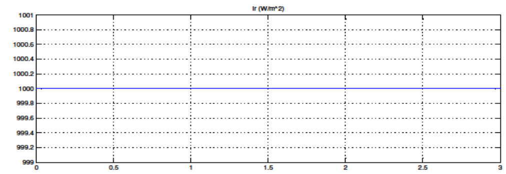
(c) Grid Power (IC control) **(c) Power (P&O control)**

Figure 5.4 Response of IC and ‘P&O’ Algorithm for Single Phase to Ground Fault

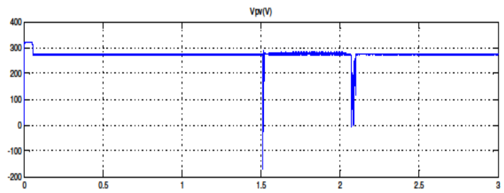
5.3 Performance under Two-Phase to ground Fault condition

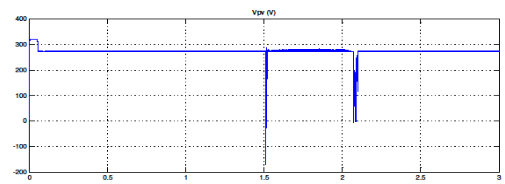
To validate the robustness of developed system we introduce a Two-Phase to ground fault near the grid is applied at t=1.5s for a duration of 0.5s. As can be seen in Fig. 5.5, and 5.6, when two-phase to ground fault occurs for Phase A and Phase B respective currents increases due to the short circuit and output power is unstable but both are within the safe limit.



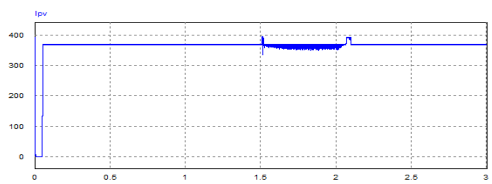


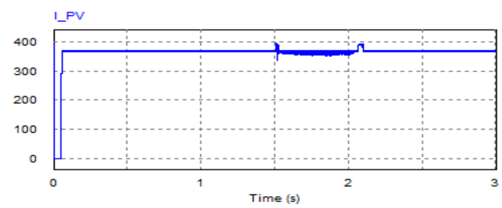
(a) Input Irradiance (IC control) **(a) Input Irradiance (P&O control)**



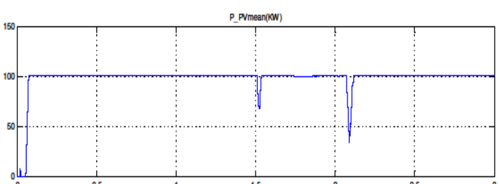


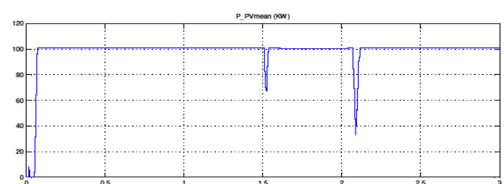
(b) PV output Voltage (IC control) **(b) PV output Voltage (P&O control)**



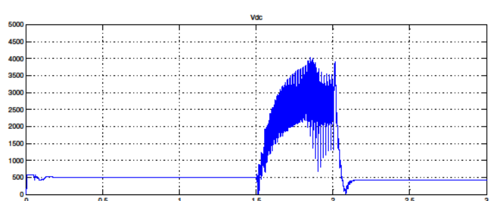


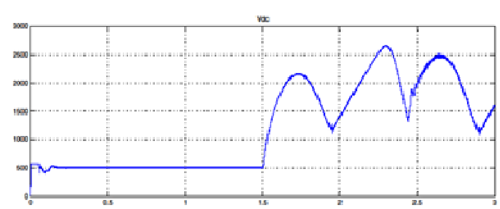
(c) PV output Current (IC control) **(c) PV output Current (P&O control)**





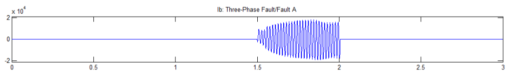
(d) PV output Power (IC control) **(d) PV output Power (P&O control)**

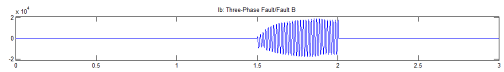




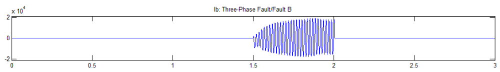
(e) dc Voltage (IC control) **(e) dc Voltage (P&O control)**

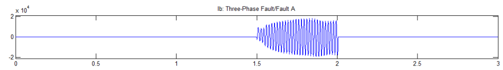
Figure 5.5: Response of IC and 'P & O' Algorithm for Two-Phase to ground Fault



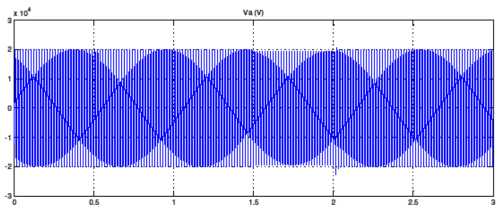


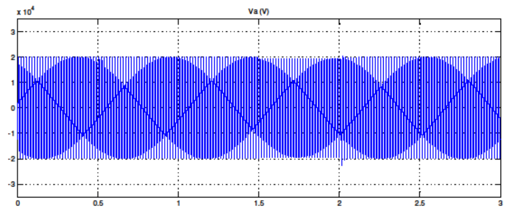
(a)Fault Current in phase A(IC control) **(a) Fault Current in phase A (P&O control)**



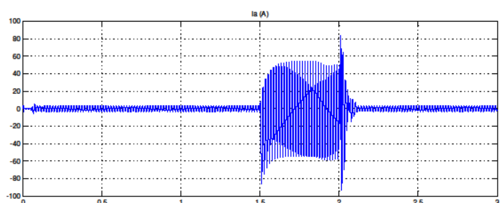


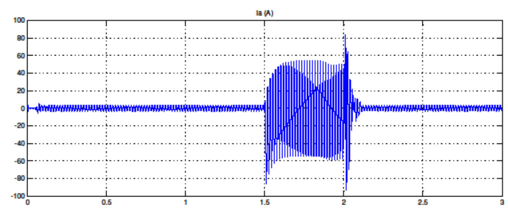
(b)Fault Current in phase B(IC control) **(b) Fault Current in phase B (P&O control)**



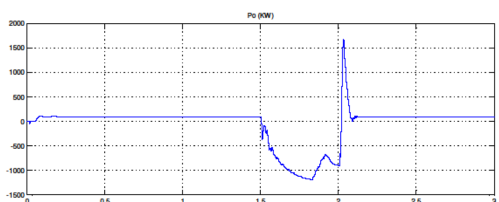


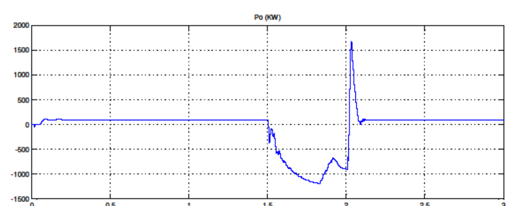
(c) Grid Voltage (IC control) **(c) Grid Voltage (P&O control)**





(d) Grid Current (IC control) **(d) Grid Current (P&O control)**





(e) Grid Power (IC control) **(e) Grid Power (P&O control)**

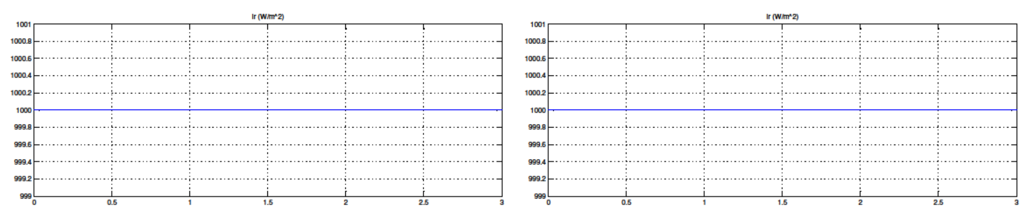
Figure 5.6 Response of IC and 'P&O' Algorithm for Two-Phase to ground Fault

5.4 Islanding Condition

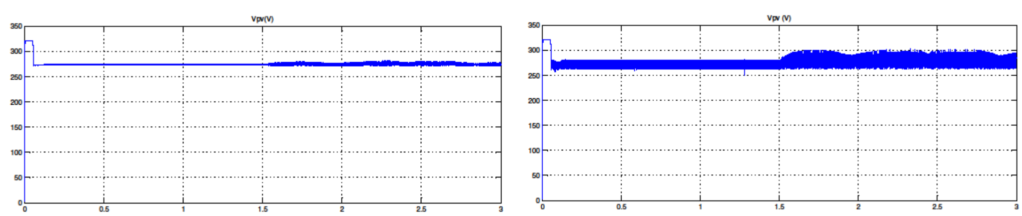
This is one of the sever condition for grid connected application. A grid connected PV system feeds the transformed electrical power to the utility grid. In order to feeding the power to the grid the PV system output voltage frequency should match with the utility supply and also the phase. As the PV system is connected to the grid it determines the phase and frequency of the grid. Any changes in the grid supply voltage frequency and phase are tracked by implementing the Phase Lock Loop for Inverter output voltage.

Islanding condition is achieved using circuit breaker in between the grid and the PV system output terminals. The circuit breaker default state is closed and when islanding condition is to be introduced at that time instant the circuit breaker is made to open state. So when this open state occurs there is no reference for inverter control algorithms which can result in unpredictable output voltage waveform. Various PV systems are parameters are captured to analyse this fault condition.

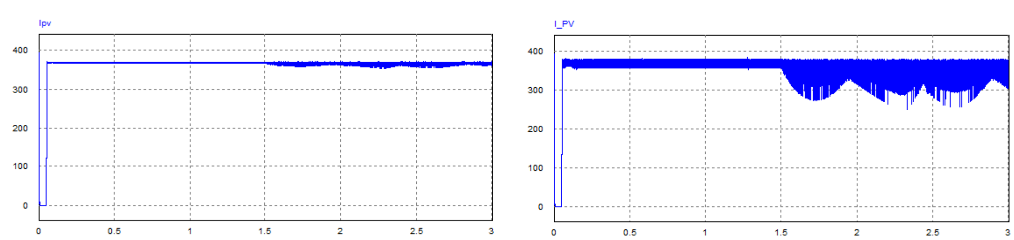
As can be seen from Fig 5.7 and 5.8 when islanding condition occurs, amplitude of output voltage of the system jumps to higher value. This sudden change is due to output load becomes zero and other major reason is loss of reference signal for PLL operation. Islanding issue is one of the major concerns which needs to be taken care of while designing a grid connected PV system.



(a) Input Irradiance (IC control) **(a) Input Irradiance (P&O control)**

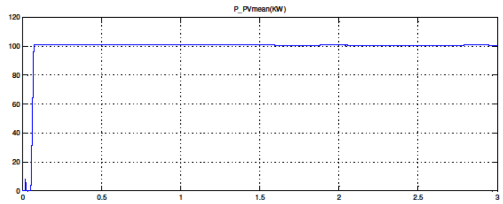


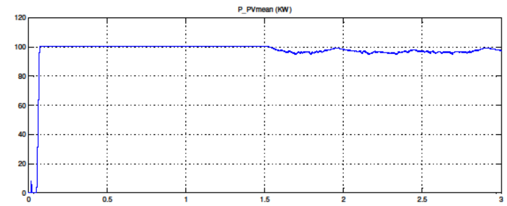
(b) PV output Voltage (IC control) **(b) PV output Voltage (P&O control)**



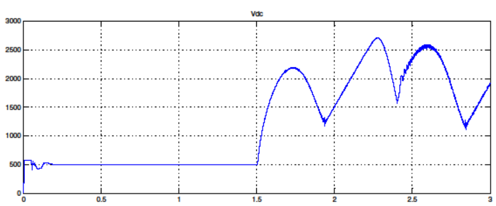
(c) PV output Current (IC control) **(c) PV output Current (P&O control)**

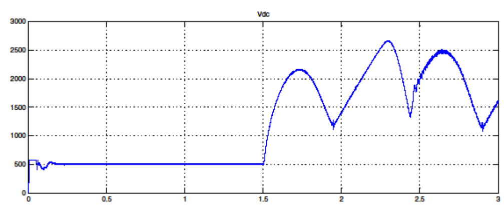
Figure \5.7 Response of IC and 'P&O' Algorithm for Islanding Condition



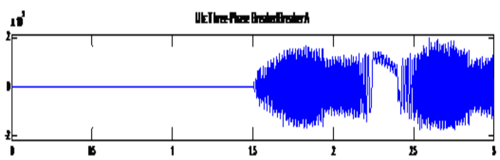


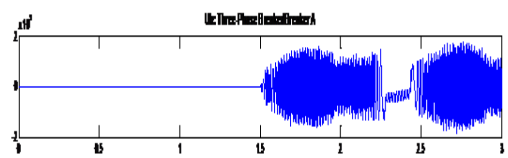
(d) PV output Power (IC control) **(d) PV output Power (P&O control)**



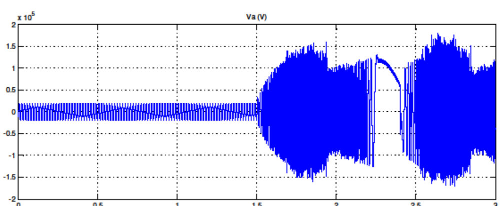


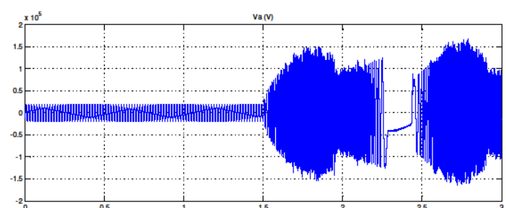
(e) dc Voltage (IC control) **(e) dc Voltage (P&O control)**



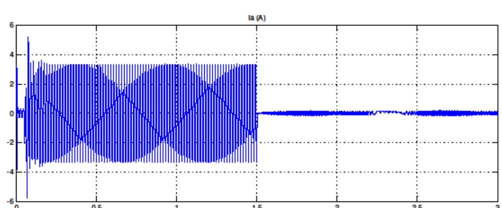


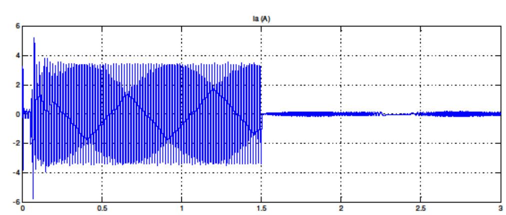
(f) CB Voltage **(f) CB Voltage**



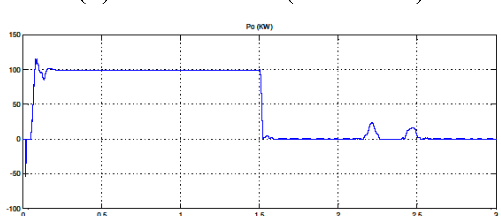


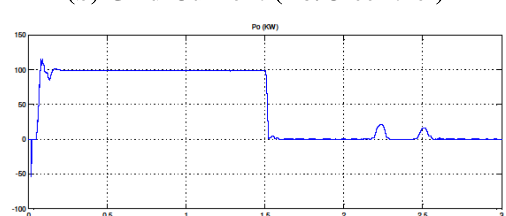
(a) Grid Voltage (IC control) **(a) Grid Voltage (P&O control)**





(b) Grid Current (IC control) **(b) Grid Current (P&O control)**





(c) Grid Power (IC control) **(c) Grid Power (P&O control)**

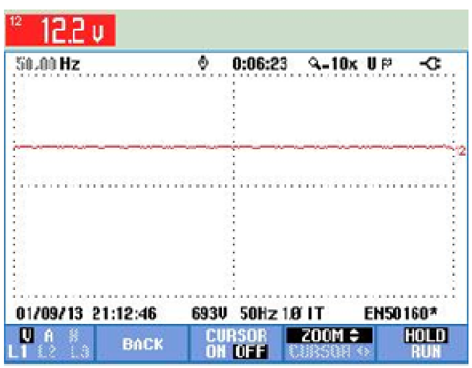
Figure 5.8 Response of IC and 'P&O' Algorithm for Islanding Condition

B. INVESTIGATION ON HARDWARE LABORATORY PROTOTYPE

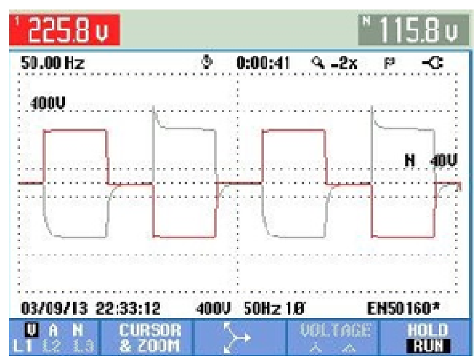
In this section, a detailed investigation on the developed hardware laboratory prototype of proposed 200 watt 'P&O' based PV system is carried out to validate the developed system and its MPPT control under different conditions. The system is a microcontroller based PV system which uses Perturb & Observe control algorithm as explained in detail in previous chapter 4. The power level strategy of this system is similar to one explained in the thesis.

5.5.1 Response for Resistive Load with MPPT Control

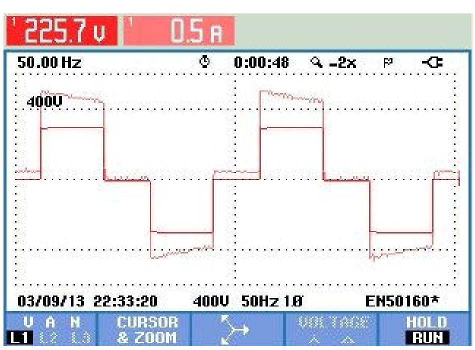
Various responses of output PV voltage, inverter output voltage, load voltage and current, phasor diagram of load voltage and current, Harmonic table for load voltage and current for the developed 'P&O' based PV system with resistive load of 120 watts are presented in Fig. 5.9.



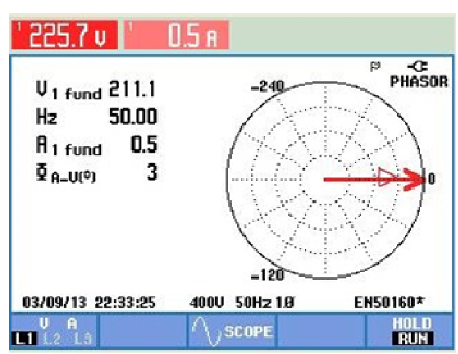
(a) PV Output Voltage



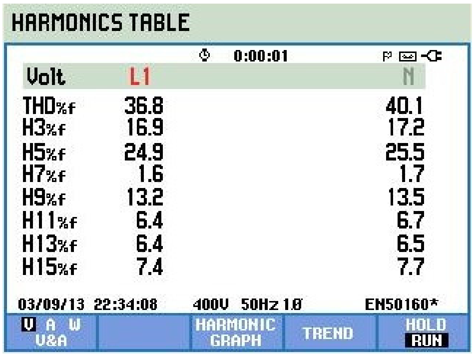
(b) Inverter Output Voltage



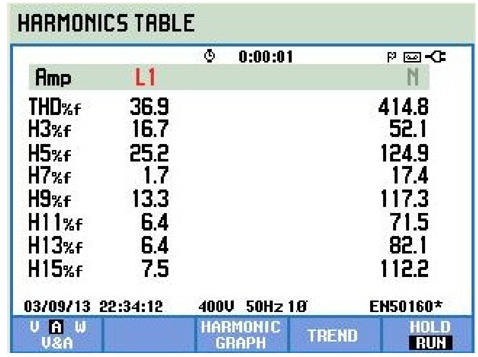
(c) Load Voltage and Current



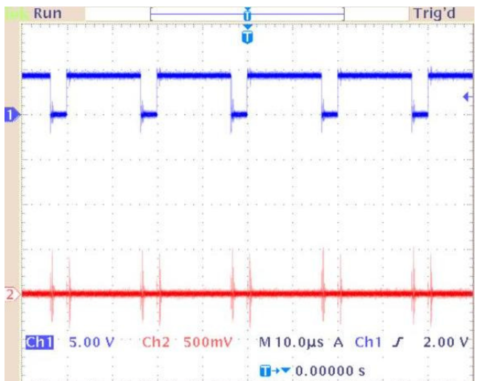
(d) Load Voltage Phaser



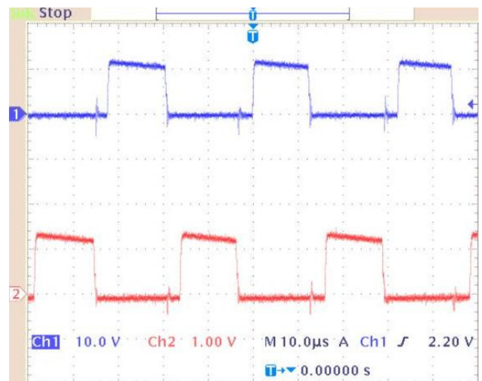
(e) Output Voltage Harmonic Table



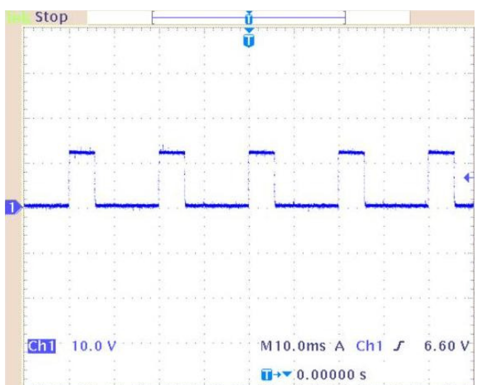
(f) Output Current Harmonics Table



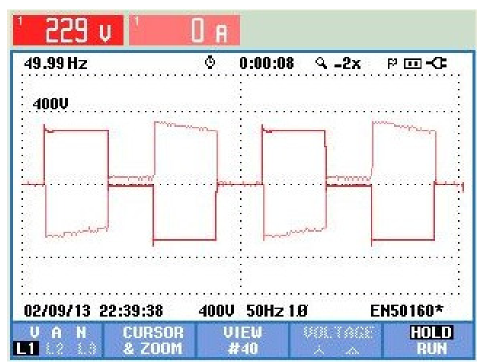
(g) Buck-Boost gate Pulse



(h) Push-Pull Converter gate pulse



(i) Inverter Gate Pulse



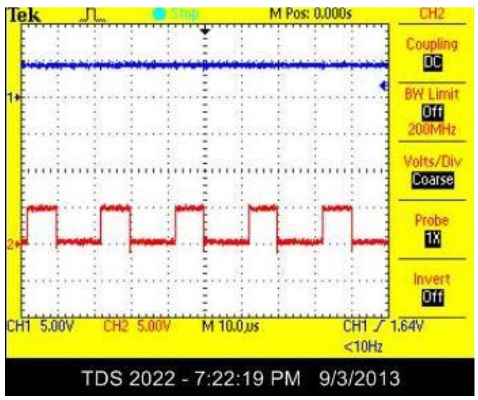
(j) Transients in Vo & Io

Figure 5.9 Response of the 'P&O' based PV system Laboratory Prototype with Resistive load of 120 watt

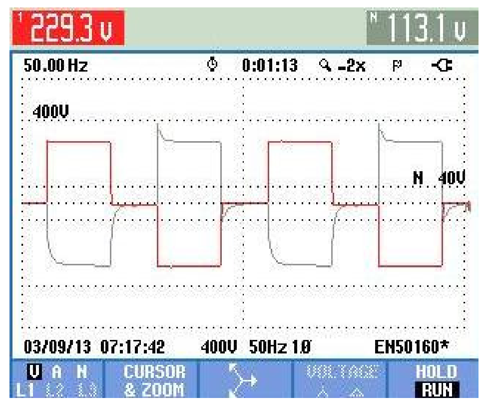
Inverter output voltage is quasi square in shape and it is in phase with the output current as output load is resistive in nature. Above results shows the system output voltage and current phasors and harmonic contents of respective signals. It can be observed from the plot that phase difference between voltage and current is near to 0°. Crest factor for output voltage and current is 1.33 and 1.55 respectively. The total harmonic distortion content for load voltage is 36.8% while that for load current is 36.9% of fundamental component.

5.5.2 Response for Inductive Load with MPPT Control

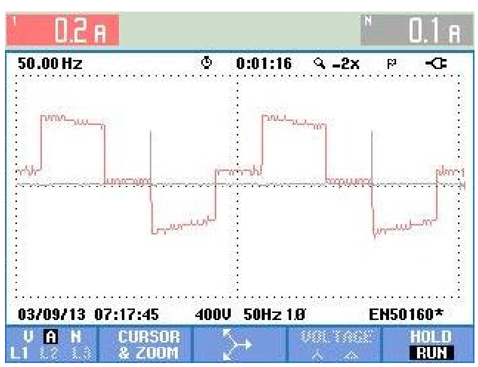
Various responses of output PV voltage, inverter output voltage, load voltage and current, phasor diagram of Vo and Io, Harmonic table for Vo and Io for the developed 'P&O' based PV system with inductive load of R=40 watts and L=100mH/10A is presented in Fig. 5.10.



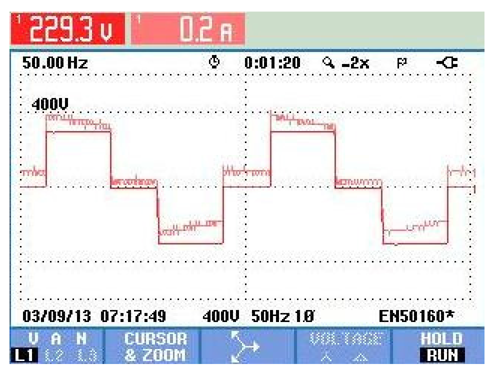
(a) Boost Converter Gate Pulse



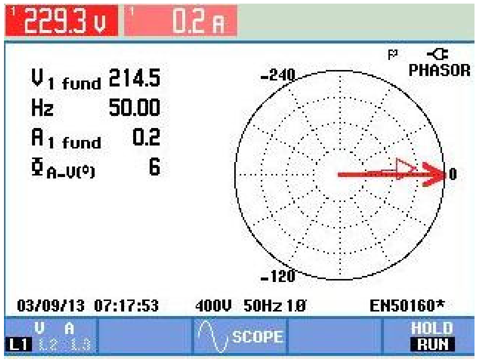
(b) Load Voltage

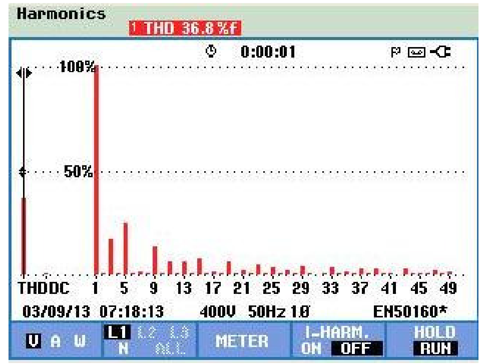


(c) Load Current



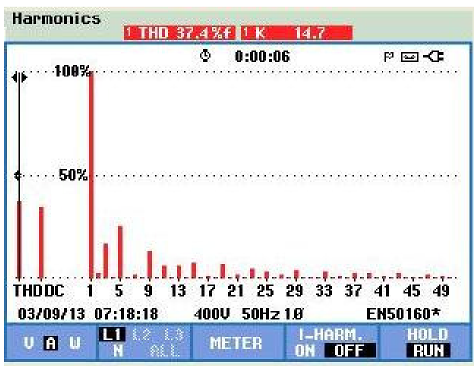
(d) Phase Load Voltage and current

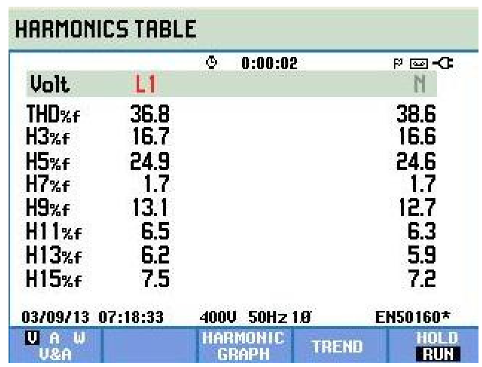




(e) Phasor diagram of Vo& Io

(f) Load Voltage Harmonics





(g) Load current Harmonics

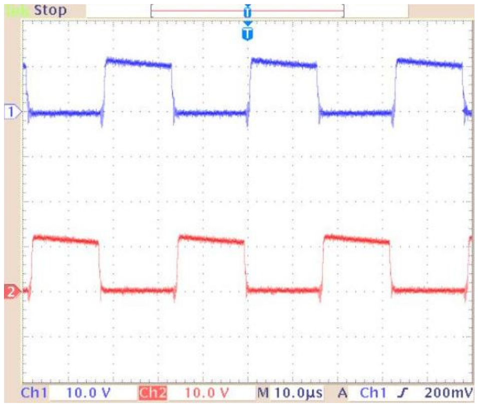
(h) Harmonic table for Voltage

Figure 5.10 Response of the 'P&O' based PV system Laboratory Prototype with RL load

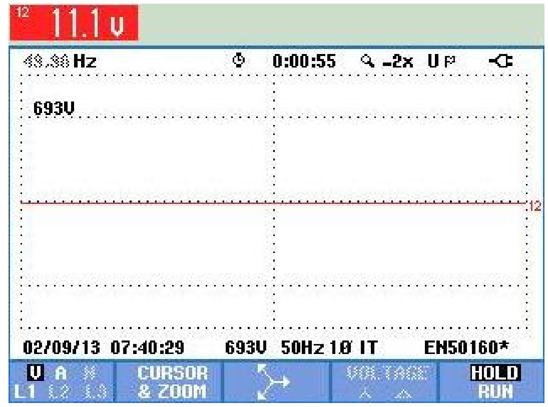
It can be verified from the Fig. 5.9(f) and Fig. 5.11(g) that THD content for load current in case of inductive load is 0.5 % more as compare to resistive load. From Fig. 5.9(d) and Fig. 5.10(e), it can be seen that with resistive load phase angle between voltage and current is almost zero degree whereas with RL load it becomes 6 degree. Also, distortion factor in waveforms of voltage and current with inductive load is more as compare to resistive load.

5.5.3 Response for Resistive Load without MPPT Control

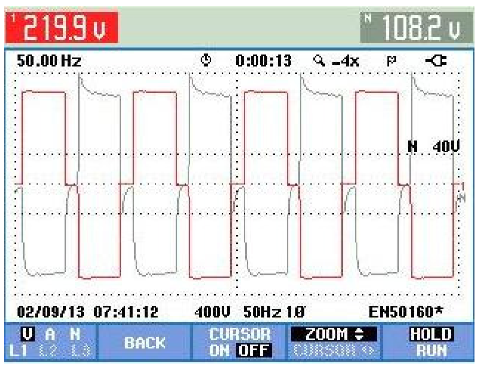
Various responses of output PV voltage, inverter output voltage, load voltage and current, phasor diagram of Vo and Io, Harmonic table for Vo and Io for the developed PV system without MPPT control for resistive load of R=40 watts are presented in Fig. 5.11.



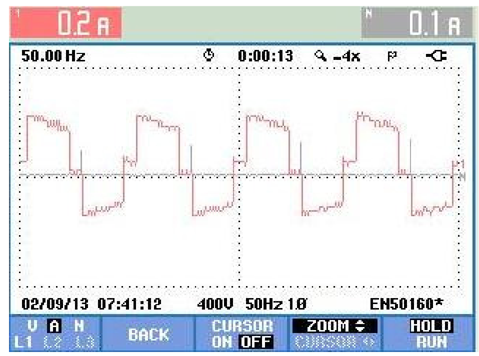
(a) Push-Pull Converter Gate Pulse



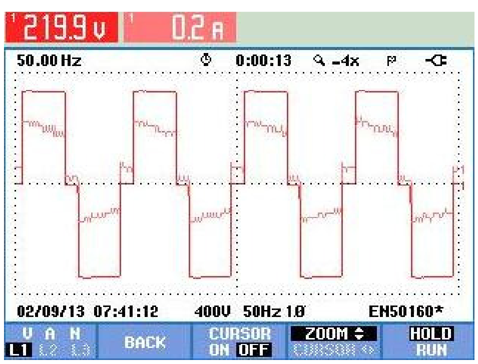
(b) Input Solar Voltage



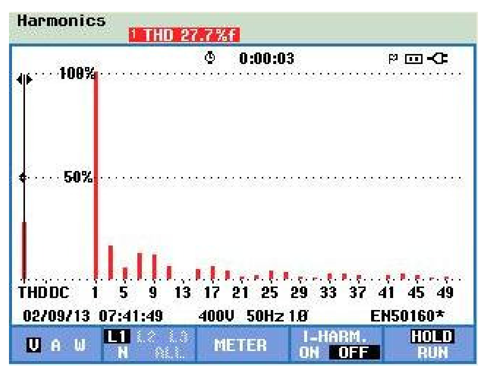
(c) Load Voltage



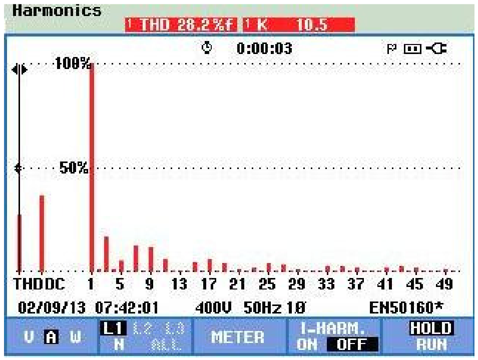
(d) Load current



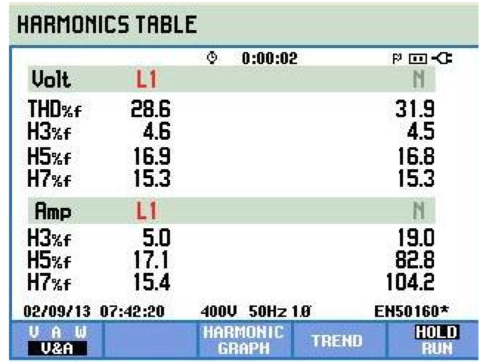
(e) Phasor diagram of Vo& Io



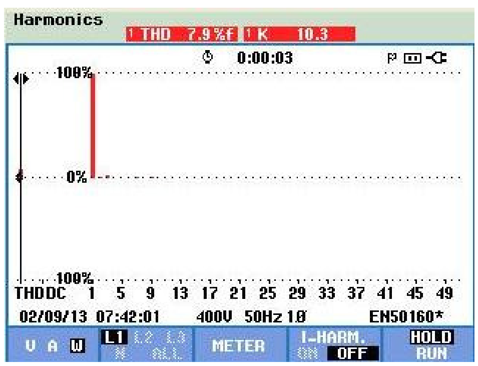
(f) Load Voltage Harmonics



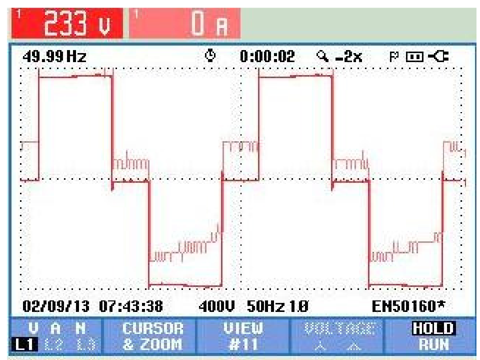
(g) Load current Harmonics



(h) Harmonic table for Vo & Io



(i) Harmonic table for Po



(j) Vo and Io Transients

Figure 5.11 Response of the Laboratory Prototype for RL load without MPPT control

On comparing experimental results of the laboratory prototype with & without MPPT control from Fig. 5.9, and Fig. 5.11, it is found that PV cell output voltage with MPPT control is 12.2 V; whereas without MPPT control was 11.1 V, see Fig. 5.9(a) and Fig. 5.11(b). It must be noted that readings for both the conditions were taken at same time for validation of developed MPPT control technique. Similarly, it was found that load voltage and current with MPPT control is 225.8 V and 0.5 A respectively (see Fig. 5.9(b), 5.11(c)); whereas without MPPT control load voltage and current is 219.9 V & 0.2 A respectively (see Fig. 5.11(c), 5.9(d)). Thus, above experimental results validates the effectiveness of the developed P&O MPPT algorithm.

CHAPTER 6

CONCLUSION

In this work, a complete grid connected PV system is developed in the MATLAB/Simulink and PSIM environment. Two MPPT algorithms are developed using PSIM which are used to maximize the energy yield from the PV module. This thesis reviews most of the MPPT algorithms which find MPP which is near to theoretical value. “Perturb & Observe” and “Incremental Conductance” algorithms were selected for further analysis for reasons like implementation simplicity, effectiveness and more energy yield. Based on the investigations made from the simulations and experimentation results following important point can be concluded:

- The developed PV system has been tested for the various input/output conditions and the results are in line with the performance characteristics of a grid connected PV system which is reviewed in the literature.
- The developed MPPT algorithms track the MPP under standard input variation conditions. Using these algorithms dynamic performance of a PV system was validated by varying the input parameter which is solar irradiance level. The variation in solar irradiance level is of step type, ramp-up and ramp down type.
- The selected MPPT techniques effectiveness was also studied by comparing the efficiency of the PV system under condition with and without the MPPT controller. It was observed that the power extraction form PV module improved by around 5% with use of MPPT algorithms under constant irradiance condition.
- From the experimental results, it was found that PV cell Voltage and Power; Load Voltage and Load Current was more with MPPT as compare to without MPPT, which validates the robustness of the developed MPPT.
- The PV system behavior under different grid fault conditions and islanding conditions is simulated and respective results are presented in the thesis. The fault conditions can be detected by monitoring the phase current and respective fail safe action can be triggered in case of practical implementation.

Future Work

In consideration with the literature reviewed and present scope of this thesis, following areas can be further worked on to develop an efficient and practically implementable PV system:

- The basic disadvantage both the ‘hill-climbing’ techniques which are analyzed in this thesis is the oscillations around the MPP. So the further investigation needs to be done to come over this drawback. One of the implementation related to this drawback back be variable step size.
- The performance of current PV system should investigated using the various intelligent MPPT techniques such as Fuzzy logic based or Neural Network based.
- Current thesis scope was to analyze a MPPT technique for PV system with a single module. If there are multiple PV modules then shading effects comes into consideration. In such case the MPPT algorithms will fail to track the MPP so different algorithms or modifications required to current algorithms needs to be analyzed further.
- As per practical implementation point of view, a PV system should be ‘fail safe’ which means it should take care of various fault conditions by triggering corrective actions in case of fault. For this purpose various fault conditions which can occur for a Grid connected PV system should be simulated and based on simulation results the corrective action for each fault condition needs to be identified.
- As the system under consideration is a grid connected application the islanding situation is one of the major trouble these application faces. In order to overcome islanding issue the inverter PLL control algorithms needs to be developed such that whenever there is occurrence of islanding condition output frequency should be at default frequency.

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