Multifunctional photovoltaic module with maximum power point tracking,islanding detection and power quality enhancement capabilities

Major Project Report

Submitted in partial fulfillment of the requirements for the

Degree of

MASTER OF TECHNOLOGY
IN
ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

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I, **Palash Kandarp Mankad** , Roll No.**12MEEE18**, give undertaking that the Major Project entitled **"Multifunctional photovoltaic module with maximum power point tracking, islanding detection and power quality enhancement capabilities"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Electrical Power Systems** of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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Certificate

This is to certify that the Major Project Report entitled **"Multifunctional photovoltaic module with maximum power point tracking, islanding detection and power quality enhancement capabilities"** submitted by **Mr. Palash K. Mankad (12MEEE18)** towards the partial fulfillment of the requirements for the award of the degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him/her under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Today distributed generation is considered one of the most anticipated mode of power generation for small industries and residences. Solar power is abundant almost everywhere across the globe which has led the non-conventional source to be the most looked after source today. During the development of more efficient solar cell, it is needed to fetch maximum power from the panels as well so that one can take advantage of the available solar potential to the fullest. Several methods have been adopted to utilize maximum power from the solar cell. One method is to track the path of sun with stepper motors and self cleaning arrays. Another method is to adjust the load on the PV array such that it generates maximum power. Generally, the method mentioned earlier is more complex and costly, and requires more maintenance and hence load adjustment method or Maximum power point tracking method has been widely accepted. This project will deal with maximum power point tracking of array and islanding detection and connection to the grid, through an inverter. Various algorithms have been adopted to find the maximum power point of the PV array. Some of the classical algorithms have been compared and suitable algorithm will be selected. At the end, a prototype shall be developed which can be used as a PV inverter module with multiple capabilities.

Abbreviations

CV .... Constant Voltage
FF .... Fill Factor
GA .... Genetic Algorithm
MPPT .... Maximum Power Point Tracking
P&O .... Perturb and Observe
PLL .... Phase Lock Loop
PV .... Photovoltaic
PWM .... Pulse Width Modulation
VSI .... Voltage Source Inverter

Nomenclature

Short circuit current .... I_s
Critical resistance .... R_{cric}
Duty cycle .... D
Inductor L
Input Voltage .... V_{in}
Open circuit voltage .... V_{oc}
Optimal voltage .... V_{op}
Output voltage .... V_o
Parasitic capacitance .... C_p
Switching frequency .... f_s
Voltage drop across diode .... V_d
Voltage drop across MOSFET .... V_{trans}

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Chapter 1

Introduction

1.1 PV systems

In the era of renewable energy sources, Photovoltaic (PV) solar panels to fetch solar energy has experienced a remarkable growth for past two decades in its widespread use from stand alone to utility interactive photovoltaic systems. A solar panel is used for the direct conversion of solar energy into elecrtical energy and generation of the electrical energy depends on solar radiation, temperature and the voltage produced in the module. The solar power thus produced is used to directly feed small loads and sometimes an inverter is added to ensure the grid connectivity of the module to make it work as a stand alone system.

1.2 IV curves of a PV array

Owing to their bad luck solar panels face two major problems: First problem is the efficiency of conversion (around 17-20 %), amount of electric power generated by solar arrays changes continuously with weather conditions and hence it has very low efficiency. Moreover, the solar cell has non linear V-I characteristic (Fig 1.1) and it varies with irradiation and temperature.

The I-V (current-voltage) curve of a PV string (or module) depicts its energy

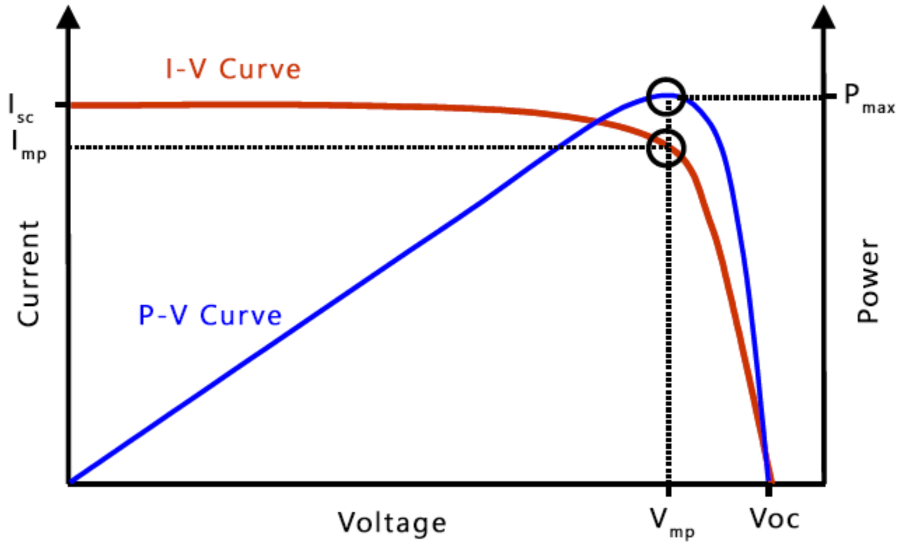

Figure 1.1: IV and PV curves of a photovoltaic device[1]

conversion capability at the existing conditions of irradiance (light level) and temperature. Conceptually, the curve represents the combinations of current and voltage at which the string could be operated or loaded, if the irradiance and cell temperature could be held constant. Figure 1.1 shows a typical I-V curve, the power-voltage or P-V curve that is computed from it, and key points on these curves. Referring to Fig1.1, the span of the I-V curve ranges from the short circuit current (I_{sc}) at zero volts, to zero current at the open circuit voltage (V_{oc}). At the knee of a normal I-V curve is the maximum power point (I_{mp}, V_{mp}), the point at which the array generates maximum electrical power. In an operating PV system, one of the jobs of the inverter is to constantly adjust the load, seeking out the particular point on the I-V curve at which the array as a whole yields the greatest DC power. At voltages well below V_{mp}, the flow of solar-generated electrical charge to the external load is relatively independent of output voltage. Near the knee of the curve, this behaviour starts to change. As the voltage increases further, an increasing percentage of the charges recombine within the solar cells rather than flowing out through the load. At V_{oc}, all of the charges recombine internally. The maximum power point, located at the knee of the curve, is the (I-V) point at which the product of current and voltage reaches

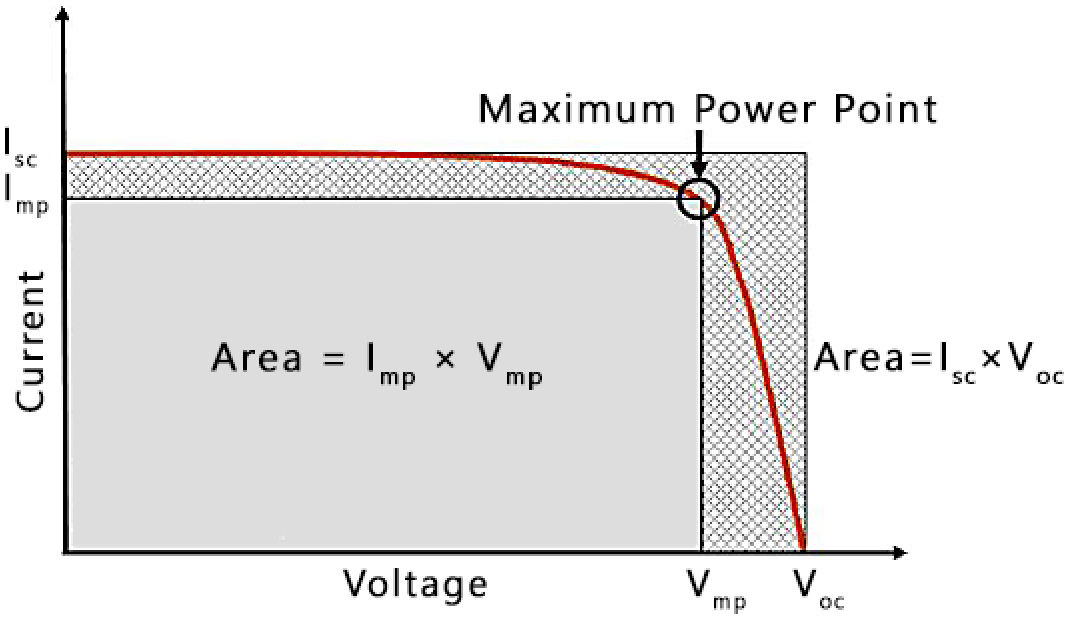

Figure 1.2: Fill factor[1]

its maximum value. The fill factor (FF) of a PV module or string is an important performance indicator. It represents the square-ness (or rectangularity) of the I-V curve, and is the ratio of two areas defined by the I-V curve, as illustrated in Fig1.2.

Although physically unrealizable, an ideal PV module technology would produce a perfectly rectangular I-V curve in which the maximum power point coincided with (I_{sc}, V_{oc}), for a fill factor of 1. This fill factor is very much important. If the I-V curves of two individual PV modules have the same values of I_{sc} and V_{oc}, the array with the higher fill factor (squarer I-V curve) will produce more power. Also, any impairment that reduces the fill factor will reduce the output power.

1.3 Problem Identification

The solar energy is abundant across the globe (1 kW/m^2 of overall power density), but the technology available today can only utilize a part of it. Photovoltaic cells are the most developed technology to convert the solar energy directly into a usable energy like electricity. However, the efficiency of conversion is still low compared with other technologies (4 to 30 %). The highly efficient solar cells are still under development, especially using different solar energy concentration techniques. And as it is well known, electronic converters are essential for the PV systems when it is necessary to convert electric energy into those quantities that match with most electric devices or public grid for instance. So, for the effectiveness, as in cost, reliability and performance, we require not only highly efficient solar cells but optimal electronic devices are also required.

Today the major drawback of photovoltaic electricity is its high price. With regards to bulk power generation, the PV system has never been cost-effective. However, in small-scale consumption such as in residential buildings or small commercial buildings, the competitiveness of PV electricity is improving. While the initial investment into a PV system demands quite big capital investment of money, operation and maintenance may require almost nothing.

Another advantage is that PV arrays are available in the range of a few watts up to several megawatts due to their modular design. That is why PV arrays can be easily expanded to meet growing electricity demand, although the electronics in the system may need some modifications.

1.4 Objective of dissertation

The principal objective of this work is to develop a practical, reliable and cost-effective solution for a module scale inverter that could be connected directly into the grid network and can work as a stand alone system. Pursuing this, following three main objectives arise:

a. Study all technologies suitable for module level PV inverters.

b. Select one of these technologies and produce a prototype.

c. Provide a clear technical outlook for the next steps of improvement of the module.

To achieve these objectives, selection of one from the various topologies in the desired scale must be made and using the simulation softwares their outcomes must be analyzed so that the selected solutions can be implemented and experimented on. Outcome of this project should be a developed prototype which can be implemented to use as a grid connected module with multiple functionalities.

1.5 Thesis organisation

Chapter 2

Literature survey

- **Mohammed A. Elgendy, Bashar Zahawi,David J. Atkinson, Assessment of Perturb and Observe MPPT Algorithm Implementation Techniques for PV Pumping Applications**[5]
  The paper presents a comprehensive analysis and experimental evaluation of the reference voltage perturbation and direct duty ratio perturbation techniques for implementing the P&O MPPT algorithm. The effects of the perturbation rate and step size on system behavior is being examined, the criteria for the choice of these parameters presented, and the energy utilization calculated at slow and rapidly changing weather conditions using an experimental setup. This provides detailed analysis of P&O method.

- **Slimane HADJI, Fateh KRIM, Jean-paul GAUBERT, Development of an algorithm of maximum power point tracking for photovoltaic systems using genetic algorithms**[8]
  This paper presents a novel GA (genetic algorithms) based method to carry out the maximum power point tracking (MPPT) based on the cell model. For that it is necessary to measure the open circuit voltage (V_{oc}) and short circuit current (I_s), then the proposed algorithm gives directly and rapidly the optimal voltage (V_{op}) so the duty cycle is adjusted.

- **R.Ramaprabha , V.Gothandaraman, K.Kanimozhi , R.Divya and B.L.Mathur, Maximum Power Point Tracking using GA Optimized Artificial Neural Network for Solar PV System**[7]
  In this paper improved modelling of solar photo voltaic array has been presented. To fetch the maximum power out of the PV array, GA technique is used. The optimized values of power and the corresponding voltage values for different insolation levels and temperatures have been used to train the ANN. Then the GA based offline trained ANN is used to provide the reference voltage corresponding to the maximum power for any environmental changes.

- **Md. Ali Azam,Syed Abdullah-AI-Nahid,Md. Ashfanoor Kabir, Shah Mahmud Hasan Chowdhury, Micro-controller based Maximum Power Tracking of PV using Stimulated Annealing Algorithm**[3]
  In this paper, a completely new algorithm based on Stimulated Annealing technique for MPPT is proposed to optimize stand alone PV panel operating point even under rapidly and significantly changing weather pattern. The proposed algorithm is as simple as traditional P&O and Hill-climbing algorithm, yet it can successfully encounter the oscillation problem and steady state error problem even under worst case scenario with efficiency more than 99.99%. The algorithm eliminates hardware complexity and can be implemented using programmable micro-controllers.

- **M. Dahmane,Bosche, A. EI-Hajjaji and X. Pierre, MPPT for Photovoltaic Conversion Systems Using Genetic Algorithm and Robust Control**[2]
  This paper proposes an algorithm of maximum power point tracking (MPPT) applied for photovoltaic (PV) power generation systems. The strategy of this algorithm considers the value of short circuit current to generate the current at the maximum power. In this work, the current reference is generated by genetic algorithm (GA).

- **Ming-Fa Tsai, Chung-Shi Tseng, and Yu-Hsiang Hung, A Novel MPPT Control Design for Wind-Turbine Generation Systems Using Neural Network Compensator**[4]
  This paper presents a novel maximum power point tracking (MPPT) algorithm in wind-turbine generation systems using neural network compensator based on the slope of the wind-turbine mechanical power versus rotation speed to avoid the oscillation problem and effect of uncertain parameters. Because the characteristics of the wind-turbine rotation speed is determined by the wind speed and air density conditions, the technologies of changing the location of the maximum power point must be developed in the applications of MPPT control in order to make the wind turbine generator get the optimal efficiency from wind energy at different operating conditions.

- **Vishal Vekhande and B. G. Fernandes, Module Integrated DC-DC Converter for Integration of Photovoltaic Source with DC Micro-grid**[9]
  This paper proposes a module integrated dc-dc converter for integration of a photovoltaic (PV) source with a dc distribution system. Current-fed topology is suggested to avoid limitations associated with large energy storage capacitor. The converter injects very low ripple, continuous current into the dc micro-grid. Effect of converter switching ripple at low insolation levels is analyzed.

- **Solmetric Corporation. Guide to interpreting i-v curve measurements of PV arrays.Application Note PVA-600-1.**[1]
  This guide is part of a series of application notes, videos and webinars designed to support users of the Solmetric PVA-600 PV Analyzer modules which talks about various characteristics of the PV arrays.

Chapter 3

Maximum power point tracking

3.1 General

Maximum power point trackers (MPPTs) play an important role in photovoltaic (PV) power systems because they maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency. Thus, an MPPT can minimize the overall system cost. MPPTs find and maintain operation at the maximum power point, using an MPPT algorithm. Many such algorithms have been proposed. However, one particular algorithm, the perturb-and-observe (P&O) method, claimed by many in the literature to be inferior to others, continues to be by far the most widely used method in commercial photovoltaic MPPTs.

In general,this operating point is not at the PV arrays MPP, which can be clearly seen in Figure 3.1. Thus, in a direct-coupled system, the PV array must usually be oversized to ensure that the loads power requirements can be supplied. This leads to an overly expensive system. To overcome this problem, a switch-mode power converter, called a maximum power point tracker (MPPT), can be used to maintain the PV arrays operating point at the MPP. The MPPT does this by controlling the PV arrays voltage or current independently of those of the load. If properly controlled by an MPPT algorithm, the MPPT can locate and track the MPP of the PV array.

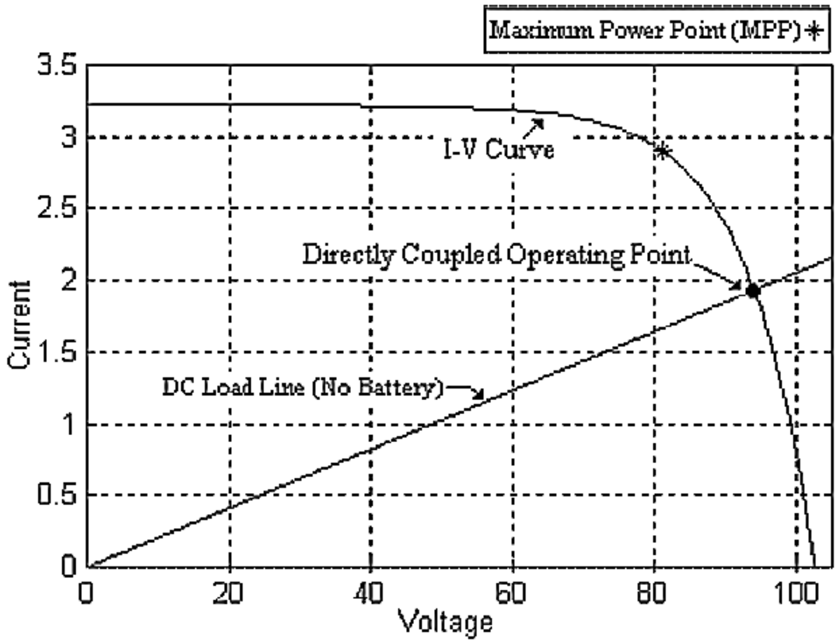

Figure 3.1: Typical currentvoltage curve for a PV array

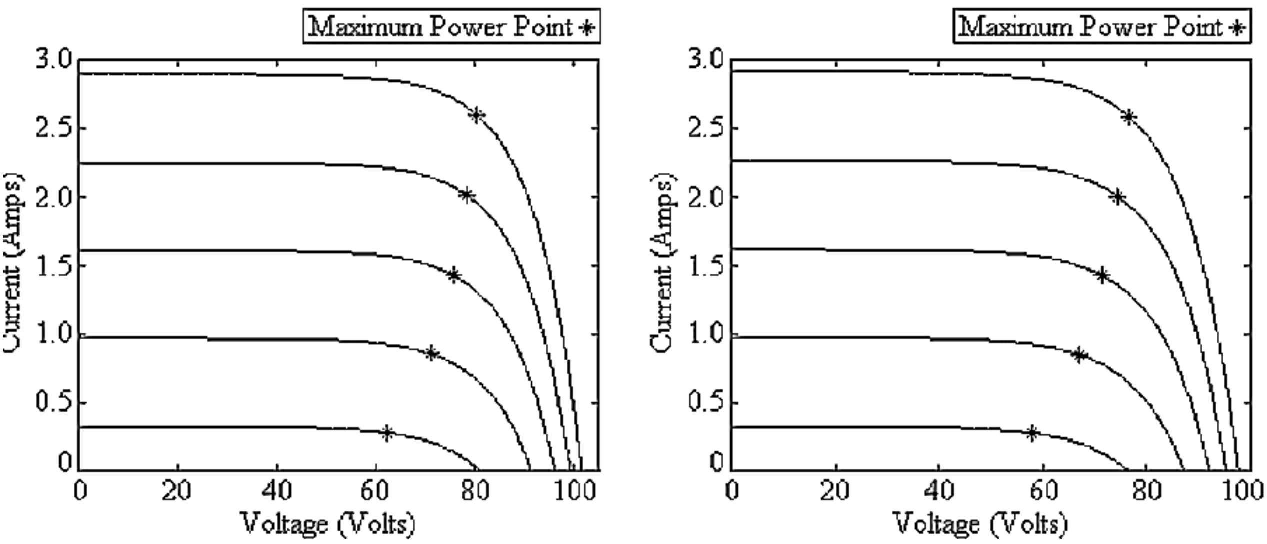

Figure 3.2: (a) PV array voltagecurrent at 40°C at different irradiance levels; (b) PV array voltagecurrent at 50°C at different irradiance levels

However, the location of the MPP in the IV plane is not known a priori. It must be located, either through model calculations or by a search algorithm. The situation is further complicated by the fact that the MPP depends in a nonlinear way on irradiance and temperature, as illustrated in Figure 3.1. Figure 3.2(a) shows a family of PV IV curves under increasing irradiance, but at constant temperature, and Figure 3.2(b) shows I-V curves at the same irradiance values, but a higher temperature. Note the change in the array voltage at which the MPP occurs.

3.2 MPPT algorithms

There are various algorithms available today which can be used to implement the Maximum power point technique. However, selection of an algorithm is affected by various factors, such as budget, complexity and need of MPPT. Few algorithms are discussed herewith.

3.2.1 Perturb-and-observe

The perturb and observe (P&O) algorithm is the most commonly used in practice because of its ease of implementation. The most basic form of the P&O algorithm operates as follows:

Consider Figure 3.2, which shows a family of PV array power curves as a function of voltage (PV curves), at different irradiance (G) levels, for uniform irradiance and constant temperature. As previously described, these curves have global maxima at the MPP. Assume the PV array to be operating at point A in Figure 3.2, which is far from the MPP. In the P&O algorithm, the operating voltage of the PV array is perturbed by a small increment, and the resulting change in power,ΔP, is measured. If ΔP is positive, then the perturbation of the operating voltage moved the PV arrays operating point closer to the MPP. Thus, further voltage perturbations in the same direction (that is, with the same algebraic sign) should move the operating point toward the MPP. If ΔP is negative, the system operating point has moved away from

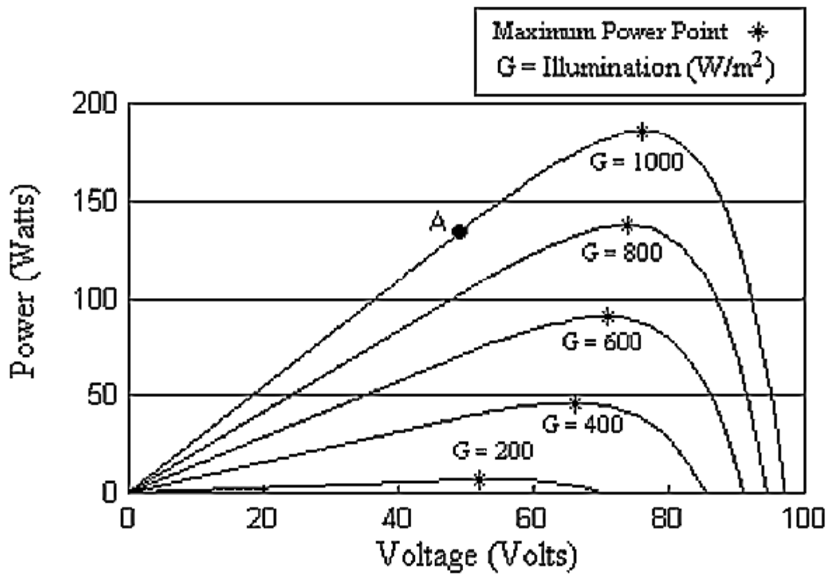

Figure 3.3: Photovoltaic array powervoltage relationship

the MPP, and the algebraic sign of the perturbation should be reversed to move back toward the MPP. The advantages of this algorithm, as stated before, are simplicity and ease of implementation. However, P&O has limitations that reduce its MPPT efficiency. One such limitation is that as the amount of sunlight decreases, the PV curve flattens out, as seen in Figure 3.3. This makes it difficult for the MPPT to discern the location of the MPP, owing to the small change in power with respect to the perturbation of the voltage. Another fundamental drawback of P&O is that it cannot determine when it has actually reached the MPP. Instead, it oscillates around the MPP, changing the sign of the perturbation after each ΔP measurement

3.2.2 Constant voltage and current

The basis for the constant voltage (CV) algorithm is the observation from IV curves like those in Figure 3.1 that the ratio of the arrays maximum power voltage, V_{MPP}, to its open-circuit voltage, V_{OC}, is approximately constant;in other words:

$$\frac{V_{MPP}}{V_{OC}} \cong K < 1 \tag{3.1}$$

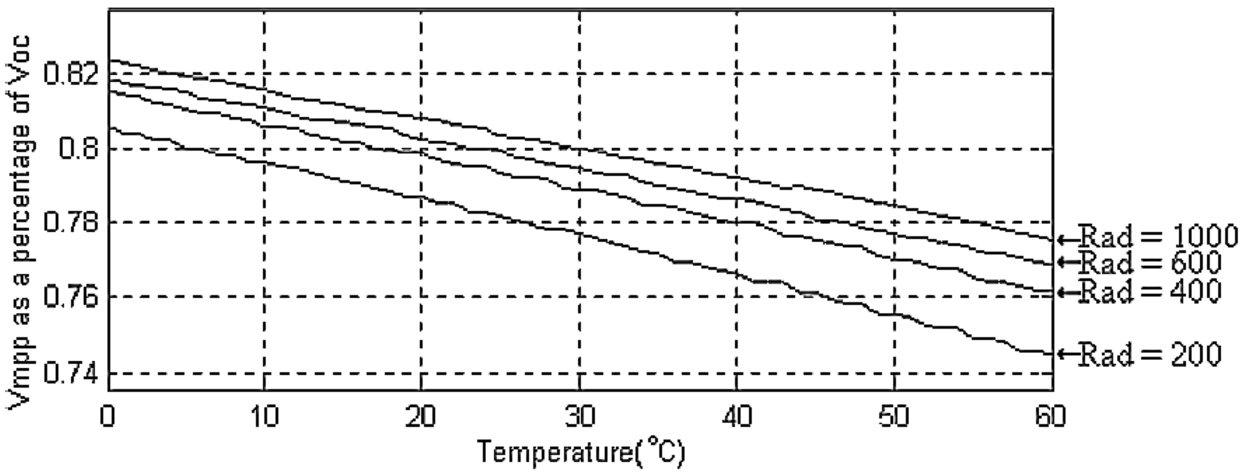

Figure 3.4: V_{MPP} as a percentage of V_{OC} as functions of temperature and irradiance

The constant voltage algorithm can be implemented as follows: The solar array is temporarily isolated from the MPPT, and a V_{OC} measurement is taken. Next, the MPPT calculates the correct operating point using Equation (3.1) and the preset value of K, and adjusts the arrays voltage until the calculated V_{MPP} is reached. This operation is repeated periodically to track the position of the MPP. Although this method is extremely simple, it is difficult to choose the optimal value of the constant K.

Figure 3.4 shows the actual K values required for a given PV array over a temperature range of 0 °C to 60 °C and irradiance levels from 200 to 1000 W/m^2.

3.2.3 Incremental conductance

The incremental conductance algorithm is derived by differentiating the PV array power with respect to voltage and setting the result equal to zero. This is shown in Equation (3.2)

$$\frac{dP}{dV} = \frac{dVI}{dV} = I + V * \frac{dI}{dV} \tag{3.2}$$

Rearranging Equation (3.2) gives

$$\frac{-I}{V} = \frac{dI}{dV} \tag{3.3}$$

Note that the left-hand side of Equation (3.2) represents the opposite of the PV arrays instantaneous conductance, while the right-hand side represents its incremental conductance. Thus, at the MPP, these two quantities must be equal in magnitude, but opposite in sign. If the operating point is off of the MPP, a set of inequalities can be derived from Equation (3.2) that indicates whether the operating voltage is above or below the MPP voltage. These relationships are summarized in Equations (3.4 , 3.5 and 3.6).

$$\frac{dI}{dV} = \frac{-I}{V}; (\frac{dP}{dV} = 0) \tag{3.4}$$

$$\frac{dI}{dV} > \frac{-I}{V}; (\frac{dP}{dV} > 0) \tag{3.5}$$

$$\frac{dI}{dV} < \frac{-I}{V}; (\frac{dP}{dV} < 0) \tag{3.6}$$

Equation (3.4) is a repeat of Equation (3.3) for convenience. Equations (3.5) and (3.6) are used to determine the direction in which a perturbation must occur to move the operating point toward the MPP, and the perturbation is repeated until Equation (3.4) is satisfied. Once the MPP is reached, the MPPT continues to operate at this point until a change in current is measured. This change in current will correlate to a change in irradiance on the array. As shown in Figure 3.3, as the irradiance on the array increases, the MPP moves to the right with respect to the array voltage. To compensate for this movement of the MPP, the MPPT must increase the arrays operating voltage. The opposite is true when a decrease in irradiance is detected (via a decrease in the measured current).

3.2.4 Parasitic capacitance

The parasitic capacitance algorithm is similar to incremental conductance, except that the effect of the solar cells parasitic junction capacitance C_P, which models charge storage in the pn junctions of the solar cells, is included. By adding this capacitance to the lighted diode equation, We can represent the capacitance using $i(t) = C\frac{dV}{dt}$, Equation (3.7) is obtained.

$$I = I_L - I_o[\exp(\frac{V_P + R_S I}{a} - 1] + C_P\frac{dV_P}{dt} = F(v_P) + C_P\frac{dV_P}{dt} \tag{3.7}$$

On the far right of Equation (3.7), the equation is rewritten to show the two components of I, a function of voltage $F(v_P)$ and the current in the parasitic capacitance. Using this notation, the incremental conductance of the array g_P can be defined as $dF(v_P)/dv_P$and the instantaneous conductance of the array, g_L can be defined as -$F(v_P)/v_P$. The MPP is located at the point where $dP/dv_P = 0$. Multiplying Equation (3.7) by the array voltage v_P to obtain array power and differentiating the result, the equation for the array power at the MPP is obtained:

$$\frac{dF(v_P)}{dv_P} + C_P(\frac{\dot{V}}{V} + \frac{\ddot{V}}{\dot{V}}) + \frac{F(v_P)}{v_P} = 0 \tag{3.8}$$

The three terms in Equation (9) represent the instantaneous conductance, the incremental conductance, and the induced ripple from the parasitic capacitance. The first and second derivatives of the array voltage take into account the AC ripple components generated by the converter. One will note that if C_P is equal to zero, this equation simplifies to that used for the incremental conductance algorithm. Since the parasitic capacitance is modeled as a capacitor connected in parallel with the individual solar cells, connecting the cells in parallel will increase the effective capacitance seen by the MPPT. From this, the difference in MPPT efficiency between the parasitic capacitance and incremental conductance algorithms should be at a maximum in a high-power solar array with many parallel modules.

3.2.5 Fuzzy Logic based algorithms

Fuzzy logic uses fuzzy set theory, in which a variable is a member of one or more sets, with a specified degree of membership. Fuzzy logic allow us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague and incomplete data, yet by applying a defuzzification process, arrive at definite conclusions. Fuzzy logic is implemented to assist the conventional MPPT technique to obtain the MPP operating voltage point faster and also it can minimize the voltage fluctuation after MPP has been recognized.

3.2.6 Genetic Algorithms

Genetic algorithms are adaptive algorithms for finding the global optimum solution or an optimization problem. The canonical genetic algorithm developed by Holland is characterised by binary representation of individual solutions, simple problem-independent crossover and mutation operators, and a proportional selection rule. Based on this various methods are proposed to obtain maximum power point of a PV array. It basically takes initial guesses and then provides generations and these generations are used to find the optimal solution. This method is widely accepted. Also, it requires less sensors and hence is cost effective as well. Finding the optimal solution leads to change in PWM signal of DC-DC converter and finally the duty cycle is so adjusted that PV array works at its MPP.

Chapter 4

Design simulations and calculations

The PV inverters are the key element of the grid connected photovoltaic systems. These operate due to solar irradiation and convert the available solar power into AC power so that it can be used in general. Some inverters might have facility to generate grid synchronized power which can be regarded as an added feature to it. Such inverters can be connected to grid to transmit the power which is in addition to the local usage. Generally the PV inverters are broadly classified as Stand-alone and Grid-Connected inverters. Another type of classification is their configuration. Which is as follows:

- **Module integrated inverters:** Typically in the range of 50 to 400 W, Considered as very small PV plants (one panel).
- **String inverters:** Typically in the range of 0.4 to 2 kW, Small roof-top plants with panels connected in one string can be considered as string inverters.
- **Multi string inverters:** Typically ranging between 1.5 to 6 kW, Medium-large roof-top plants with panels configured in one to two strings.
- **Mini central inverters:** Typically 6 kW with three-phase topology and modular design for larger roof-tops or smaller power plants in the range of 100 kW and typical unit sizes of 6, 8, 10 and 15 kW.

- **Central inverters:** Typically in the 100 to 1000kW range with three-phase topology and modular design for large power plants ranging to tenths of a MW and typical unit sizes of 100, 150, 250, 500 and 1000 kW.

In this era of renewable generation, such grid connected inverters are being installed, and a few of them are now in operation. A time will come when the roof-top PV inverters will be an important source in the distributed generation and hence such PV systems need to comply with the regulatory standards in order to ensure the seamless transfer of power to the grid with security and reliability of the same.

4.1 Grid connection regulatory standards

The most relevant international bodies that are developing worldwide standards for grid requirements are: IEEE (Institute of Electrical and Electronic Engineers) in the US, IEC (International Electrotechnical Commission) in Switzerland and DKE (German Commission for Electrical, Electronic and Information Technologies of DIN and VDE) in Germany, the dominants in PV market.

Today the single most influential standard for interconnection of all forms of distributed resources is IEEE 1547-2003,"Standard for Interconnecting Distributed Resources with Electric Power Systems". The IEEE 1547 standard has benefited greatly from earlier utility industry work documented in IEEE and IEC standards (e.g. IEEE 929, 519, 1453; IEC EMC series 61000; etc.) and ANSI C37 series of protective relaying standards.

In the grid interconnection requirements, the standard IEC 61727,"Photovoltaic (PV) Systems Characteristics of the Utility Interface", published in December 2004. The standard applies to utility-interconnected PV power systems operating in parallel with the utility and utilizing static (solid-state) non islanding inverters for the conversion of DC to AC and lays down requirements for interconnection of PV systems to the utility distribution system.

IEC 61000-3-2 deals with the limitation of harmonic currents injected into the public supply system. It specifies limits of harmonic components of the input current, which may be produced by equipment tested under specified conditions. IEC 61000-3-3 is concerned with the limitation of voltage fluctuations and flicker impressed on the public low-voltage system. It specifies limits of voltage changes that may be produced by an equipment tested under specified conditions and gives guidance on methods of assessment.

4.2 Configuring Solar panels

First and the foremost thing to begin with is to configure solar panels for the PV module. The simulations to be performed will be more accurate when the I-V curves of the modelled solar panels are more near to the actual panels. Manufacturer's data is filled into the model and by adjusting the parameters such as Ideality factor of the diodes, Band energy, Series resistance,I-V curve has been generated for the available panels. Specifications of the panel are as follows:

Parameter	Values
No. of cells N_s	36
Maximum power P_{max}	80 watts
Voltage at P_{max}	19.011 volts
Current at P_{max}	4.535 amperes
Open-circuit voltage V_{oc}	22.701 volts
Short-circuit current I_{sc}	4.902 amperes
Std. Light intensity S_0	1000 W/m^2
Std. Temperature T_{ref}	25 degree C

This data is filled in and by adjusting various parameters, we obtain a curve near to the curve given in the manufacturer's data sheet as given in figure 4.1. We will be configuring two panels in series to gain more voltage. Our input voltage level will be around 34 volts at maximum power and hence it will be easier to achieve 48v through

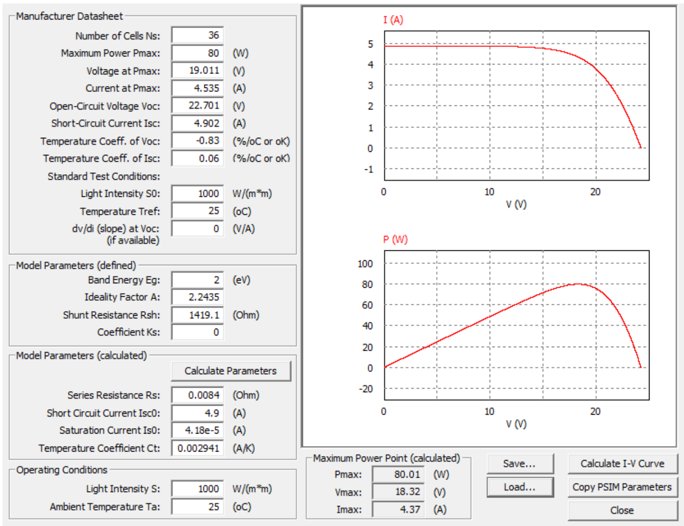

Figure 4.1: Configuration of Solar module for the simulation

boost converter. Combined curve for the panel is shown in figure 4.2. This curve will be used in the model of PV arrays for the simulation purpose.

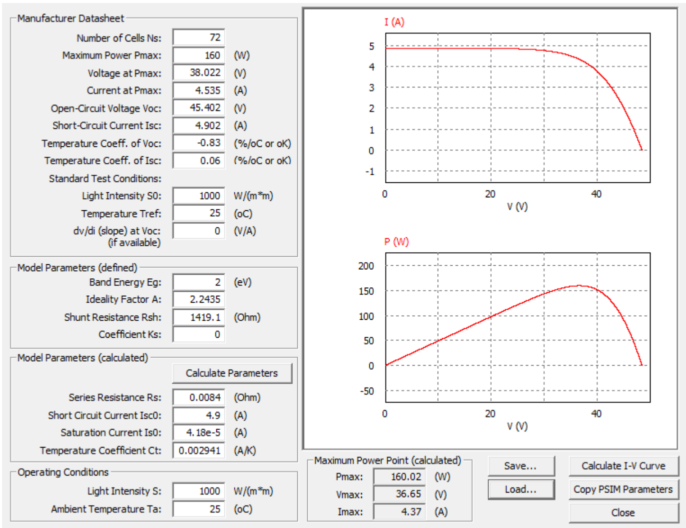

Figure 4.2: Curve for two panels in series

4.3 Design Concept of PV Inverters

Various topologies are available for PV inverters, which are classified on basis of their power processing stages as single stage or two stage topologies and on the basis of galvanic isolation to the grid as with or without galvanic isolation. Generally, the output voltage of the PV array is not high enough and varying with the changing environmental conditions. This creates a requirement of a additional DC/DC converter stage which maintains a constant DC link voltage irrespective of changing input voltage. This topology adds a voltage-up link part, usually configured as shown in figure 4.3 below.

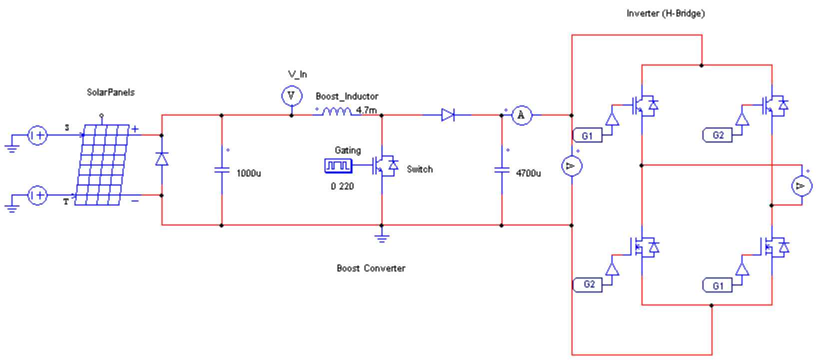

Figure 4.3: Two stage PV Inverter topology

Commonly, the output voltage of the PV array is not high enough to connect to the grid. Moreover, the voltage source inverter (VSI) usually has a voltage-down property, which causes the"PV array + Inverter" topology to output a lower voltage, thus two stages topology is suggested. The DC/DC part often adopts a Boost circuit or some other derived versions, like Buck-boost, isolated Boost, etc. Besides voltage-up function, the Boost circuit can also offer a more stable input voltage for the inverter. The main advantage of the two stages topology is the flexibility of designing its control scheme since it has a higher freedom degree, i.e. more controllable variables, which means multiple control objectives (MPPT, grid connecting, VAR compensating, active filter, etc.) can share by two stages respectively simultaneously.

4.4 Stage 1 : DC-DC Boost converter

Several methods exist to achieve DC-DC voltage conversion. Each of these methods has its specific benefits and disadvantages, depending on a number of operating conditions and specifications. Examples of such specifications are the voltage conversion ratio range, the maximal output power, power conversion efficiency, number of components, power density, galvanic separation of in- and output, etc. When designing fully-integrated DC-DC converters these specifications generally remain relevant, nevertheless some of them will gain weight, as more restrictions emerge. For instance the used IC technology, the IC technology options and the available chip area will be dominant for the production cost, limiting the value and quality factor of the passive components. These limited values will in-turn have a significant impact upon the choice of the conversion method. Proposed converter is DC-DC boost converter.

4.4.1 Boost Converter Design

A boost converter is a switch mode power supply that has an output voltage higher than its input voltage. The switching in a boost converter is done through a MOSFET or IGBT. When the switch is closed the current flows in the first loop only, the current through the inductor grows. The switch then opens, and the voltage across the inductor and the input combine in series to charge up the output capacitor to a higher voltage than the input. The duty cycle of the switching signal determines the output voltage. The longer the switch is closed, the higher the output voltage will be expected.

4.4.2 Proposed Boost converter and Design Equations

Proposed Boost Converter is shown in Figure 4.4 and the output is shown in fig 4.5. The purpose of the boost converter in this system is to take the input voltage from the photovoltaic panels and boost it to a voltage high enough for the inverter to convert the DC voltage to 230 V_{RMS} AC.

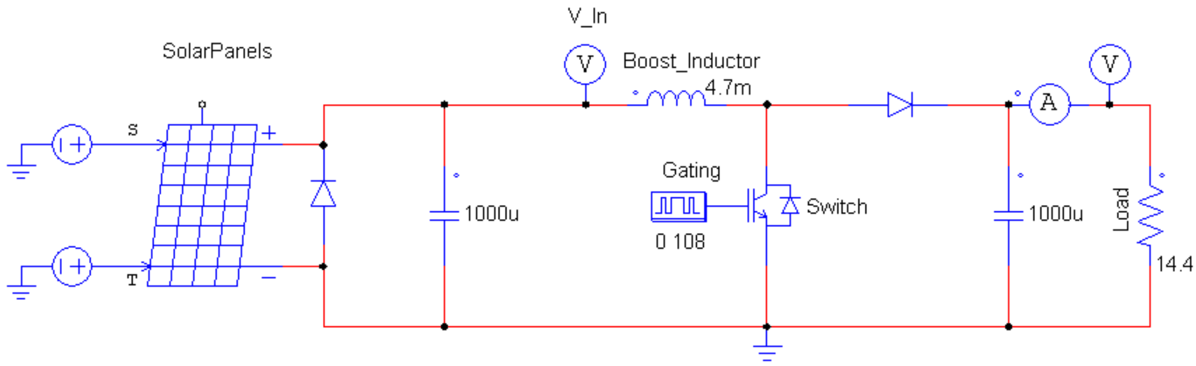

Figure 4.4: Proposed Boost converter

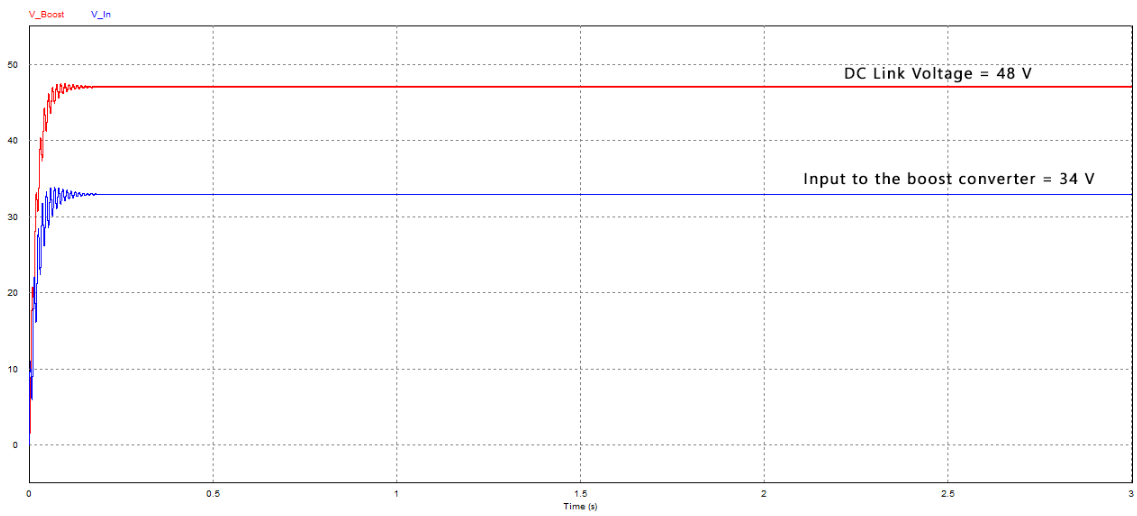

Figure 4.5: Output of the boost converter

One thing that must be calculated when designing a boost converter is the expected voltage output. The maximum power point tracking system would vary between 30% and 42% duty cycle. The expected maximum output voltage can be calculated by the equation below.

$$V_0 = \frac{V_{in} - V_{trans} D}{1 - D} - V_d \tag{4.1}$$

V_{trans} is the voltage drop across the MOSFET, and V_d is the voltage drop across the diode in the system. This calculation shows that the output voltage should be around 48 volts within a range of 29% and 47% duty cycle. An important consideration that must be made during the design of a boost converter is the size of the inductor. One way to determine an appropriate size for the inductor is to take into consideration the switching frequency, duty cycle, output voltage, and minimum load current. As can be seen from equation(4.2), at the lighter the load, the higher the inductance needed. This can even be applied to switching frequency. Hence, Switching frequency is considered as 10kHz.

$$L = \frac{V_{out} - V_{in}V_d \cdot (1 - D)}{min(loadcurrent) \cdot f_s} \tag{4.2}$$

It is important for the boost converter to remain in continuous conduction mode for control purposes. This means that the current through the inductor never reaches zero during a full switching cycle of the boost converter. If the boost converter is in discontinuous mode, the output voltage equation becomes a function of frequency, inductance, and output current, as well as duty cycle as seen in equation 4.3:

$$\frac{V_0}{V_i} = 1 + \frac{V_i \cdot D^2.T}{2 \cdot L \cdot I_0} \tag{4.3}$$

By using equation (4.4) an appropriate resistance for the output load can be determined for the amount of available inductance. If a higher resistance than R_{crit} is used, the load will be too light and the boost converter will enter into discontinuous mode.

$$R_{crit} = \frac{2 \cdot L \cdot f_s}{D(1 - D)^2} \tag{4.4}$$

A simplified yet perfect design of a boost converter is then ready for use. To fetch the maximum power output from the panels, duty cycle of the boost converter will be adjusted and DC-DC link will provide steady output voltage at the output terminals.

4.5 Stage : 2 Inverter Design

For the feeding of sinusoidal current and voltage into the grid or to use the AC load and for the conversion of DC voltage at the DC link into AC, effective DC-AC conversion stage (Inverter) has been kept into the system. Being a low power system, it can have a full bridge inverter. H-Bridge topology is the most commonly preferred topology and will be used here as shown in figure 4.6.

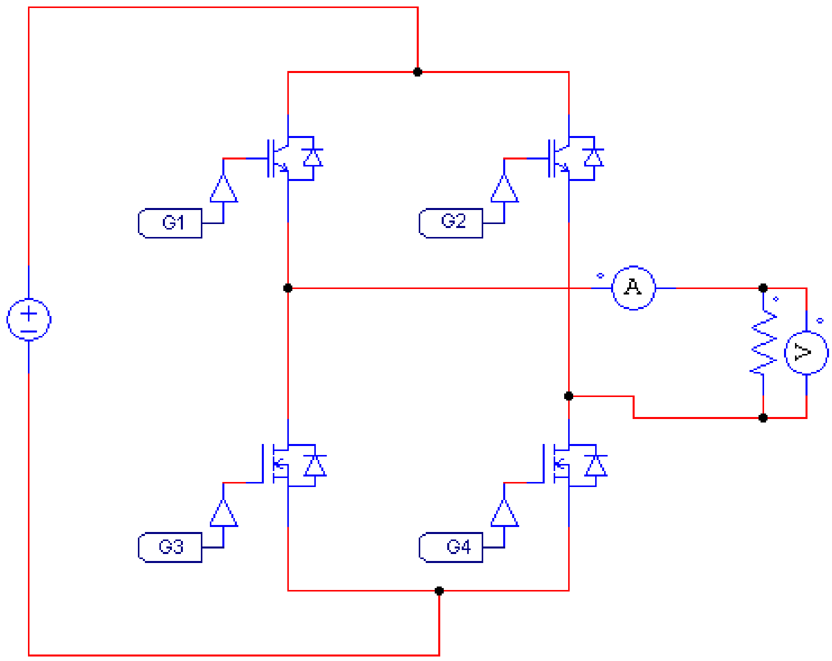

Figure 4.6: H-Bridge Inverter topology

For this, the hardware used will be discussed in the next chapter.

4.5.1 Control Logic and other features

Pulse width modulation

The main advantage of PWM converters is the possibility of controlling the converter gain and consequently the converter output voltage. There are numerous PWM techniques used with different converter configurations. SPWM being the most popular PWM method, the width of each pulse is varied in proportion to the amplitude of a sine wave or so-called control waveform as shown in the figure 2.7:

The switches are controlled in a way that the turn-on and turn-off pulses correspond to the crossing points of the control waveform with the carrier waveform of

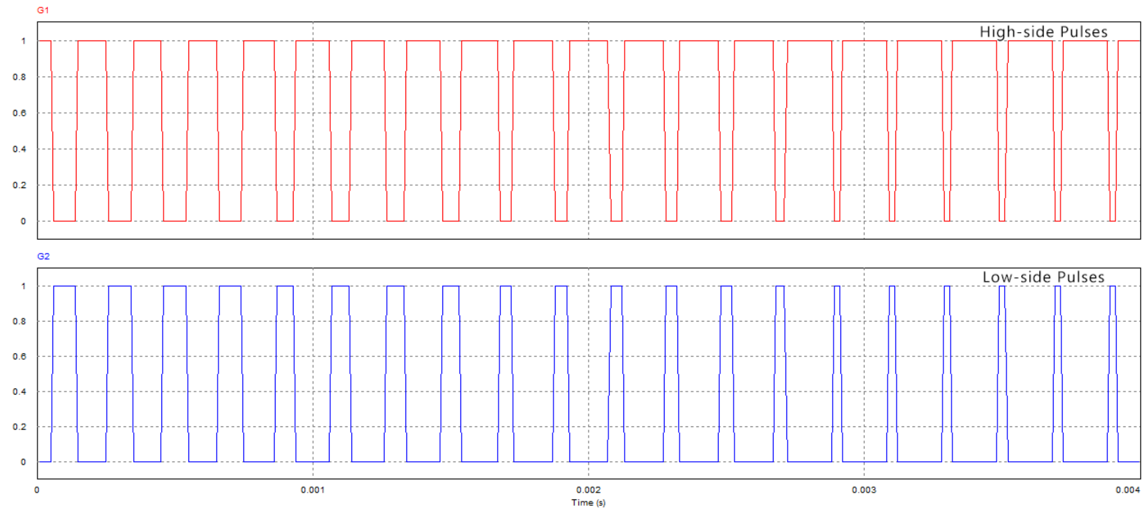

Figure 4.7: Sine PWM for inverter bridge

corresponding phase. The frequency of the carrier waveform determines the fundamental frequency of the output voltage (which should be 50 Hz in this case). The frequency modulation ratio is the ratio between frequencies of the carrier and control waveforms i.e

$$m_f = \frac{f_{carr}}{f_{cnt}} \tag{4.5}$$

By varying the amplitude of the control waveform A_{cnt} from zero to the amplitude of the carrier waveform A_{carr}, the pulse width can be varied from 0 to 180°. The modulation ratio m_a defines the ratio between the control and carrier waveforms i.e

$$m_a = \frac{A_{cnt}}{A_{carr}} \tag{4.6}$$

This switching technique will require a feedback if the converter is to be connected to the grid. Because we have to ensure the switching generates voltage which are in phase with the grid voltage and have same frequency as the grid. Phase locked loop is a closed loop switching control which will control the PWM generation according to the grid voltage. The module will offer a feature to work as a stand alone grid connected inverter as well. And hence, Control of PWM will be a necessity.

Phase-Locked loop

Phase-locked loop is considered as the control scheme of PWM for the grid connected inverters. In this system, Phase Locked Loop (PLL) system is used to synchronize the output voltage of the inverter with the utility grid voltage by calculating appropriate theta (in radian) angle. When the inverter will be used to make solar as a stand alone resource, grid connection measures will have to be taken to ensure seamless and reliable power flow of good quality. The figure 4.8 shows the PLL logic. This

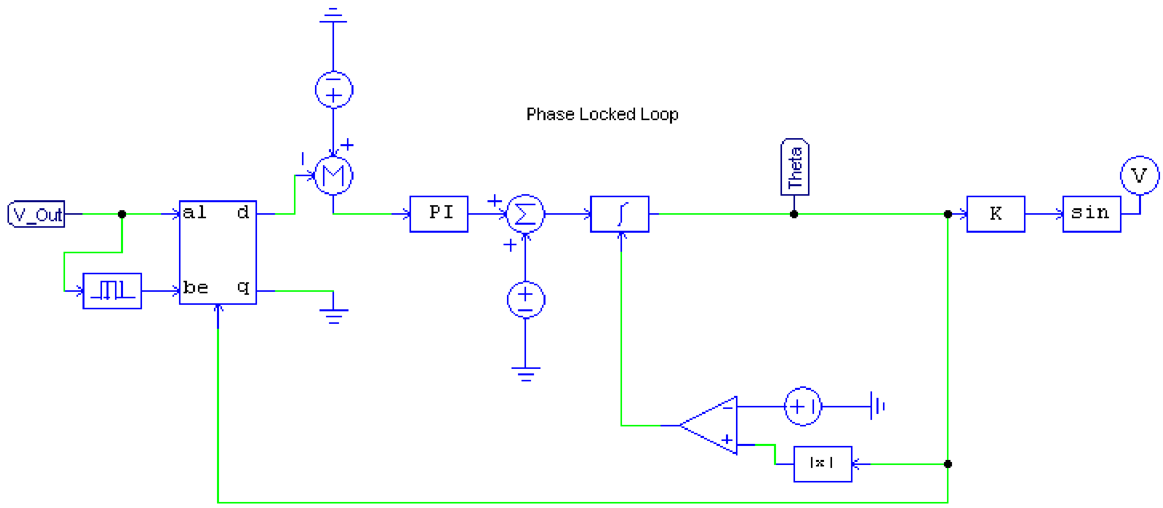

Figure 4.8: Basic PLL Logic

will generate the theta which will be used to switch the inverter switches to generate output in synchronisation with the grid. The generated outcome is shown in figure 4.9. where gating pulses are generated by controlling the SPWM logic. For this, output current of inverter is sensed and converted into i_d and i_q with accordance to θ calculated by the PLL. These i_d and i_q components generated with reference to θ are again converted into phase current i and comparing this sine wave, SPWM signals are generated as per logic given in circuit of figure 4.10.

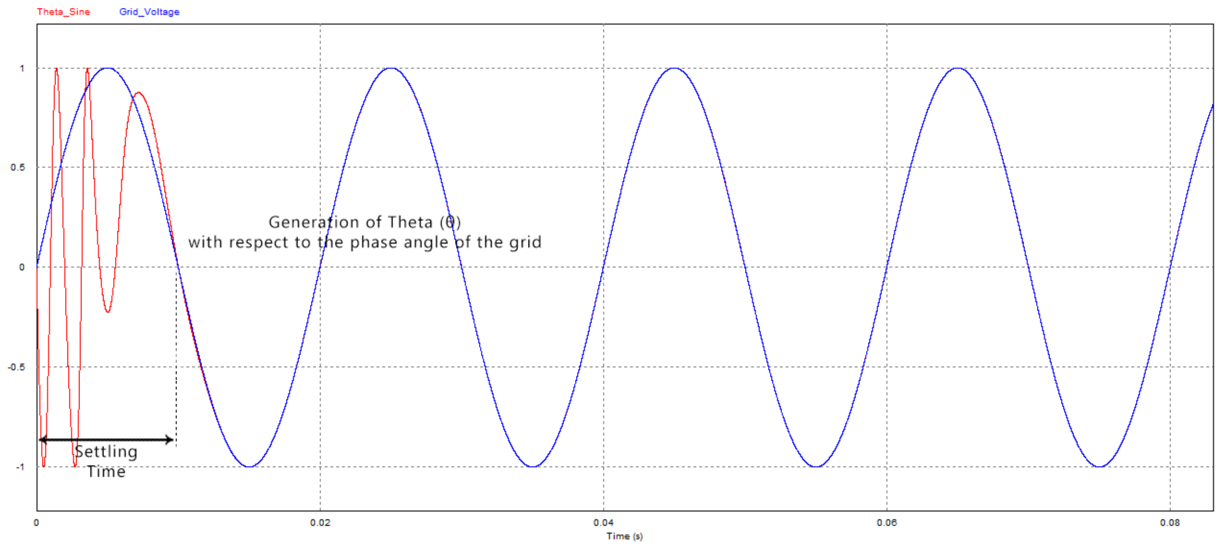

Figure 4.9: Generation of angle with respect to input

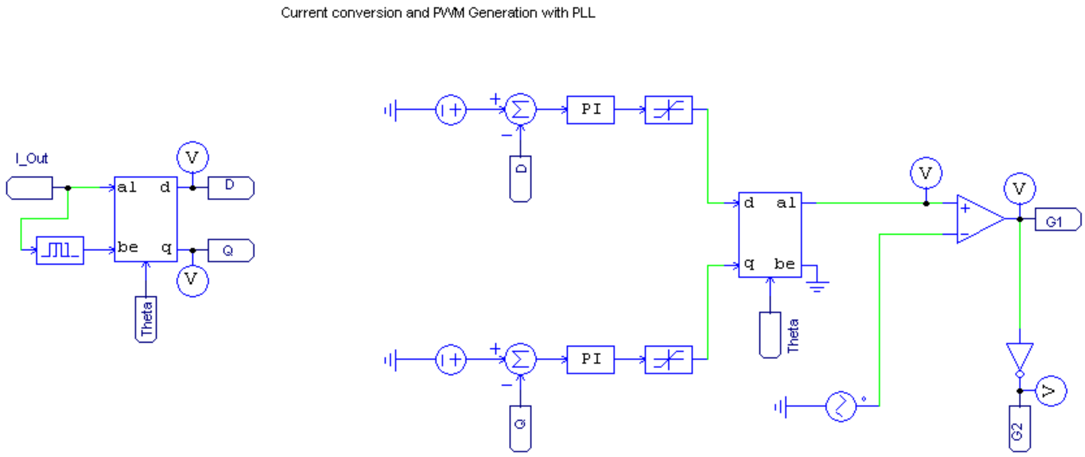

Figure 4.10: Control Circuit for SPWM with PLL

The gate pulses will be generated accordingly, as shown in figure 4.11 given below:

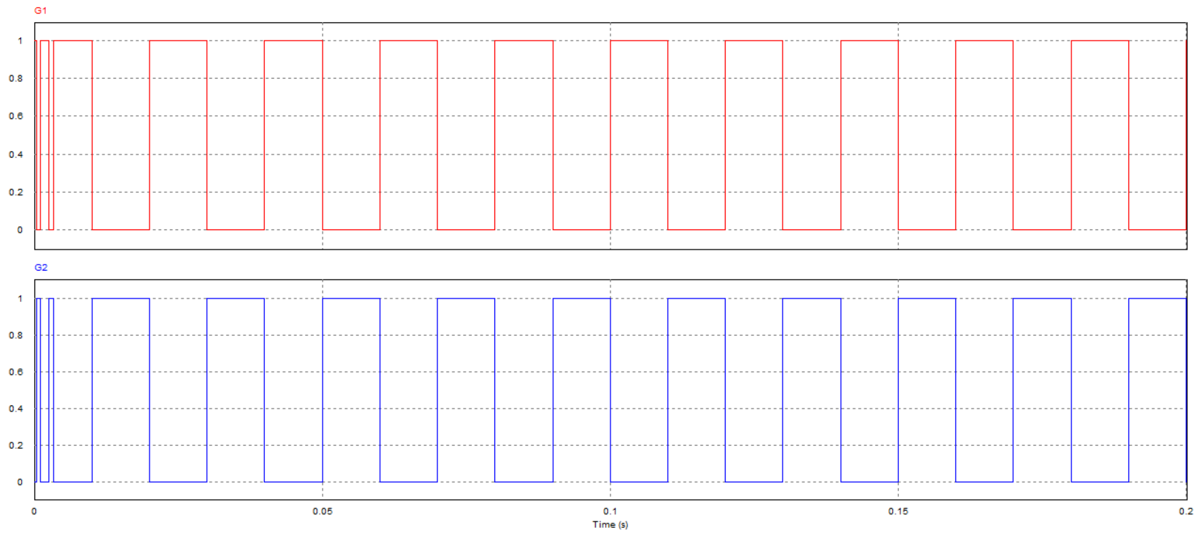

Figure 4.11: PWM Gate pulses of switch 1,4 and 2,3

Islanding detection

A simple code given below defines the Islanding detection by means of a simple voltage sensor. Here a fall in voltage can be detected by the sensor and then the interrupt routine can be called upon until the condition changes.

Example code:

```
int pin=13;will show the status
int pin1=5, pin2=6, pin3=9;
volatile int grid = high;
void setup()
{
pinmode(pin, OUTPUT);
attachinterrupt (0,Trip,LOW);
}
void loop()
```

{

Code goes here

}

void Trip()

{

grid=!grid; This will get the LED connected to this pin blinking, letting us know that the gird has tripped and so as the inverter.

digitalWrite (pin1,LOW);

digitalWrite (pin2,LOW);

digitalWrite (pin3,LOW);

}

In the event of power failure in a grid, it is required that any grid-tie inverters attached to the grid turn off instantly. This prevents the inverters from continuing to feed power into small sections of the grid, known as "islands". Powered islands present a risk to workers who may expect the area to be unpowered, but equally important is the issue that without a grid signal to synchronize to, the power output of the inverters may drift from the tolerances required by customer equipment connected within the island. So, grid connected inverters need to detect the islanding and immediately go off to prevent the risk to the workers. A simple way to detect islanding is to sense the voltage from the grid, and trip the unit when the sensed voltage becomes zero so that when grid fails, inverter will not operate and by this, it will get isolated from the grid. This can be termed as islanding detection. Various international standards have mentioned that a grid connected inverter must have a feature called islanding detection.

Detecting the presence or lack of a grid source would appear to be simple, and in the case of a single inverter in any given possible physical island (between disconnects on the distribution lines for instance) the chance that an inverter would fail to notice the loss of the grid is effectively zero. However, if there are two inverters in a given island, things become considerably more complex. It is possible that the signal from one can be interpreted as a grid feed from the other, and vice versa, so both units continue operation. As they track each other's output, the two can drift away from the limits imposed by the grid connections, say in voltage or frequency. There are a wide variety of methodologies used to detect an islanding condition. None of these are considered fool-proof, and utility companies continue to impose limits on the number and total power of solar power systems connected in any given area.

Chapter 5

Project testing and hardware implementation

Chapter 6

Hardware Design

The key components found in a boost converter are the IGBT, Inductor, Diode, and Gate driver. The boost converter also contains capacitors on the output in order to smooth out voltage ripples. Since this boost converter is boosting the voltage from a photovoltaic panel, it was also a key component to be considered when designing the boost converter.

6.1 Solar Panels

The Available solar panels are yielding approx 4 ampere current at P_{max} and if we connect them in series, we will have a 34 volt, 160W source at the maximum power condition. This means that the loading on the entire system cannot exceed 160 watts. This is the primary thing that one needs to know before designing the blocks of the hardware.

6.2 Gate Driver circuit

In many situations, we need to use IGBTs configured as high-side switches. Many a times we need to use IGBTs configured as high-side and low-side switches. Such as in bridge circuits. In half-bridge circuits, we have 1 high-side IGBT and 1 low-side

IGBT. In full-bridge circuits we have 2 high-side IGBTs and 2 low-side IGBTs. In such situations, there is a need to use high-side drive circuitry alongside low-side drive circuitry. The most common way of driving IGBTs in such cases is to use high-low side IGBT drivers. Undoubtedly, the most popular such driver chip is the IR2110. As

GateDriver.png

Figure 6.1: Gate driver circuit configuration

seen in Figure 3.1, only the low side output is being used in our boost converter. The high side driver may be needed for other applications, such as a full bridge inverter. To drive this IR-2110 IC, 15V dc power supply was needed. A simple configuration can be a 230/15 step down transformer connected to a full bridge rectifier. The output of the rectifier is then regulated with LM 7815 IC (Voltage Regulator IC) and a pari of capacitors. This configuration is shown below:

16.png

Figure 6.2: Configuration of the power supply

This forms a Gate driver circuitry with its power supply. The whole circuit fabricated as shown in the photograph given below:

18.png

Figure 6.3: Hardware circuit for Gate Driver

The above mentioned configuration (Figure 3.1) will give the low side pulses which can drive a single switch. The output pulses were captured in the DSO as shown below:

GateDriver_op_for_single_switch.JPG

Figure 6.4: Gate-Driver Output for single switch

6.3 Other key components

The IGBT, inductor, diode, and capacitor were all chosen such that they can be used anywhere in the system. This means that the IGBT had to have a high breakdown voltage,and be able to withstand high currents. The IGBT chosen is the FGA25N120ANTD, which has collector to emitter voltage 1200 V and a max drain current of 50 A at 25 degree Celsius. The diode chosen is the IN5408. This is an ultra fast diode with a reverse recovery time of 50ns. The peak repetitive reverse voltage is 1000 V and forward current is 3 A. This diode should not have any problem during operation of the module.

The inductors and capacitors were chosen with voltage and current ratings that were well above the highest expected currents and voltages in the designed module.

6.4 Inverter Circuit

As mentioned in the previous chapter, Inverter H-bridge topology has been selected. This means that we need to have a High-Low side gate driver arrangement and not like the previous configuration which can drive only low side switch. For driving both high and low side switches with the same gate driver IC IR 2110, boot strapping circuitry is needed. In order to drive a high side IGBT the IR2110 uses an external bootstrap capacitor. The bootstrap capacitor is charged to 15 volts and when the high side device is to be turned on the IR2110 references the capacitor voltage to the source voltage of the high side IGBT. As the high side IGBT turns on the capacitor voltage keeps the gate of the IGBT 15 volts higher than the source, which is now at Vd. It is important to initially charge the bootstrap capacitors before the inverter is operated. The bootstrap capacitors are only charged when the high side device is off and the low side device is on. It takes on the order of several milliseconds to charge the bootstrap capacitors. It is also important not to leave the high side device ON indefinitely. The bootstrap capacitor will leak current over time and eventually the charge will not be sufficient to keep the high side device ON. The configuration for the inverter gate driver will be as shown below: This gate driver circuit will drive a

Gate_driver_for_inverter.png

Figure 6.5: Gate driver circuit for Inverter

full H-bridge inverter. Basic requirement for driving a bridge is that the pulses needs to be of complimentary nature and should have dead band such that it can avoid the accidental short-circuit of two switches operating in the same leg. For this, a dead band circuitry was used. Initially, this circuit is used for the testing of inverter. Afterwards, the dead-band can be generated directly through the programming of controller. The dead band circuit is configured as follows:

Deadbandckt.png

Figure 6.6: Dead-band circuit configuration

This dead band circuit consists of a NOT gate IC 74LS04D, a NAND gate IC 74LS00D and a Buffer IC HEF4050B. These ICs require +5 volts Vcc to work. A simple setup used in the testing is show below: This combination of resistance and capacitance will generate a dead-band of 10μs. This dead band circuit will generate a dead-

Deadbandckt_hardware.jpg

Figure 6.7: Hardware setup for dead-band generation

band between the two pulses of each leg. The dead-band circuit shown in Figure 3.6 wil generate dead-band for all four switches. The dead-band generated is shown below: The output from A,B,C and D (Refer figure 3.6) can be directly given to the

Deadband_waveform.png

Figure 6.8: Dead band generation

switches of the H-bridge inverter. The H-bridge inverter will consist of the switches (IGBTs) mounted on their heat sinks, Snubber circuit and gate to source resistors for protection of IGBTs. The H-bridge setup is as shown below:

H-bridge.jpg

Figure 6.9: H-Bridge for Inverter

The test was conducted on each leg. The IGBTs on the same leg were triggered through the setup. The test setup and the pulses on High and Low side switches are shown below:

Project_Setup.jpg

Figure 6.10: Test Setup

High-Low_Pulses.JPG

Figure 6.11: High side and Low side Pulses

Chapter 7

Conclusion and scope of work

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