Simulation and Analysis of Three-Phase Grid Connected Solar Photovoltaic System

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Abstract: So, on possessing continual development the renewable energy is getting employed side by side with the traditional energy system. This paper lays down the working of a three-phase grid-connected solar photovoltaic system. The midway DC-DC boost converter facilitates the solar PV system to achieve the utmost point (MPP) besides raising its output voltage (VPV). Perturb and observe method (P&O) based maximum point tracking (MPPT) algorithm are executed to supply a controlled duty cycle to DC-DC boost converter for the production of maximum power from the solar PV system. Voltage-oriented control (VOC) with decoupled controller scheme is employed for the control of three-phase inverter, which takes on the conversion of stationary abc axis into synchronously rotating dq axis, and another way around. A correct synchronization between grid voltage and inverter current is acquired through a phase-locked loop (PLL) using the input's quadrature method. The whole system and control schemes employed have been modelled in MATLAB/SIMULINK environment under several conditions of irradiance and temperature [3].

Keywords: MATLAB Simulink, Photovoltaic Grid-Connected System, Maximum Power Point Tracking, Converter, Inverter, PLL, Load, Source.

I. Introduction

The energy requirements have grown within the years following. The economic revolution and rapid climb within the human population. The tremendous increase in the use of energy has created problems of demand and supply. If this grown energy demand is to be met with fossil fuels, then they're not going to be available for energy production in the future. So, the Concerns about conventional energy sources and their scarcity have set off engineers to seek an alternative to tackle the energy crisis. It's a requirement of today's world to consider renewable energy sources to satisfy the demand and conserve our finite natural resources for generations to come. To make a nation independent and self-sufficient renewable energy is the most productive method. Renewable energy includes wind, solar, biomass, geothermal, etc. Among these renewable energies, solar energy generation has strengthened its foothold because of its easy availability, simple structure, less maintenance, long life, good efficiency, etc. Solar Power is among the renewable sources which have seen vast growth within the last decade. Solar energy is attractive because it's available in an ample amount and provides an important solution to fuel emissions and global climate change. Many industrialized nations have inserted notable solar energy capacity into their electrical grids to supplement or provide an alternative to standard energy sources. This paper presents a three-phase grid-connected 6 KW -PV system model under different conditions of irradiance and temperature. During this design, major PV system components like solar panels/array, DC-DC converter, DC-AC inverter, three-phase utility grid, linear load, and non-linear load are modeled. The general controller with MPPT is meant and integrated with the converter and inverter. By surveilling the DC-DC boost converter duty cycle, the DC link voltage is kept continuous. The DC link voltage is the input of a three-phase inverter where the voltage of grid and current of the inverter is controlled in a synchronously rotating dq coordinate system using a voltage-oriented controller with the decoupled controller. Proper designing of PLL allows the synchronization between grid and inverter. To analyze, the extraction of maximum generated power from the solar PV system is the key objective of this paper using a well-built MPPT algorithm under various conditions of irradiance and temperature.

II. Overview of Proposed Model

Figure 1 depicts an entire block diagram of the three-phase grid-connected solar PV system. The proposed model is made up of a solar PV array making about 6 kW power, a DC-DC boost converter, three-phase inverter, load, and grid. An entire PV system is formed from several tiny structures referred to as PV cells and is the essential developing block of the entire system. Each PV cells are in charge to supply a really bit of power, typically 1-2W. Such solar cells are organized in several series and parallel configurations to reinforce the facility rating and encased during a weatherproof covering to make a bigger unit called a module. On varying environmental conditions like solar irradiance and temperature, the efficiency of the solar PV module is counted. Vpv of the PV array is enhanced by a DC-DC boost converter whose switching is controlled by the MPPT algorithm which not only successfully controls the DC link voltage but also operates a solar PV system at MPP. DC-AC conversion is administered by a three-phase inverter. Here IGBTs are used as a switching device and are connected to the grid. The detailed design of each section is considered below [3]

Figure 1: Block Diagram of Proposed Model

III. Design and Simulation

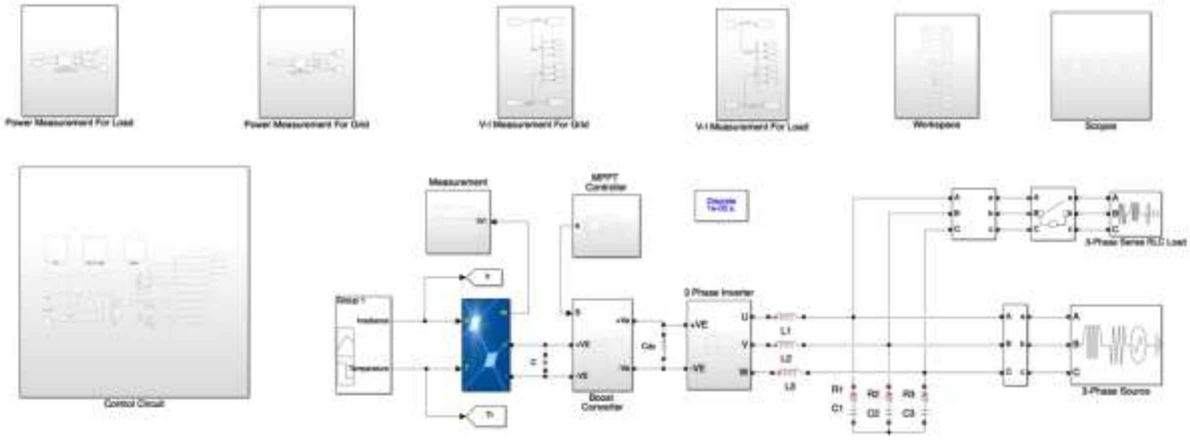

Figure 2: MATLAB/Simulink Model

A. Modelling of Solar PV Array

A linked collection of photovoltaic modules is known as a photovoltaic array. Practically array is composed of several connected PV cells and therefore the observation of the characteristics at the terminal of the PV array requires the inclusion of additional parameters to the essential equation,

$$I = I_{pv} - I_0 \left[\exp\left(\frac{V + R_s I}{V_t a} \right) - 1 \right] - \frac{V + R_s I}{R_p}$$

Where I_{PV} and I_0 are the photovoltaic current and saturation current, singly, of the array and $V_t = N_S\, kt/q$ is that the thermal voltage of the array with N_S cell connected serially. Cells connected in parallel increases the present and cells connected serial provide greater output voltages. Here the PV array block performs an array of photovoltaic modules. The array are made of string of modules connected in parallel, each string consisting of modules connected serial.ly Two parallel strings are connected with a ten series-connected solar array of 300 W per string which provides us the output power of 6 KW. Table.1 shows the specification of the solar PV module.

Table.1 Solar PV Module Specification

No. of series connected cells	72
Open Circuit Voltage	44.4 V
Short Circuit Current	8.69 A
Maximum Power	300.12 W
Voltage at Max. Power	36.6 V
Current at Max. Power	8.2 A

B. Designing of DC-DC Boost Converter

As shown in the Figure 3 Boost Converter is a DC-DC power converter device that steps up voltage from its input to its output. The voltage level of the PV array, V_{PV} is made to be boosted to make it feasible for grid integration. This purpose is served by DC-DC boost converter which reinforce Vpv of Solar PV array also maintain an unbroken DC link voltage to be feed to inverter within the grid side.

$$L = \frac{V_{PV} * D}{\Delta I * F_{SW}}$$

The values of the inductor and capacitor applied within the boost configuration are often calculated by, where D denotes the duty ratio, V_{pv} is that the output of the SPV array, F_{SW} is that the switching frequency of the switch used, ΔI is that the ripple current within the output of the solar PV array. The tactic of energy absorption and injection in boost converter is performed by a mix of 4 components which are inductor, electronic switch, and diode and output capacitor. The tactic of energy absorption and injection will constitute a switching cycle. In other word, the standard output is controlled by the switching on and off time duration. At constant switching frequency, adjusting the on and off duration of the switch is known as Pulse-Width-Modulation (PWM) switching. The ratio of the on duration to the switching period of your time is understood as switching duty cycle S.

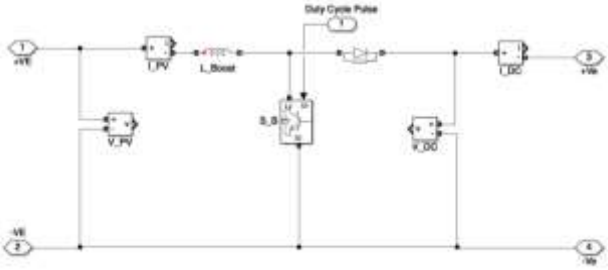

Figure 3 Boost Converter

C. Maximum Power Point Tracking and Algorithm

For any PV system, the output power is often increased by tracking the MPP (Maximum Power Point) of the PV module by employing a controller connected to a dc- dc converter (usually boost converter). However, because of the nonlinear characteristic of PV modules the MPP changes within the insolation level and temperature. Each kind of PV module has its own specific characteristic. Generally, there's one point on the V-I or V-P curve, called the utmost Point (MPP), at which the entire PV system operates with maximum efficiency and produces its maximum output power. Now are often located with the help of MPPT (Maximum Point Trackers). Many different algorithms are proposed for tracking MPP within the past. Commonly used algorithms are Perturb and observe method, Increase conductance method, Constant voltage method, Constant Current method etc. Perturb & observe method is written as P&O method. During this method voltage or current of the PV array is modified to achieve in the MPP as shown within the Figure 4. The PV output power is obtained and compared with the previous one. If the output power increases, the same process is sustained otherwise perturbation is reversed as shown within the Figure 5. During this algorithm perturbation is given to the PV module or the array voltage. This MPPT algorithm is straightforward, easy to implement, and low cost with high accuracy.

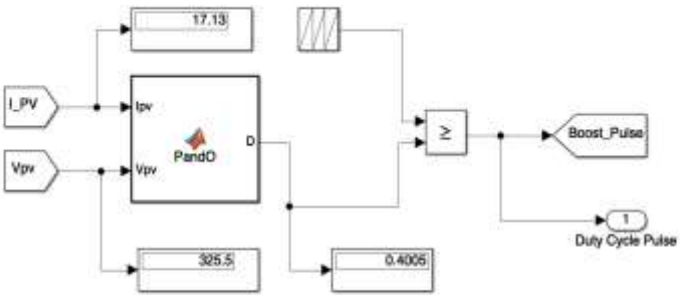

Figure 4 MPPT Controller

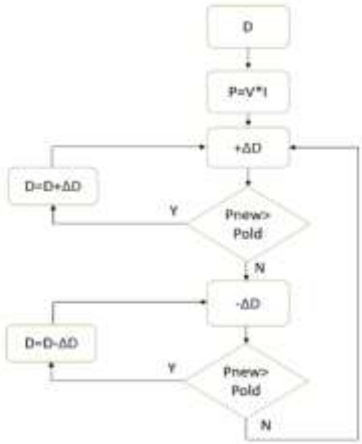

Figure 5 Perturb & Observe Algorithm

D. Three-Phase Inverter and Filter

A 3-phase inverter is used to convert DC voltage into AC voltage and feeds power to consumer loads and utility grid. The 3-phase inverters are utilized in grid connected SPV systems. A 3-phase inverter could also be a six-step bridge inverter. It uses a minimum of six devices as shown within the Figure 6. As stated earlier, the transistor family of devices is now very widely utilized in inverter circuits. Presently the utilization of IGBT in three-phase inverter is on the rise. A capacitor connected at the input terminals makes the input dc voltage constant. This capacitor also represses the harmonics fed back to the source. In inverter terminology, a step is defined as a change within the firing from one IGBT to subsequent IGBT in proper sequence. For a six – step inverter one cycle of 360, each step of 60 intervals. This means that the IGBT would be gated at orderly intervals of a six-step inverter. There are two possible specimens of gating the switches. In one pattern, each switch conducts for 180 and within the opposite each switch conducts for 120. But in both these specimens gating signals are applied and removed at 60 intervals of the output voltage. Here the IGBT switch of three phase inverter conducts for 180 degree. IGBT pairs in each arm i.e. (T1, T2), (T3, T4) and (T5, T6) are turned on with a interval of 180 degree. It means G1 remains on for the 180 degree and G2 conducts for subsequent 180 degree of a cycle. You'll notice from the first row of the above table that T1 conducts for 180° while T4 conducts for next 180° but T1 for 180° then on. Within the second row, T4 from the upper group is shown conducting 120° after T1 starts conducting. After T4 conducting for 180°, T3 conducts for the next 180° and again T4 for next 180° then on. Further, within the third row, T5 from the upper group starts conducting 120° after T3 or 240° after T1. After T5 conduction for 180°, T6 conducts for next 180°, T5 for subsequent 180° then on. During this approach, the pattern for firing of thyristors are recognized.

50Hz frequency output to consumer loads and electric grid is supplied through LCR type filter as shown in Figure 7. The selection of filter resistor, capacitor and inductor are decided by various factors. Generally, the resonant frequency of the filter should be greater than 6 times of desired output frequency to eliminate the upper order harmonics.

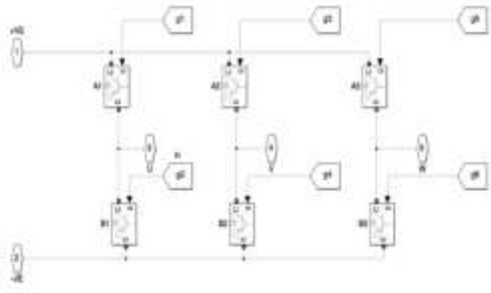

Figure 6 Three-Phase Inverter

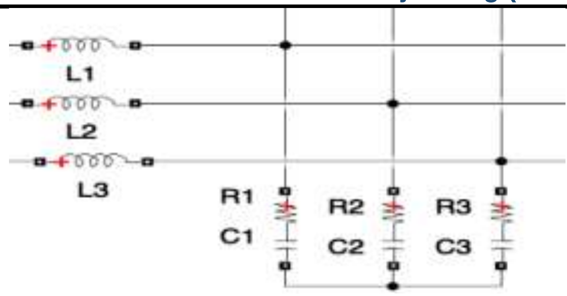

Figure 7 LCR Filter

E. Phase Lock Loop

A closed loop control system which tracks the frequency and maintains the same phase between the input or the reference signal and the output signal by using an internal frequency oscillator is known as Phase Lock Loop (PLL) as shown in the Figure 8. The phase angle of the grid voltage is used to transform the feedback variables (grid's voltages and currents) to a reference frame suitable for the control algorithms. The phase angle in MATLAB is calculated by modelling and designing the PLL. The command signals of reference active and reactive powers are used to calculate the phase angle at which the inverter reference voltage must operate. To achieve synchronization between the two systems; the grid and the PV, the PLL is designed.

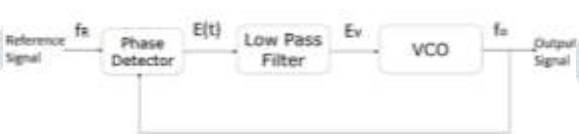

Figure 8 Phase Lock Loop

IV. Control Strategy

Figure 2 shows an absolute control strategy of a three-phase grid-connected PV system based on three phase inverters. The absolute control strategy has been divided into two parts, control of boost converter to maintain a constant DC link voltage as well as to boost the input voltage V_{PV} and control of the inverter configuration in order to achieve unitary power factor operation and proper grid synchronization [3].

A. Control of the DC-DC Converter

Figure 9 depicts that for the maximum power generation from a solar PV module it should operate at MPP. Various MPPT techniques have been studied which not only tracks MPP but also decides the DC link voltage by proper and efficient control of DC-DC boost converter. Amongst various MPPT techniques, Perturb & Observe /Hill climbing is the most widely used technique. P&O algorithm is rooted on perturbation in V_{pv}. From Figure 10 it can be seen that on the left-hand side of the P-V curve, going up the slope, transfers the operating point to MPP whereas on the right-hand side, going down the slope transfers the operating point away from MPP. Thus, the controlled variable V_{pv} of the MPPT can be given as: $Vpv_{new} = Vpv_{old} + \Delta Vpv^{*}$ beta where ΔV_{pv} is the perturbation step size and the multiplier beta denotes the direction of tracking. Beta is +1 if there is increase in power with each successive perturbation in V_{pv} and -1 if there is decrease in power. The polarity of multiplier is maintained sustained until MPP is reached. Once the MPP is reached and crossed the power starts decreasing for which beta reverses its polarity and pushes operating point to MPP from opposite direction of the curve thereby rendering oscillation of the operating point around MPP. This oscillation can be shortened by declining the step size but on the cost of dynamic response of the system. Due to accuracy, ease and feasibility P&O algorithm has been extensively used but as MPPT efficiency is governed by the perturbation step size hence there is a trade-off between efficiency and speed of convergence [3].

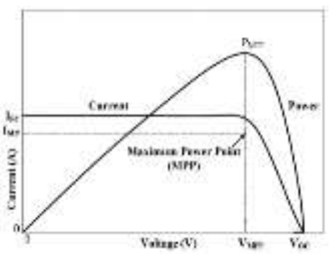

Figure 9 Voltage and Current at MPP

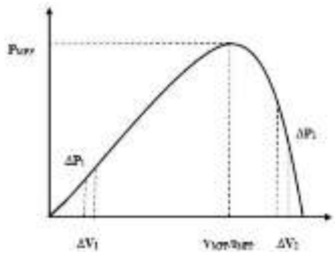

Figure 10 PV Curve of Solar PV System

B. Inverter Controller

A Simulink model for the inverter controller is developed as shown in Figure 11. Using the phase angle of the grid voltages (Θ), the grid's voltages and inverter currents (V_{abc} and I_{abc}) are transformed into dq frame that rotates in synchronous with the grid's voltages and inverter currents. The controller tasks are achieved mainly by two loops; an external voltage loop, which adjusts the DC-link voltage, and an internal current loop, which regulates the inverter currents (I_d and I_q). The reference active-current component (I_d*) is generated by the DC-link voltage controller. Whilst the reactive power controller sets the reference reactive-current component (I_q*). Then, the current references are compared with the measured ones, and the error signals are fed into the current controllers. V_{di} and V_{qi}, output of the current controller, are used as references to the PWM [1]. The MATLAB/Simulink model for grid-voltages and inverter-currents transformation from "abc" to "dq" is shown in Figure 12, Figure 13 shows the generation of PWM gate signals to control the inverter IGBTs. The DC voltage reference is set to 800 V, active power reference is set to 6kW. The simulation results, shown in Figure 14 respectively, match well the set values [1].

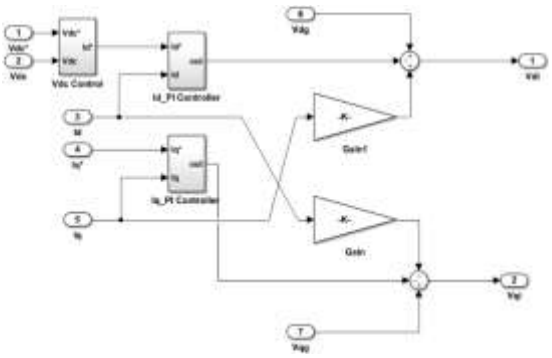

Figure 11 Simulink Model of Inverter Controller

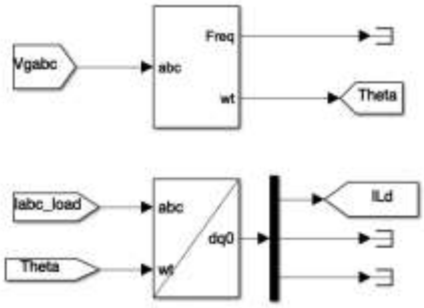

Figure 12 Simulink Block for transforming grid voltages and current from abc-dq0 component

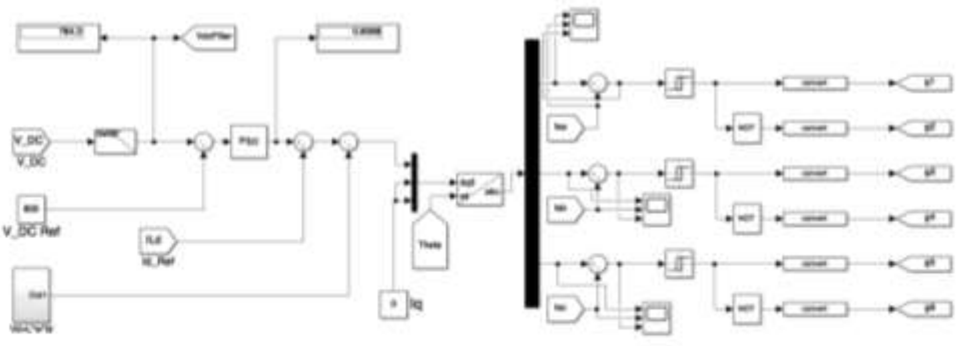

Figure 13 Simulink Block for PWM signals generation to control IGBTs in the inverter

V. Result and Discussion of Grid-Connected PV System

The system is simulated under various irradiance, temperature and grid conditions, and the results are analysed and discussed.

- The PV Array comprises of two parallel strings. Each string has 10 Tata Power Solar System TP300LBZ PV modules connected in series. The PV array is generating a maximum power of 6kW at STC (1000 W/m^2 sun irradiance and 25°C temperature).

- The DC-DC Boost Converter is used to step-up the PV array MPP output voltage (VMPP) from 389V at STC to 700V. The Boost converter is operated at a switching frequency of 10kHz. The duty cycle of the Boost converter is generated by the MPPT controller.

- The MPPT Controller uses the Perturb and Observe (P&O) technique to generate the duty cycle of the Boost converter. This controller automatically varies the duty cycle of the Boost converter in order to extract the maximum power from the PV array.

- Inverter used to convert the 700V DC-link voltage to a rms value of the line- to-line voltage of 415V. The inverter IGBTs are controlled via PWM scheme. The PWM signals are generated by the inverter controller [1].

- The VSI Controller is used to generate the appropriate gate signals for the IGBTs in the inverter in order to generate the required AC voltages and currents, and power [1].

- The Grid Filter is an LCR filter used to filter harmonics produced by the inverter [1].

- The Grid is a 415V grid, to which the PV system is connected [1].

A. Effect of Irradiance on V-I Curve

The first simulation is conducted by increasing irradiance from 0W/m^2 to 1000W/m^2 at 25°C temperature as per the STC shown in the Figure 14.a. The simulation results are shown in Figure 14 (a, b, c, d). From the figures, it is possible to conclude the followings: The DC-link voltage is equal to the set value; 800V DC [1]. Increasing the irradiance will increase the PV voltage and current which obviously give rise in the output power. The output power for the inverter equals 5860W, which means that the inverter has 96% efficiency (the PV array power is 6kW).

Figure 14.a Irradiance and Temperature

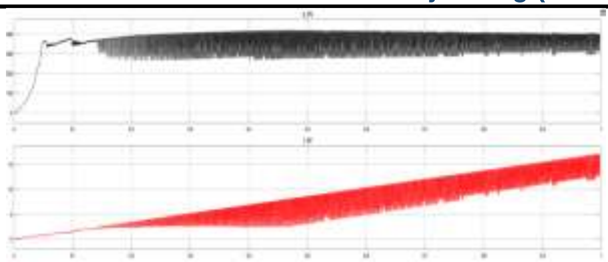

Figure 14.b PV Voltage and Current

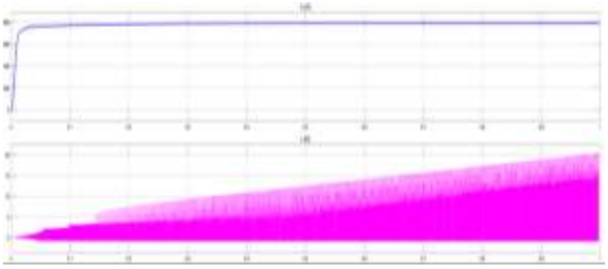

Figure 14.c DC Voltage and Current

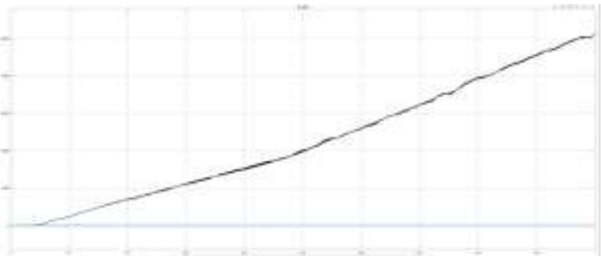

Figure 14.d DC Output Power

B. Effect of Temperature on V-I Curve

The second simulation is conducted by increasing temperature from 0°C to 25°C at a constant irradiance 1000W/m^2 per the STC shown in the Figure 15. a. The simulation results are shown in Fig.15 (a, b, c, d). From the figures, it is possible to conclude the followings: The DC-link voltage is equal to the set value; 800V DC. Increasing the temperature will decrease the PV voltage and increase the PV current which obviously decreases the output power. The output power for the inverter equals 5200W, which means that there is a decrease in the inverter efficiency.

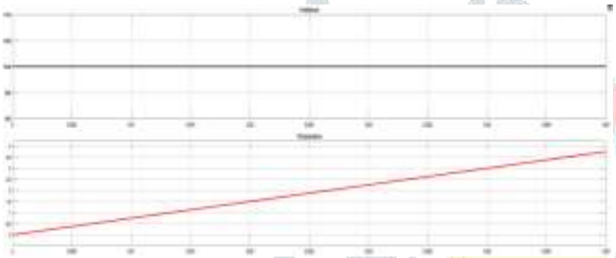

Figure 15.a Irradiance and Temperature

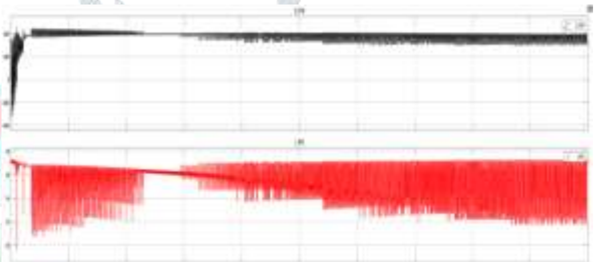

Figure 15.b PV Voltage and Current

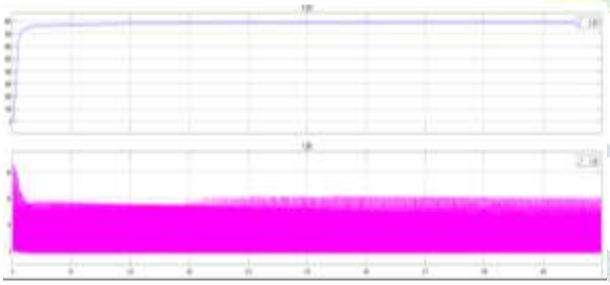

Figure 15.c DC Voltage and Current

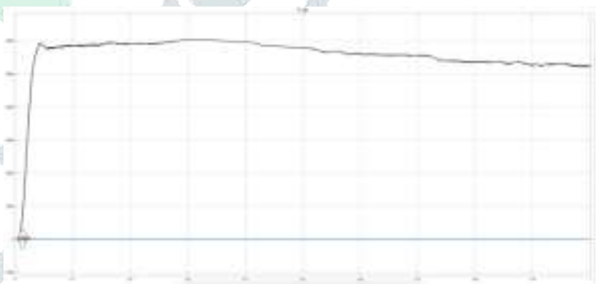

Figure 15.d DC Output Power

C. Effect of Linear Load on PV System

The third simulation is conducted by using linear load in the PV system keeping the irradiance and temperature as per the STC condition. The simulation results are shown in Figure 16. From the figures, it is possible to conclude the followings: voltage and the current waveforms are in phase with each other and are also in sinusoidal.

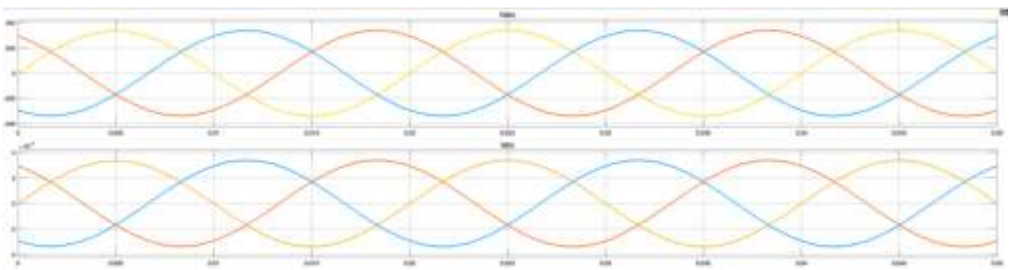

Figure 16 AC Voltage and Current of Linear Load

D. Effect of Non-Linear Load on PV system

The fourth simulation is conducted by using non-linear load in the PV system keeping the irradiance and temperature as per the STC condition. The simulation results are shown in Figure 17. From the figure, it is possible to conclude the followings: the current isn't proportional to the voltage and it fluctuates based on the alternating load impedance. It draws current in abrupt short pulses. These pulses distort the current waveform, which conducts harmonics that can affect power in both the distribution system equipment and the load connected to it.

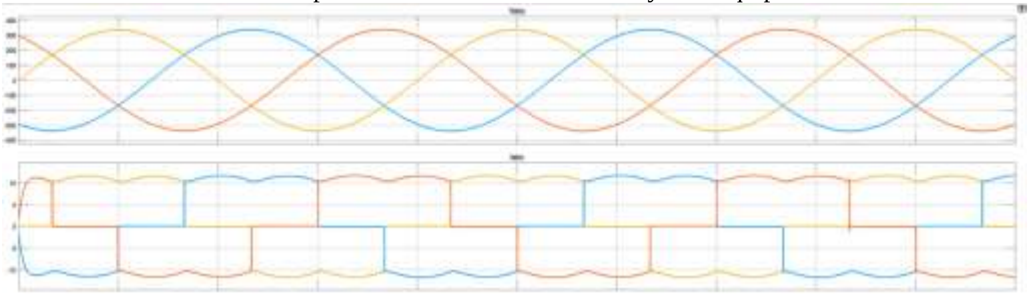

Figure 17 AC Voltage and Current of Non-Linear Load

VI. Conclusion

In this paper, a detailed modelling of the complete Grid-Connected Photovoltaic System in MATLAB/Simulink environment is presented and implemented. The model is simple and accurate, and imitates a real Grid-Connected PV system. The model achieves Maximum Power Point Tracking, via Perturb and Observe algorithm [1] is implemented which show highly efficient tracking with an efficiency of 99.4%, voltage-oriented controller with decoupled controller is implemented as a algorithm for three-phase inverter current to be in synchronization with the grid, and an accurate control over the injected active and reactive powers to the grid. The simulation results are validated against the Datasheet of real Photovoltaic Array (Tata Power Solar System), and the simulation results match well the real Datasheet. The gate signals of the inverter's IGBTs implement PWM (Pulse Width Modulation) scheme to reduce the switching losses and improve the PV system's efficiency. The simulation results show that the modelled system operates successfully under different irradiance and temperature conditions. It also shows the effect of linear and non-linear load on the PV system.

VII. References

1. Motan, N. and Abu-Khaizaran, M., Design and Modelling of a 6kW Grid-Connected Photovoltaic System-AC Stage. In *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*(pp. 1-7). IEEE.

2. Cen, Z., 2017. Modeling and simulation for an 8 kW three-phase grid-connected photo-voltaic power system. *Open Physics*, *15*(1), pp.603-612.

3. Pathak, P.K., Yadav, A.K. and Tyagi, P., 2018, December. Design of three phase grid tied solar photovoltaic system based on three phase vsi. In *2018 8th IEEE India International Conference on Power Electronics (IICPE)* (pp. 1-6). IEEE.

4. Arjyadhara, P., Ali, S.M. and Chitralekha, J., 2013. Analysis of solar PV cell performance with changing irradiance and temperature. *International Journal of Engineering and Computer Science*, *2*(1), pp.214-220.

5. Mahanta, P.K., Debnath, K. and Rahman, M.H., 2014. Modeling and Simulation of a PV Module Based Power System Using MATLAB/Simulink. *Dhaka University Journal of Science*, *62*(2), pp.127-132.

6. Lakshmanan, S.A., Rajpourhit, B.S. and Jain, A., 2014, March. Modeling and analysis of 3-phase VSI using SPWM technique for grid connected solar PV system. In *2014 IEEE Students' Conference on Electrical, Electronics and Computer Science*(pp. 1-6). IEEE.

7. Anil, G., Murugan, N. and Ubaid, M., 2013. PI Controller based MPPT for a PV System. *IOSR Journal of Electrical and Electronics Engineering*, *6*(5), pp.10-15.

8. Parkhi, V.P. and Punam, S.R., Technology of Grid Connected Solar PV System.

9. Sharma, G., A Review on Grid-Connected PV System.

10. S. Sumathi, L. Ashok Kumar, P. Surekha. "Solar PV and Wind Energy Conversion Systems", Springer Science and Business Media LLC, 2015