Modeling and Simulation of Single Phase Grid Connected Photovoltaic System

Dr. Arun Moyal

Associate Professor
Department of Electrical and Electronics Engineering
SRM Institute of Science and Technology

***Abstract*: This research work presents modelling of 10kw single-phase grid-connected Photovoltaic system with the use of MATLAB / Simulink software. This research paper outlined the design of PV model by the help of mathematical equations, solar maximum power point tracker (MPPT), DC/DC Boost converter, single-phase full-bridge inverter with pulse width modulation (PWM) switching technique and phase lock-loop (PLL). To design the proposed model, firstly all the parameters which are necessary, has been calculated and the system integration is done by using MATLAB/Simulink software. The Simulink results represents that the proposed model is able to synchronize with grid system, which has matching frequency and amplitude. Along with an appropriate low pass LC filter circuit is designed, Which reduces the total harmonic distortion (THD) in the ac output voltage significantly i.e. from 67.99% to 1.54%.The Modelling technique is very simple, Which is discussed in detail in this paper.**

***Keywords*: PVcell; PVarray; P&OMPPT algorithms; Boost converter; single phase inverter; PLL, LC filter.**

I. INTRODUCTION

Now a days the requirement of electric energy increases gradually. As a result, we are focusing on rapid production of that. The most common method of power production is the thermal power generation. And the use of coal produces flue gas and ash which is responsible for atmospheric pollution and greenhouse gas.

Hence, we should focus on alternate source for the production of electric energy from non-renewable sources. As it is a clean and permanent source of energy.

Time comes to hold the hands of renewable energy which comprises solar energy, tidal energy and wind energy.

Solar energy becomes a most important and efficient form of energy production from all the forms of renewable energy as it needs fewer maintenance. Along with that it has no pollution and long life. To deliver the power to the load or to grid, power converters are used along it. So that generated power can be transferred most efficiently. The complete is called as photovoltaic system. The photovoltaic system has two types from its configuration and application, i.e. grid connected system and stand-alone system [1].

Grid connected solar PV system has more advantages as compare to the standalone PV system. Here exchange of electricity can be made possible from or to the electric grid depends upon the load demand. Hence the cost of electricity bill will be reduced automatically because the net electricity consumption is condensed by directing the extra electricity to the grid. The main advantage of using grid connected system is, it doesn't require any battery backup system by which there is no storage losses in the system so that more power can be delivered to the load [2].

In this paper, the detail modelling of 10kW grid connected PV system in MATLAB/Smulink has been discussed. The proposed modelled system consists of a solar PV array, MPPT (P&O algorithms) to extract maximum power the PV array to feed the system, DC-DC boost converter for regulation and boosting the output of PV array, a single phase inverter to convert DC power into AC power an LC filter to filter harmonics from the inverter output.

II. PHOTOVOLTAIC MODEL

From the study of physics, it has been cleared that Photovoltaic cell is a semiconductor device with thin wafer fabrication. The solar radiation is consisting of beam of electromagnetic wave. According to the law of physics by the great scientist, Einstein i.e. $E=h\lambda$, Which describes the photovoltaic effect and its working principle, Means when the spectrum of electrons in the form of solar irradiance fall on the PV cell, which is a P_N junction diode that converts the sunlight directly into the direct electricity (DC).The definition of solar irradiance is 'The rate of flow solar intensity per unit area (kW/m2)'. PV cell is current source rather than voltage source. The output of the PV cell is DC in nature rather than AC. The generated photons, which are obtained from solar panel will be get absorbed by the further electric system only if the those photons crosses the band-gap energy barrier of that semiconductor which is used for that PV cell design, if not they will create electron-hole pair.[1-3].The pv output power generation depends on mainly two parameters i.e. solar irradiance and temperature, where the solar irradiance directly proportional to the power generation mean while temperature is inversely proportional to it. By these environmental effects PV cell has nonlinear I_V & P_V characteristics.

A. *Solar Cell:*

It is one type of P-N junction diode. A single solar cell is insufficient for the application because it capable of producing maximum 2-watt power [13].

B. *Solar module:*

To overcome the insufficient power generation of PV cell, a number of PV cell will be connected in series and parallel to give rise the sufficient power for our normal application requirement, this is called as solar module.

C. *Solar array*:

When the solar module connected to the electrical equipment to transfer the generated electricity from the cell to the load, this complete unit is called as Solar array. According to the demand of the load the solar module can be connected in series and parallel to comprise the PV array. PV array modelling has been done by considering single diode of PV cell [1]. The basic equations and circuit diagram came into consideration for the modelling of solar cell. When the number of solar cell and solar panel will be connected in series or parallel then the equations will be changed according to them.

The equivalent circuit diagram of a single solar cell is shown in Fig. 1.

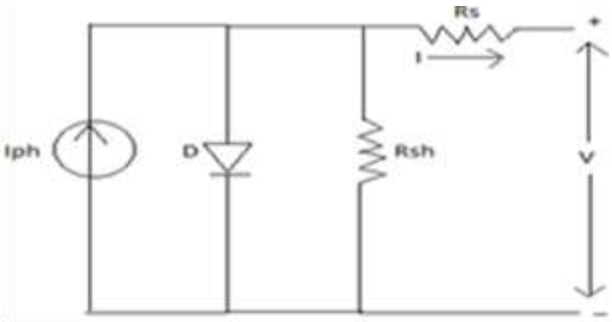

Figure 1: Single diode model of PV Cell.

The below written equations from (1) to (6) are used to model the single solar cell where equation (7) represents the number of cells connected in series and parallel.

$$\mathrm{I} = Iph - Id - Ish \qquad (1)$$

$$Iph = [Isc + Ki(Tc - Tref)]G \qquad (2)$$

$$Id = Is[\exp\left(q\left(\frac{V + I * Rs}{Ki * Tc * A}\right) - 1\right] \qquad (3)$$

$$Ish = (V + IRs) \div Rsh \qquad (4)$$

$$Is = Irs\left(\frac{Tc}{Tref}\right)^{3\exp}\left[\frac{qEg\left(\frac{1}{Tref} - \frac{1}{Tc}\right)}{kA}\right] \qquad (5)$$

$$Irs = \frac{Isc}{[\exp\left(\frac{q * Voc}{Ns * k * A * Tc)}\right) - 1]} \qquad (6)$$

$$I = NpIpv - NpI0\left[\frac{\exp \quad \left(\frac{(V + IRs)}{Ns}\right)}{ANVth} - 1\right] - \frac{V + IRs}{Rp} \qquad (7)$$

Where:
G: Solar irradiance
I: PV output current
Iph: Current from PV cell (Photo current)
Is: Cell reverse saturation current
Irs: Reverse current in the cell.
q: Electric charge (1.6e-19C)
Id: Schottky diode current.
Ish: Current from shunt resistor
Ki: Cell current temp. Coefficient

Tc: Cell temperature
Tref: Ambient temperature (25℃)
A: PV cell ideal factor
N: Total number of modules
K: Boltzman'sconstant (1.38e-23 J/K)
Eg: Energy band-gap.
Ns:Number of series connected solar panels
Voc: PV cell open circuit voltage
Isc: PV cell short circuit current
V: PV Boltzmann's voltage
Rs: Series resistance
Rsh: Shunt resistance
Np:Number of parallel connected solar panels

C. *Solar irradiance(G):*

'The rate of flow of solar intensity per unit area' is recognized as solar irradiance. The solar irradiance variable in nature it varies according to the geographical regions. It has directly proportionality property with the generated photo current. 1000W/m2 solar irradiance has been taken as standard test condition in world wide.

D. *PV Output Current(I):*

The output current of PV is the summation of mainly three current sources that are photo current, Schottky diode current and the current through shunt resistance of the solar array. It has been represented in the equation (1) and modelling of I shown in the fig.2

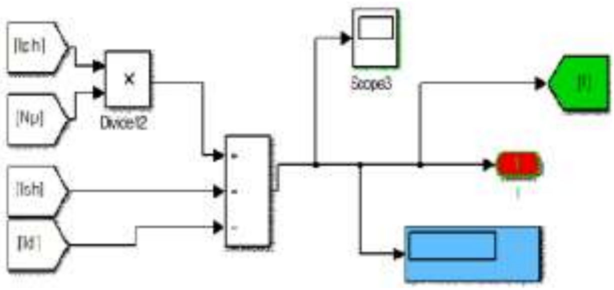

Figure 2: PV output current Modelling

E. *Photo Current (Iph):*

The electric current obtained from photosensitive diode when this diode is exposed to the sunlight is called as photo current. The photo current has been represented in the equation (2) and its modelling shown in the fig.3.

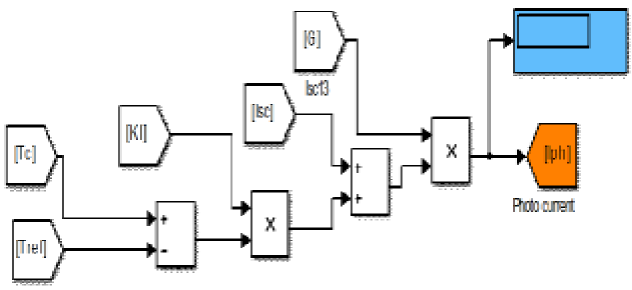

Figure 3: Photo Current Modelling

G. *Diode Current (Id)*:

The Current has been obtained through the Schottky diode, is known as diode current. The equation (3) represents the diode current, from the equation it can be observed that Id depends upon the reverse saturation current. Fig.4 represents the diode current model.

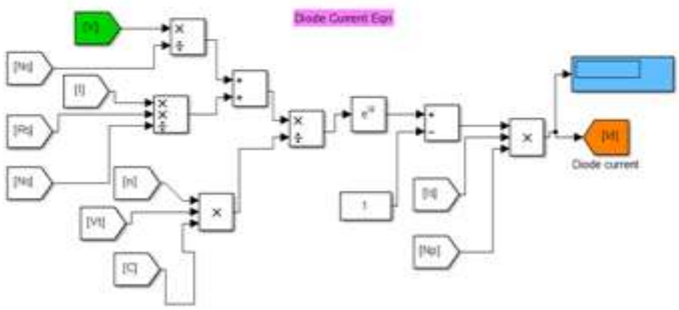

Figure 4: Diode Current Modelling

F. *Cell reverse saturation current (Is):*

When the solar cell is exposed to the low intensity of solar light then cell reverse saturation current will be developed within the solar cell. The reverse saturation of one diode will affect another diode. The recombination in the device has been measured by the Is. In equation (5) the reverse saturation current is represented and its modelling shown in the fig.5

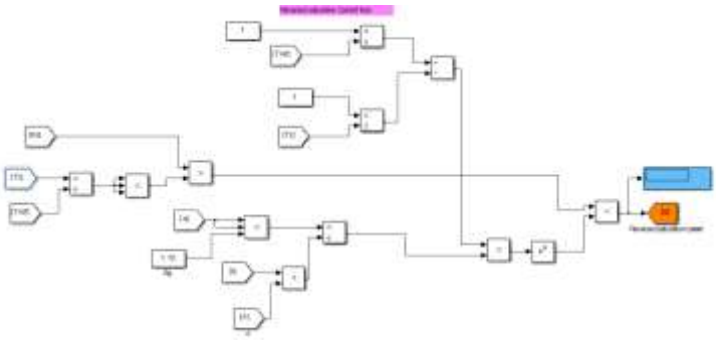

Figure 5: Reverse saturation current Modelling

E. Cell Reverse Current (Irs):

The cell reverse current depends upon the open circuit voltage, short circuit current and cell ambient temperature. The equation (6) represents the reverse current and its modelling shown in the fig.6.

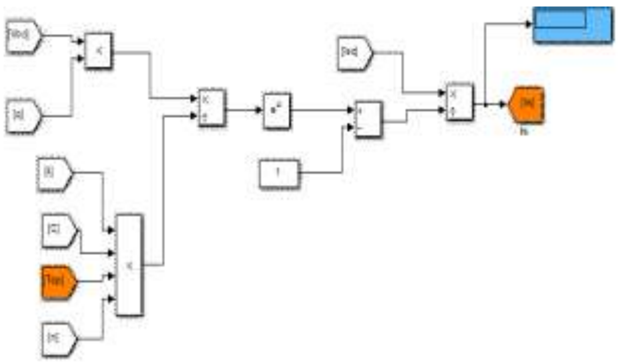

Figure 6: Cell Reverse current Modelling

F. *Series resistance (Rs):*

While designing the solar cell the series resistance value is kept very low and some manufacture ignore it because it is connected in series with load, so that if we take Rs value high then the current from the cell to load decreases because of the property of the resistance.

G. *Shunt resistance (Rsh):*

By reducing the cell leakage current the power loss will be reduced too, it can be achieved when the cell shunt resistance will be kept high. Because it plays an obstacle path for the current flow to the ground. So virtue of that maximum amount of current will flow to the load through low series resistance path. It plays important role at low intensity levels. The current through the shunt resistor is called as shunt current and it has represented in the equation (4). The modelling of shunt current has shown in the fig.7.

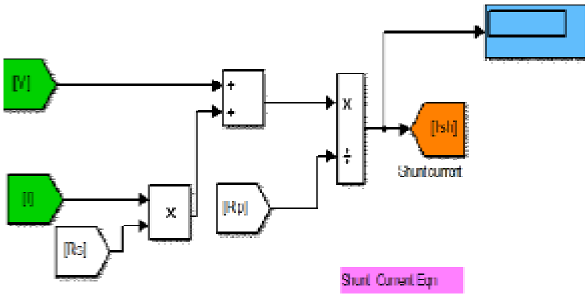

Figure 7: Shunt Current Modelling

H. *Modelling of PV array:*

The PV array of 10kW has been modelled by taking 5 sun hours from 350W solar panels. In Appendix-A the datasheet of this panel is given. The values of parameters given in the datasheet are being used in the design of PV array model. PV array has been modelled using all equations (7). The complete modelling of PV array has been shown in fig.8.

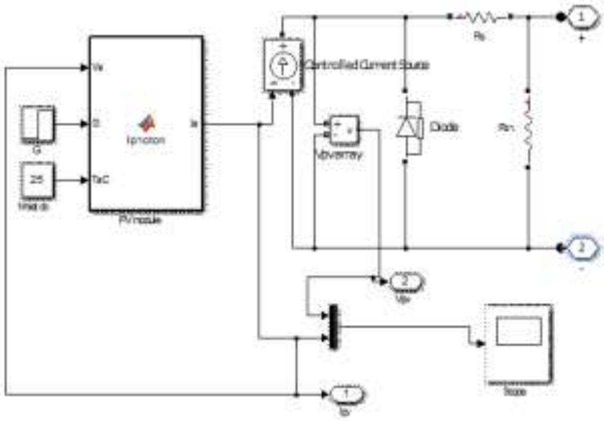

Figure 8: Complete PV array modeling.

III. Maximum Power Point Tracking (MPPT)

.Now a days it has been observed electricity generation from photovoltaic system increasing rapidly, so that it can be taken into consideration as a prominent alternative source to fossil fuels. However the initial cost for installation is quite and also its efficiency is typically low (18%-22%). To emphasize the efficiency another important feature is added to the PV system which can track the maximum power from the PV array [8]. That special feature is known as maximum power point tracker (MPPT). It is used in both grid connected and standalone system, because temperature and solar radiation changes throughout the day along different seasons and also different geographical conditions. Since there are various MPPT approaches available in the literature, which are mainly the fixed duty cycle method, constant voltage (CV), perturb and observe (P&O), and incremental conductance (IC). Among all P&O technique has been considered for this proposed model. MPPT is nonlinear because it considers the climatic conditions (i.e. temperature, irradiance, cloud, wind velocity) at each and every second at that geographical region where it is working.

A. *Perturbation observation (P&O) method:*

Typically, P&O method has been used for tracking the MPP in the P_V curve. A minor Perturbation has been introduced in this technique, to cause the power variation of the PV array and it has observed .In this technique the power obtained from PV array has been measured periodically and then present obtained power is compared with the previously obtained power .If this technique the power curve has been observed and the process will be continued if the power increases or else the perturbation will be reversed. This algorithm technique can be applied to the array voltage or module. In this technique to check the power is increasing or decreasing, the PV module voltage has been checked first. The operating point of PV module will be on the left of the MPP, when the PV module voltage increases which leads to increase the power [9]. Further perturbation has required towards the right to reach MPP. If it is observed that increase in voltage leads to decrease in power that means the operating point is on the right of the MPP and hence further perturbation toward the left has been required to reach MPP.

The flow chart of the adopted P&O algorithm for the charge controller is shown in fig. 9. This MPPT algorithm is quite simple, easy to implement. Its cost is low with high accuracy [8]. In application it is found that it most effective.

Figure 9: Flowchart of P&O Algorithm

IV. BOOST CONVERTER

A DC-DC boost converter has been implemented to boost and the regulate the PV array output voltage [4-6]. The voltage obtained from the PV module will be fed into the boost converter and it is regulated by the MPPT tracker through the gate pulse into the use IGBT of the boost converter. The parameters values have been obtained by the equation (8) to (10). The boost converter circuit model has shown in the Fig.10.

The converter output is given by:

$$Vout = {}^{Vin}/_{1-D} \quad (8)$$

$$L > Vin * D/f * \Delta I \quad (9)$$

$$C1 = C2 = Vout * D/2f\Delta Vout * Rload \quad (10)$$

Where, Vout is nominated for output voltage, Vin for the input voltage, D is for duty cycle, f is the converter frequency, ΔI represents current ripple, $C1$ and $C2$ are the capacitances of the capacitors, $\Delta Vout$ is given for the output voltage ripple and $Rload$ is for the load resistance given by $Vout/Iout$.

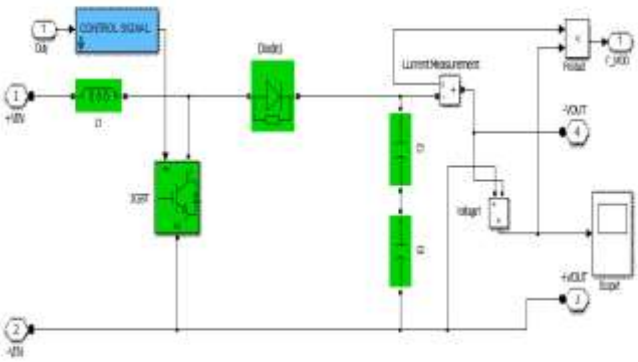

Figure 10: Boost Converter Modelling

V. DC to AC Converter:

To convert DC power into AC, Single phase voltage source converter is used. In the inverter, the on and off period of the IGBT has been controlled by the gate signals. Inverter control loop generates these gate signals. The inverter control loop which has been designed for the proposed work consists of Phase locked loop (PLL) and 2-level PWM generator, which are Simulink blocks. Single phase grid voltage and current are inputs to the control loop. The controlled PWM signals has been obtained from the inverter control loop [7-9]. The controlled PWM signals are being used for switching on and off of IGBT switch in inverter. After all this process the inverter starts to generate single phase synchronized sinusoidal voltage and currents. To reduce the voltage and current harmonics from the inverter output, then the low pass LC filter circuit has been implemented along with the inverter circuit.

A: Phase locked loop (PLL)

The wide ranges of applications of PLL circuits in telecommunication and in system engineering has been found. In its feedback look, it contains an adjustable frequency oscillator and a phase detector. From the oscillator the periodic signal has been produced and then that periodic signal will be compared with the period of the input signal to the PLL circuit by the phase detector. To keep the phase match, meanwhile the oscillator adjusts the phase of the signal. In this case, PLL has been used to monitor the AC grid frequency utility and then signal matches to the frequency is being generated. For any change in the grid frequency, the PLL circuit should response and then the signal will be used for the synchronous of the switching of inverter [10-11].

To have a PLL module in the grid connected system is essential. In the PLL loop the grid AC voltage has been taken as a reference for the generation of the estimated grid frequency and the estimated phase angle. Then the two signals have been compared with the reference input signals and the feedback the signal in every single point by the phase detector. A terrain of pulse will be produced from the phase detector when the phase of the two-input signal is different. The degree of phase difference is being proportional with the width of the pulse. For making equal inverter output and grid angle, PLL plays an important role. The modelled PLL block is shown in the Fig.11.

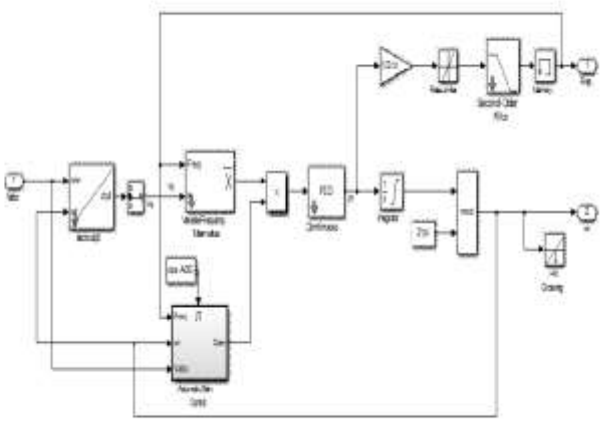

Figure 11: PLL Converter Modelling

B: LC filter:

For filtering the inverter output a LC low pass filter is being used in this paper. By using it the harmonics has been reduced from the output voltage. In the perfect voltage source, the distortion in voltage will not occur even if there will be any imbalance load or nonlinear load. The inverter output impendence must be kept zero [12]. In the low pass filter the capacitance value should be increased and the inductance value should be limited at the chosen cut-off. To reduce the reactive power in the system, the values of inductance and capacitance should be determined. The value of the internal resistance of the inductor is taken as very small. The single-phase LC filter can be calculated by equation (11).

$$Voltage\ gain = \frac{Vin}{Vout} = \frac{1}{LCS2 + RCS + 1} \qquad (11)$$

For investigation the filter is made in the frequency domain. In equation (12) represents the pick-up voltage for a low pass LC filter.

$$H(j\omega) = \frac{W_p^2}{s^2 + \frac{sW_p}{Q} + W_p^2} \qquad (12)$$

Where, Wp and Q represents the natural oscillating frequency and quality factor respectively. It is demonstrated with explanation of peaked resonances in (13), or $Q > \frac{1}{\sqrt{2}}$,the frequency at which H(jω) has maximized and the corresponding maximum shown on (14)

$$\frac{W}{W_p} = \sqrt{(1 - \frac{1}{2}Q^2)} \qquad (13)$$

$$H(j\omega)_{max} = \frac{Q}{\sqrt{(1 - \frac{1}{4}Q^2)}} \qquad (14)$$

The sufficiently large Q will be obtained, when Q> 5, W/Wp=1 and H(jω) max=Q. By arranging equation (13) and then by comparing with the equation (11) will results

$$LC = \frac{1}{W_p^2} \qquad (15)$$

$$RC = \frac{1}{QW_p} \quad (16)$$

The value of Capacitance(C), inductance (L) and resistance (R) has been obtained by solving the equation (15) and (16).

VI. SIMULATION AND RESULTS

The 10kW designed grid connected system has been tested with Single phase 1.5 kW load. The complete grid connected model is shown in the fig.12. The total harmonic current compensation has been implemented in the proposed model by using a LC low pass filter. In the proposed system the rms value of the voltage source (grid)has been given 220v along with the single-phase universal bridge rectifier nonlinear RL load across it, by virtue of this nonlinear load the harmonics has been introduced into the system. The Grid synchronization has been obtained by Using PLL represented in the fig.13. In fig.14 represented the power obtained from this 10kW model. When the inverter output is less than the load demand at that point the grid supplies the power, it can be analyzed from the positive half of the power plot. On the other hand, when the output of inverter is more than the load demand, then the extra amount electricity will be fed to the grid, it can be analyzed from the negative half of the power plot. The Total Harmonic Distortion (THD) spectrum in the system without filter is shown in Figure 14, which indicate a THD of 67.99%. The THD with LC lowpass filter is observed to be 1.54% which is within the allowable harmonic limit. Figure 15 shows the THD spectrum with LC low pass filter in the circuit.

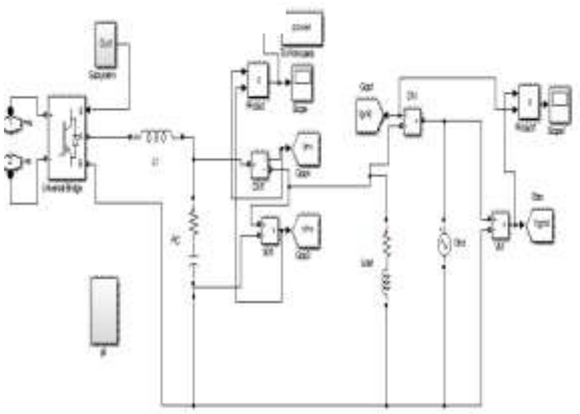

Figure 12: Single phase Grid connected system modelling

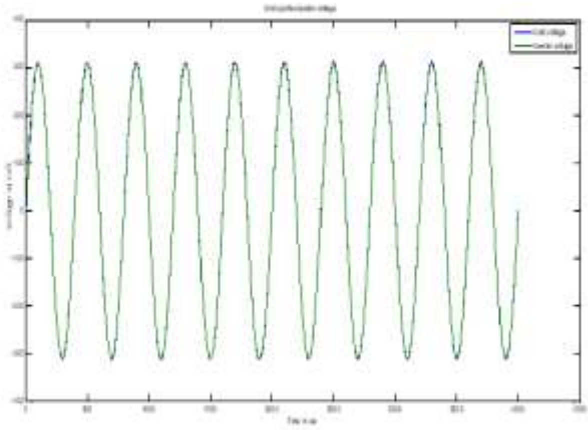

Figure 13: Output Synchronized Voltage wave form

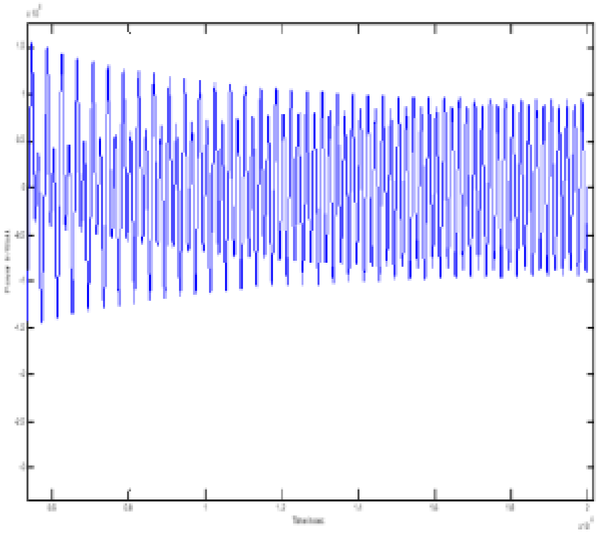

Figure 14: Output Power wave form

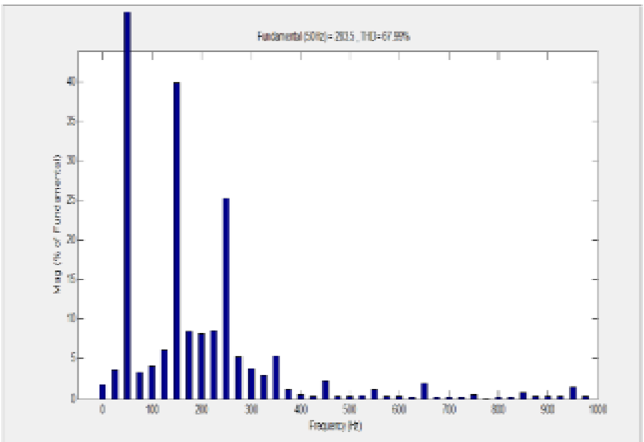

Figure 15: FFT analysis of voltage without filter circuit

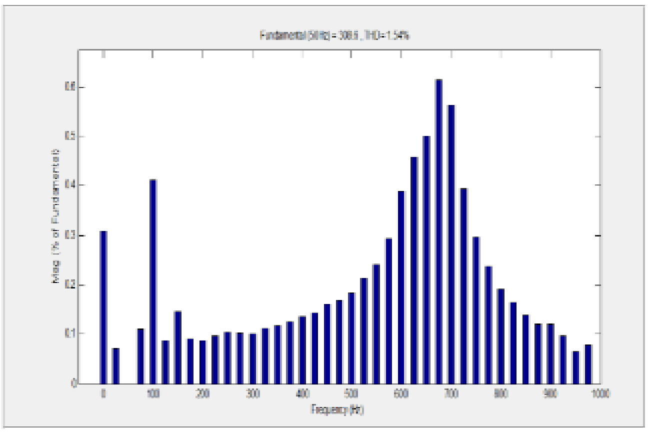

Figure 16: FFT analysis of voltage with filter circuit

VII. CONCLUSION

The modelling of 10kW grid connected photovoltaic system by aiming at home based solar PV application is being proposed in this paper. The modules which we are using in the model have defined in the details. For maximizing the output obtained from the PV array, P&O algorithm based MPPT was used along with the boost converter. For the propose of application and also for feeding to the load, an inverter was designed which converted the DC voltage and current to AC values along with the LC filter, the THD was significantly reduced from 69.77% to 1.54%..The inverter was designed along with PLL, which locked the phase of the grid and inverter voltages. The model is designed successfully using MATLAB/Smulink software. Future work is to implement this model in real time and design the three phase grid connected system by taking the same datasheet of PV array.

APPENDIX-A

In Appendix electrical parameters are stated which are used in simulation.

PARAMETER	VALUES
Ki	0.00023A/K
Irr	0.00002A
K	1.38065*10^-23 J/K
Q	1.6022*10^-19C
A	2.15
Eg0	1.66ev
α	4.73*10^-4 ev/k
β	636k
Np	4
Ns	90
Iscr	3.75A
Tr	40 ℃
Vnormal	47.1v
Inormal	8.9A
Pmax	350Watt

REFERENCES

[1] Chedid, R.; Tajeddine, R.; Chaaban, F.; Ghajar, R., "Modeling and simulation of PV arrays under varying conditions," In Mediterranean Electrotechnical Conference (MELECON), 201417th IEEE , vol., no.,pp.536-542

[2] M. G. Villalva, J. R. Gazoli and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," in IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198- 1208.

[3] Gow, J.A.; Manning, C.D., "Development of a photovoltaic array model for use in power-electronics simulation studies," in Electric Power Applications, IEEE Proceedings, vol.146, no.2, pp.193-200

[4] Analysis of photovoltaic cells with closed loop boost converter, International Journal of Advances in Engineering & Technology, Mar. 2013. ©IJAET ISSN: 2231-1963.

[5] A. A. Bakar, W. M. Utomo, S. A. Zulkifli, E. Sulaiman, M. Z. Ahmad,and M. Jenal, "DC-DC Interleaved Boost Converter using FPGA," in *IEEE Conference on Clean Energy and Technology*, 2013, pp. 97–100.

[6] A. A. Bakar, W. M. Utomo, T. Taufik, and S. Aizam, "Dc / Dc BoostConverter With Pi Controller Using," *ARPN J. Eng. Appl. Sci.*, vol. 10,no. 19, pp. 9078–9082, 2015.

[7] "A New Approach to Design of an optimized Grid Tied Smart Solar Photovoltaic (PV) System". International Journal of Advancements in Research & Technology, Volume 1, Issue6, ISSN 2278-7763, November-2012

[8] S. Borekci, E. Kandemir, and A. Kircay, "A Simpler Single-PhaseSingle-Stage Grid-Connected PV System with Maximum Power PointTracking Controller," *Elektron. ir Elektrotechnika*, vol. 21, no. 4, pp.44–49, 2015.

[9] A. H. Mollah, P. G. Kpanda, and P. P. Ksaha, "Single Phase Grid-Connected Inverter for Photovoltaic System with Maximum Power," pp.648–655, 2015Power Electronics, Mohan, Undeland, Riobbins.

[10] K N Dinesh Babu, Ramaprabha, Ramabadran, Veeraraghavalu Rajiniand Bansal Kamal, "Charge Pump Phase Locked Loop SynchronizationTechnique in Grid Connected Solar Photovoltaic Systems," *IOSR J.Comput. Eng.*, vol. 16, no. 1, pp. 91–98, 2014

[11] M. Barnes and Siyu Gao, "Phase-Locked Loops for Grid-Tied Inverters:comparison and testing," *8th IET Int. Conf. Power Electron. Mach.Drives (PEMD 2016)*,no. c, p. 6 .-6 ., 2016.

[12] A.A. Bakar, M.A.N. Amran, S. Salimin, M.K.M. Jamri and A.F.H.A.Gani" Modeling of Single-Phase Grid-Connected usingMATLAB/Simulink Software" 2019 IEEE Student Conference on Research and Development (SCOReD)October 15-17, 2019, Seri Iskandar, Perak, Malaysia

[13] http://pveducation.org/pvcdrom