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Three Phase Grid Connected Photovoltaic System with Maximum Power Point Tracking

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ABSTRACT: This paper proposes a three phase grid connected photovoltaic system in which maximum power point of PV array is traced using perturb and observe algorithm. Power converter consists of a switch mode DC-DC boost converter and a neutral point clamped 3-level inverter. An overview of the dq transformation and sinusoidal PWM technique are presented for the inverter control system along with grid synchronization condition. The boost DC converter is controlled using an open loop maximum power point tracking technique in order to achieve fast control response to transients and changes in weather conditions. A DC link capacitor is used after the DC converter. The capacitor’s voltage is regulated using a DC link controller that balances input and output powers of the capacitor. The performance of the system is simulated via MATLAB SIMULINK. Furthermore, voltage source inverter is controlled in the rotating *dq* frame to inject a controllable three phase AC current into the grid. To achieve unity power factor operation, current is injected in phase with the grid voltage. A phase locked loop (PLL) is used to lock on the grid frequency and provide a stable reference synchronization signal for the inverter control system, which works to minimize the error between the actual injected current and the reference current obtained from the DC link controller.

KEYWORDS: DC-DC Boost Converter; MPPT;SPWM; Power Electronics; Grid Tie Inverter(GTI)

I.INTRODUCTION

In the present scenario of world energy sector renewable sources are growing their importance day by day. This is mainly because of limited resource and bad environmental impacts of the conventional energy. Among the all renewable energy resources available, solar energy seems to be a major competitor as it is abundant in nature and its conversion to electricity through photovoltaic (PV) process is pollution-free. Increasing interest in PV systems, demands growth in research and development activities in various aspects such as Maximum Power Point Tracking (MPPT), PV arrays, anti-islanding protection, stability and reliability, power quality and power electronic interface. With increase in penetration level of PV systems in the existing power systems, these issues are expected to become more critical in time since they can have remarkable impact on the overall system performance. More efficient and cost-effective PV modules are being developed and manufactured, in response to the concerns raised by the PV system developers, utilities and customers. The output of solar PV arrays is dependent on the level of solar irradiance and surface temperature of the array itself. Maximum power output from the array can be achieved by a combination of mechanical solar trackers to maximize the amount of light received, and a maximum power point tracking (MPPT) algorithm to operate the PV array around its maximum power output for a given load under varying atmospheric conditions. The task of MPPT for a fixed load is similar to impedance matching, where a power electronic DC/DC converter tries to match the load impedance to the ratio between voltage and current of the array at the maximum power point (MPP). One of the most common algorithms to achieve this task is the Perturb and Observe (P&O) algorithm. It perturbs the duty cycle of the DC/DC converter switch and then observes the resulting change on the delivered power to the load. The algorithm performs this systematically until any resulting change in the duty cycle causes the power delivered to the load to decrease. The situation in grid connected systems is different, however, since the load impedance is not fixed. In addition, a fast MPPT algorithm is needed to reach maximum output power from the array under quick variations like load or weather changes. Although the incremental conductance technique is faster than

P&O, it is still relatively slow for grid connected applications as it performs computations that help it keep the sense of direction towards the maximum power point. As for fuzzy logic based techniques, they suffer from implementation complexity and require previous experience to carefully set the fuzzification parameters for the algorithm despite their quick response after careful tuning. The aim here is to estimate the PV array voltage at the maximum power point using test cells that keep track of the current radiation and temperature levels, and then use this information to drive the main PV array to maximum power output. This technique is simple and offers fast dynamic response to variations in atmospheric conditions. But the tradeoff is that it does so by approximating the MPP of the array. The control approach in designing the grid connected PV system employs two control loops: an outer control loop that is used to regulate the output power from the PV array to the grid, and an inner control loop that is used to regulate the injected current to the grid and keep it in phase with voltage to achieve unity power factor operation.

This paper is also intended to help researchers working in the general area of distributed generation to incorporate PV arrays into their systems without having to use simplifications as a DC power source, which ignores the array dynamics, or having to implement a complex MPPT algorithm that can delay simulations significantly.

II. PHOTOVOLTAIC CELL EQUIVALENT CIRCUIT MODEL

The equivalent circuit model of a PV cell is needed in order to simulate its real behavior. One of the models proposed in literature is the double exponential model depicted in figure 1. Using the physics of p-n junctions, a cell can be modeled as a DC current source in parallel with two diodes that represent currents escaping due to diffusion and charge recombination mechanisms. Two resistances, R_s and R_p, are included to model the contact resistances and the internal PV cell resistance respectively. The values of these two resistances can be obtained from measurements or by using curve fitting methods based on the I-V characteristic of the cell.

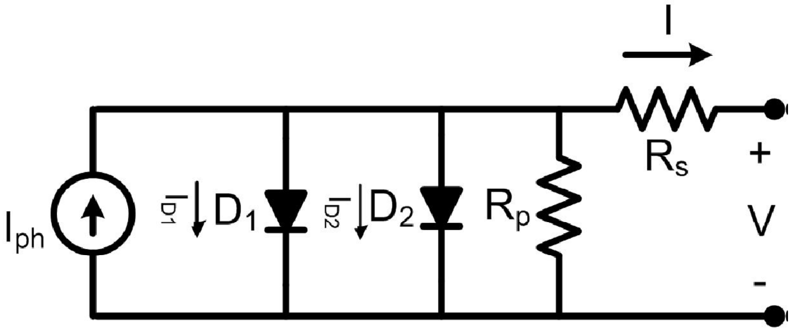

Figure 1: Double exponential PV cell model

The relationship between the PV cell output current and terminal voltage is governed by:

$$I = I_{ph} - I_{D1} - I_{D2} - \frac{V + IR_s}{R_p}$$
$$I_{D1} = I_{01}\left[exp\left(\frac{q(V+IR_s)}{akT}\right) - 1\right] \quad (1)$$
$$I_{D2} = I_{02}\left[exp\left(\frac{q(V + IR_s)}{akT}\right) - 1\right]$$

Where, I_{ph} is the PV cell internal generated photocurrent, I_{D1} and I_{D2} are the currents passing through diodes D_1 and D_2, a is the diode ideality factor, k is the Boltzmann constant (1.3806503 × 10−23 J/K),
T is the cell temperature in degrees Kelvin, q is the electron charge (1.60217646 × 10−19 C), I_{01} and I_{02} are the reverse saturation currents of each diode respectively.
Assuming that the current passing in diode D_2 due to charge recombination is small enough to be neglected, a simplified PV cell model can be reached as shown in figure 2.

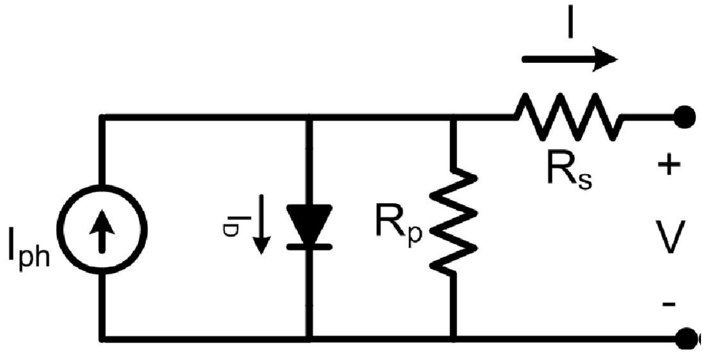

Figure 2: Simplified PV cell model

This model provides a good compromise between accuracy and model complexity and has been used in several previous works.In this case, current I_{D2} can be omitted from (1) and the relation simplifies to:

$$I = I_{ph} - I_0\left[exp\left(\frac{q(V+IR_S)}{akT}\right) - 1\right] - \frac{V+IR_S}{R_p} \tag{2}$$

It is clear that the relationship between the PV cell terminal voltage and output current is nonlinear because of the presence of the exponential term in 1 and 2. The presence of the p-n semiconductor junction is the reason behind this nonlinearity. The result is a unique I-V characteristic for the cell where the current output is constant over a wide range of voltages until it reaches a certain point where it start dropping exponentially.

III. COMPONENTS OF GRID-CONNECTED PHOTOVOLTAIC POWER SYSTEMS

A.MPPT

A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel. According to Maximum Power Transfer theorem, the power output of a circuit is maximum when the Thevenin impedance of the circuit (source impedance) matches with the load impedance. Hence our problem of tracking the maximum power point reduces to an impedance matching problem. In the source side we are using a boost convertor connected to a solar panel in order to enhance the output voltage so that it can be used for different applications like motor load. By changing the duty cycle of the boost converter appropriately we can match the source impedance with that of the load impedance.

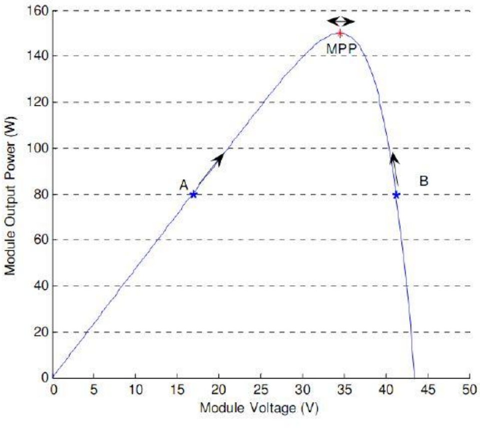

Figure.3 Solar panel characteristics showing MPP and operating points A and B

The Perturb & Observe algorithm states that when the operating voltage of the PV panel is perturbed by a small increment, if the resulting change in power ΔP is positive, then we are going in the direction of MPP and we keep on perturbing in the same direction. If ΔP is negative, we are going away from the direction of MPP and the sign of perturbation supplied has to be changed. The algorithm is represented in figure 4.

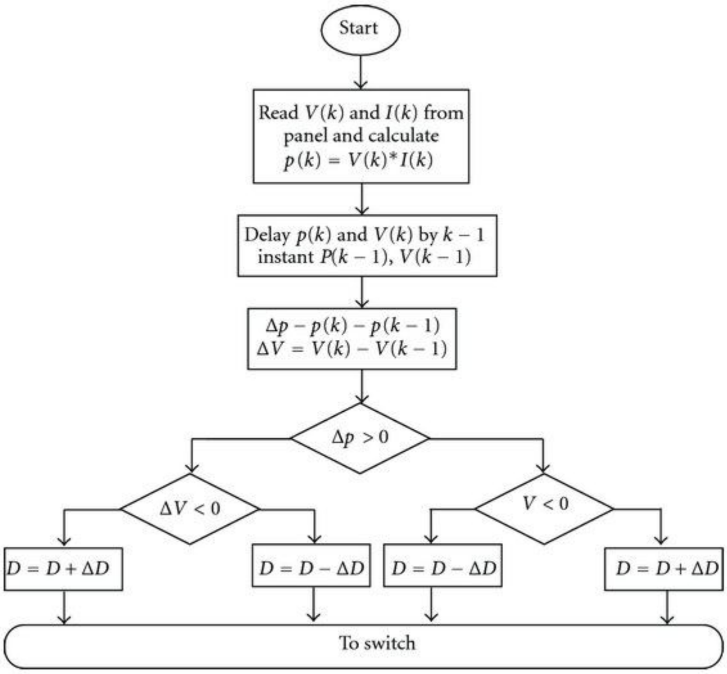

Figure 4: Flowchart of the perturb and observe algorithm

Figure 3 shows the plot of module output power versus module voltage for a solar panel at a given irradiation. The point marked as MPP is the Maximum Power Point, the theoretical maximum output obtainable from the PV panel. Consider A and B as two operating points. As figure 3 shown, the point A is on the left hand side of the MPP. Therefore, we can move towards the MPP by providing a positive perturbation to the voltage. On the other hand, point B is on the right hand side of the MPP. When we give a positive perturbation, the value of ΔP becomes negative, thus it is imperative to change the direction of perturbation to achieve MPP.

Table 1: Perturbation directions for the P&O algorithm based on output power variations

Change in duty cycle, ΔD	Effect on output power	Next perturbation, ΔD(n+1)
Increase	Increase	Increase
Increase	Decrease	Decrease
Decrease	Increase	Decrease
Decrease	Decrease	Increase

B. DC-DC CONVERTER

Switched mode DC-DC converter converts unregulated DC input voltage into regulated DC output voltage at a specified voltage level. Switching power supplies offer much more efficiency and power density compare to linear power supplies. Basic converters that step up or step down voltage input contains elements like transistors, diodes, capacitor and inductors. Three basic converter topologies exist, they are buck (step-down), boost (step-up) and buckboost (step-up or step-down). In our proposed design boost topology is used because its free wheeling diode can be used for blocking reverse current and it efficiently amplify PV arrays output voltage into higher level. Converters are controlled by pulse width modulation (PWM) duty cycle since the output of converter being determined by state of transistor switch. Thus optimum load impedance of PV module is achieved by varying duty cycle.

The boost DC converter is used to step up the input voltage by storing energy in an inductor for a certain time period, and then uses this energy to boost the input voltage to a higher value. The circuit diagram for a boost converter is shown in figure 5. When switch *Q* is closed, the input source charges up the inductor while diode *D* is reverse biased to provide isolation between the input and the output of the converter. When the switch is opened, energy stored in the inductor and the power supply is transferred to the load. The relationship between the input and output voltages is given by:

$$V_{in}t_{on}+(V_{in}-V_{out})t_{off}=0$$

$$\frac{V_{out}}{V_{in}}=\frac{t_{on}+t_{off}}{t_{off}}=\frac{1}{1-d} \qquad (3)$$

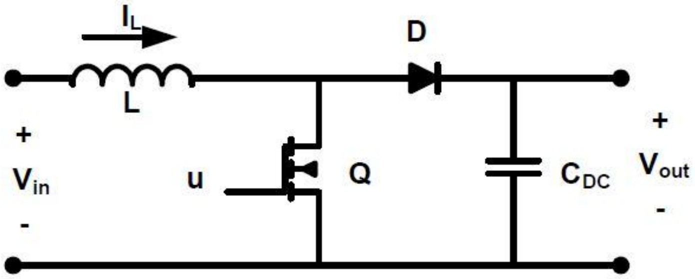

Figure 5: Schematic diagram of a DC boost converter

C. THREE PHASE INVERTERS (DC-AC CONVERTERS)

Voltage source inverters (VSI) are mainly used to convert a constant DC voltage into 3-phase AC voltages with variable magnitude and frequency. The converter used in this project is a Neutral-Point-Clamped three-level converter with three bridge legs. “Three-level” means that each bridge leg, A, B and C can have three different voltage states. The converter topology can be seen in Figure 6. Switch 1 and 3 on each leg are complementary, which means that when switch 1 is on, switch 3 is off and vice versa. Switch 2 and 4 is the other complementary switching pair.

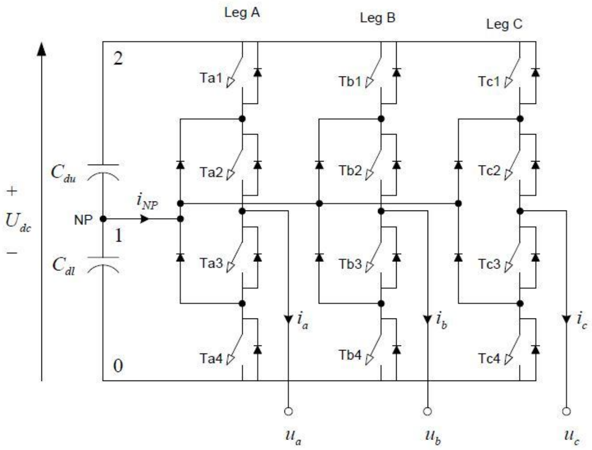

Figure 6: Three phase voltage source inverter (VSI)

If each of the capacitors has a constant voltage of 0.5 U_{dc}, then having the two upper switches on will give an output voltage of U_{dc} compared to level 0, switch 2 and 3 on will give 0.5 U_{dc} and by having the two lower switches on, an output voltage of 0 will occur. In addition to these three states there is a forbidden state where the first switch is on while the second is off.

Table 2: Bridge leg voltages at different combinations of switch states

Leg State	U_{a0}	T_{a1}	T_{a2}	T_{a3}	T_{a4}
2	U_{dc}	ON	ON	OFF	OFF
1	$0.5U_{dc}$	OFF	ON	ON	OFF
0	0	OFF	OFF	ON	ON

The AC output voltage from the inverter is obtained by controlling the semiconductor switches ON and OFF to generate the desired output. Pulse width modulation (PWM) techniques are widely used to perform this task. In the simplest form, three reference signals are compared to a high frequency carrier waveform. The result of that comparison in each leg is used to turn the switches ON or OFF. This technique is referred to as sinusoidal pulse width modulation (SPWM). It should be noted that the switches in each leg should be operated interchangeably, in order not to cause a short circuit of the DC supply. 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.

IV. CONTROL OF THREE PHASE GRID CONNECTED PV SYSTEM

A.SYSTEM STRUCTURE

The PV system under study is shown in figure 7. A photovoltaic array is used to convert sunlight into DC current. The output of the array is connected to a boost DC converter that is used to perform MPPT functions and increase the array terminal voltage to a higher value so it can be interfaced to the distribution system grid at 400V. The DC converter controller is used to perform these two functions. A DC link capacitor is used after the DC converter and acts as a temporary power storage device to provide the voltage source inverter with a steady flow of power. The capacitor's voltage is regulated using a DC link controller that balances input and output powers of the capacitor.

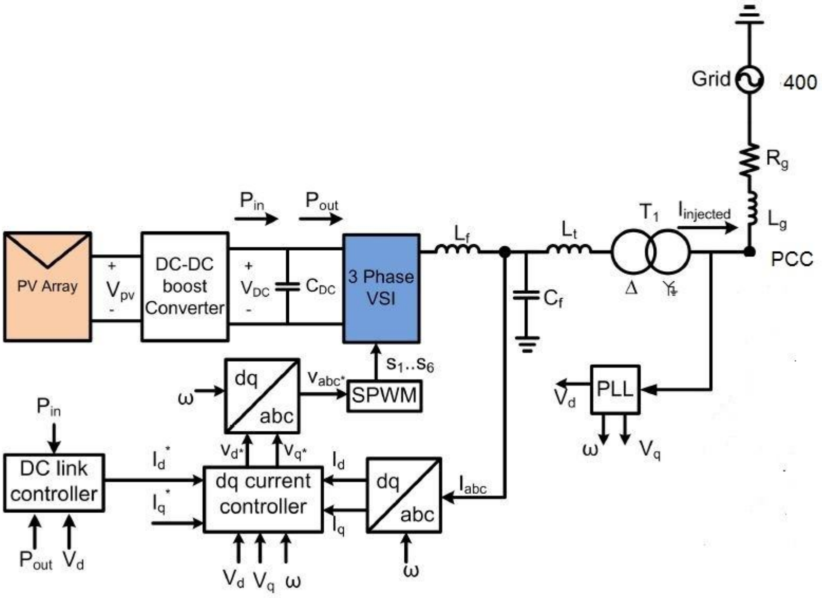

Figure 7: Grid connected PV system structure

The voltage source inverter is controlled in the rotating *dq* frame to inject a controllable three phase AC current into the grid. To achieve unity power factor operation, current is injected in phase with the grid voltage. A phase locked loop (PLL) is used to lock on the grid frequency and provide a stable reference synchronization signal for the inverter control system, which works to minimize the error between the actual injected current and the reference current obtained from the DC link controller. An LC low pass filter is connected at the output of the inverter to attenuate high frequency harmonics and prevent them from propagating into the power system grid. A second order LCL filter is obtained if the leakage inductance of the interfacing transformer is referred to the low voltage side. This provides a smooth output current which is low in harmonic content.

A. THE *abc/dq* TRANSFORMATION

The *dq* transformation is used to transform three phase system quantities like voltages and currents from the synchronous reference frame (*abc*) to a synchronously rotating reference frame with three constant components when the system is balanced. The relationship that govern the transformation from the *abc* to *dq* frame is

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \mathrm{T} \times \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

$$T = \sqrt{\frac{2}{3}} \times \begin{bmatrix} \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin(\omega t) & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (4)$$

Where, x can be either a set of three phase voltages or currents to be transformed, T is the transformation matrix or ω is the angular rotation frequency of the frame. The angle between the direct axis (d-axis) and phase a-axis is defined as θ as shown in figure 8.

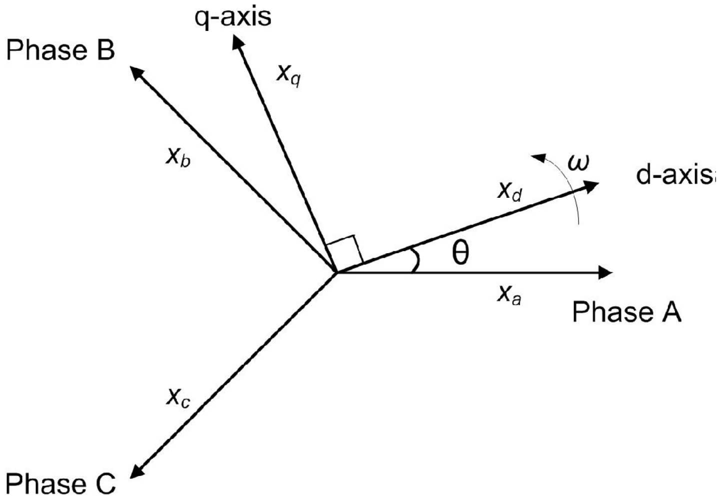

Figure 8: Relationship between the abc and dq reference frames

B. PHASE LOCKED LOOP (PLL)

The role of the phase locked loop is to provide the rotation frequency, direct and quadrature voltage components at the point of common coupling (PCC) by resolving the grid voltage *abc* components. Multiple control blocks of the PV system rely on this information to regulate their output command signals. As stated earlier, the PLL computes the rotation frequency of the grid voltage vector by first transforming it to the *dq* frame, and then force the quadrature component of the voltage to zero to eliminate cross coupling in the active and reactive power terms. A proportional-integral controller is used to perform this task as shown in figure 9. The proportional (K_p) and integral (K_i) gains of the controller were set through an iterative process to achieve a fast settling time.

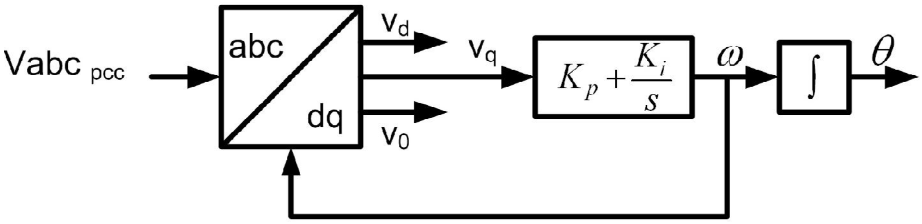

Figure 9: Schematic diagram of the phase locked loop (PLL)

The output from the PI controller is the rotation frequency ω in rad/s. Integrating this term results in the rotation angle θ in radians. The operation of the PLL is governed by

$$\omega = K_p V_q + K_I \int V_q dt$$
$$\theta = \int \omega dt \tag{5}$$

C. SINUSOIDAL PULSE WIDTH MODULATION (SPWM)

The sinusoidal pulse width modulation technique is used to control the voltage source inverter by producing the gating signals for the semiconductor switches. This technique is used to obtain three phase output voltages that can be controlled in magnitude and frequency. A reference or modulating signal is compared to a high frequency carrier signal; the result of this comparison in each phase is used to activate the switches accordingly. A separate modulating signal is used for each phase with a phase shift of 120° between them. Two important quantities in SPWM are the amplitude and frequency modulation indices, m_a and m_f respectively. The amplitude modulation index, m_a, is defined as the ratio between the amplitude of the modulating signal to the carrier signal, while the frequency modulation index, m_f, is the ratio between the frequency of the carrier signal to that of the modulating signal in 6 .

$$m_a = \frac{V_{in}}{V_{carrier}}$$
$$m_f = \frac{f_{carrier}}{f_m} \tag{6}$$

Figure 10 shows the output line voltage of the 3-level inverter before filtering. It is clear that the output voltages need to be filtered to obtain clean sinusoidal voltages. The harmonic content in the output voltages of the inverter depends on the choice of the frequency of the carrier signal.

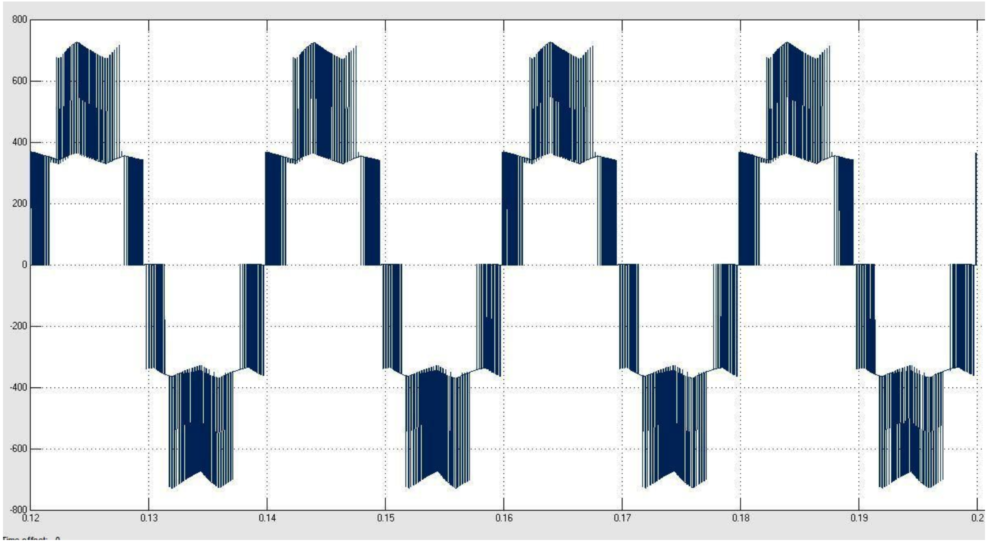

Figure 10: Output line voltage of the 3-level inverter before filtering

V. MATLAB SIMULINK MODEL AND RESULTS

This chapter presents the simulation model and results for the grid connected PV system shown in figure 7 using Matlab software.

The detailed model contains:

- PV array delivering a maximum power of 100 kW at 1000 W/m^2 sun irradiance.
- Boost converter increases voltage from PV natural voltage to 700 V DC. Switching duty cycle of the boost converter is optimized by the MPPT controller that uses the " Perturb and Observe " technique.
- 4950 Hz 3-level 3-phase VSC. The VSC converts the 700 V DC to 400 V AC and keeps unity power factor.
- 10-kvar capacitor bank filtering harmonics produced by VSC.
- 100-kVA 400V/400V three-phase coupling transformer.

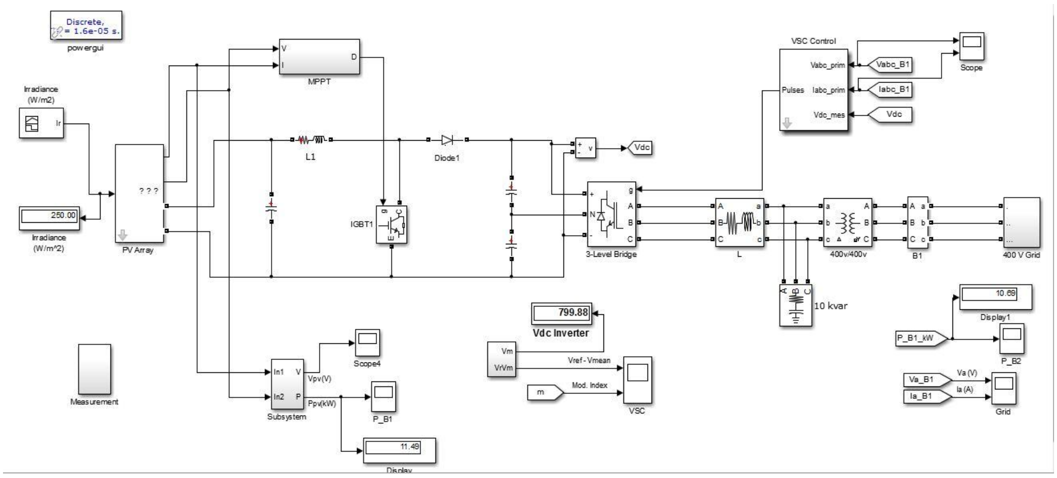

Figure 11: Simulink model of 3 phase grid connected photovoltaic system

Table 3: System Parameters

Grid frequency	50 Hz
PWM carrier frequency	4950 Hz
Nominal power	100 kW
Line Grid voltage	400 V
DC link voltage	700 V

Specifications for one PV module are:

- Number of series-connected cells : 96
- Open-circuit voltage: Voc= 64.2 V
- Short-circuit current: I_{sc} = 5.96 A
- Voltage and current at maximum power : V_{mp} =54.7 V, I_{mp}= 5.58 A

The PV system is constructed using a 100 kW array connected in centralized mode. The array composed of 66 parallel strings each containing 5 modules in series to obtain a terminal voltage suitable for grid connection purposes. To simulate the control system and the resulting output currents and voltages of the VSI, the array is subjected to a variable solar irradiation and a temperature of 25° C. The DC output current and terminal voltage of the array is monitored during simulation to determine the current operating conditions at the specified atmospheric conditions.

Figure 12 shows the DC link capacitor voltage. The capacitor's voltage is regulated using a DC link controller that balances input and output powers of the capacitor.The DC link voltage is monitored to verify the operation of the DC link controller and make sure it reached a constant value for the VSI to operate correctly and generate the required output currents. The purpose of the controller is to force the mismatch between the capacitor input and output DC power to zero. The output of the controller is the reference direct current responsible for setting the output power from the inverter. It took about 0.08 seconds for the capacitor to reach a steady state voltage of 700 V as shown in figure 12.

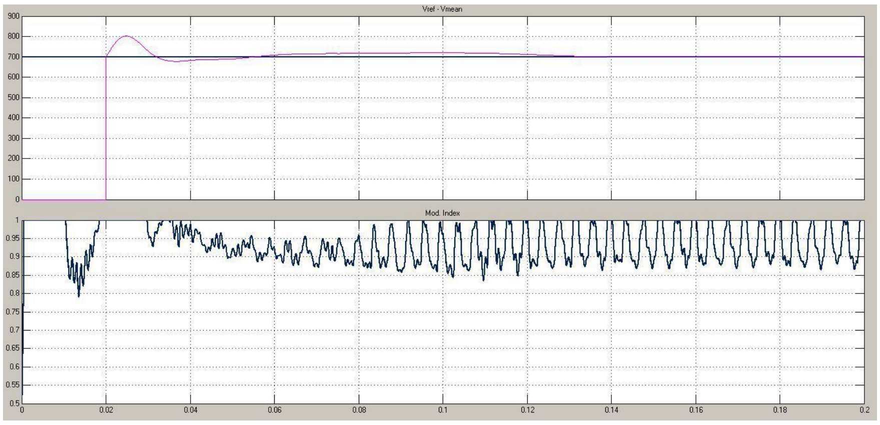

Figure 12: DC link capacitor voltage and modulation index

This fixed voltage DC bus would feed the required power to the inverter to inject the sinusoidal AC currents shown in figure 13. These currents suffered from transients at the start of system operation as the PLL synchronized the control system and due to having a changing DC link capacitor voltage.

Figure 13 shows the grid voltage and current. Grid voltage is 400 volts. When solar irradiation is constant at 1000 W/m^2 then injected current to grid is near about 129 A.

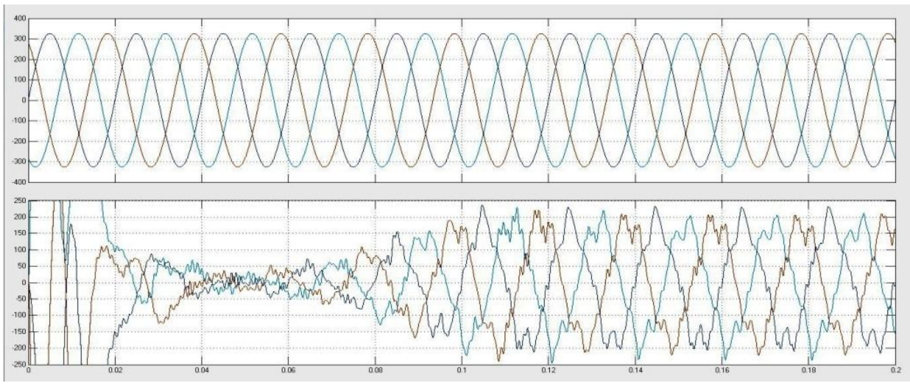

Figure 13: Grid voltage and current

Table 4: Simulation results for 1000 W/m^2 solar irradiation and 25 ℃ (run time 0.20 sec, FFT start time 0.14 sec)

Frequency of Carrier Signal of PWM	P_{in} (kW)	P_{out} (kW)	Efficiency of the Inverter (%)	Injected Current into Grid		Grid Voltage	
				THD (%)	Fundamental (50 Hz)	THD (%)	Fundamental (50 Hz)
1650	91.72	90.09	98.22	19.02	183.1 A	0.01	326.6 V
4950	91.64	90.51	98.77	18.07	186.8 A	0.01	326.6 V
14850	91.65	90.62	98.88	16.90	183.8 A	0.00	326.6 V

VI.CONCLUSION

The design of a control system for three phase grid connected photovoltaic arrays has been detailed in this project. In the proposed design, an MPPT algorithm using a boost converter is designed to operate using (P&O) method to control the PWM signals of the boost converter, which is adapted to the maximum power tracking in our PV system. DC –DC boost converter is used to increase the voltage from natural voltage to 700 V DC, which is then transformed into line frequency (50Hz) sinusoidal three phase AC 400V voltage by the inverter. A DC link voltage controller is presented in order to solve the problem of regulating the voltage at the input of the three phase VSI. This problem arises due to the nonlinear characteristics of the PV array. By matching input and output powers of the DC link capacitor, its voltage can be fixed at a constant value for the inverter to operate correctly and produce AC output voltages that can be controlled in magnitude. The simulation results show that the photovoltaic inverter trace the maximum point of solar cell array power and then converts it to a sinusoidal AC power with a voltage THD of .01 % and current THD of 18.07 % with grid synchronisation.

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