An Efficient Constant Current Controller for PV Solar Power Generator Integrated with the Grid

Sweeka Meshram
Deptt. of Electrical Engg.
MANIT, Bhopal
Bhopal (MP), INDIA 462051
sweekam@gmail.com

Ganga Agnihotri
Deptt. of Electrical Engg.
MANIT, Bhopal
Bhopal (MP), INDIA 462051
ganga1949@gmail.com

Sushma Gupta
Deptt. of Electrical Engg.
MANIT, Bhopal
Bhopal (MP), INDIA 462051
sush_gupta@yahoo.com

Abstract— **This paper presents the detailed design and modeling of grid integrated with the Photovoltaic Solar Power Generator. As the Photovoltaic System uses the solar energy as one of the renewable energies for the electrical energy production has an enormous potential. The PV system is developing very rapidly as compared to its counterparts of the renewable energies. The DC voltage generated by the PV system is boosted by the DC-DC Boost converter. The utility grid is incorporated with the PV Solar Power Generator through the 3-□ PWM DC-AC inverter, whose control is provided by a constant current controller. This controller uses a 3-□ phase locked loop (PLL) for tracking the phase angle of the utility grid and reacts fast enough to the changes in load or grid connection states, as a result, it seems to be efficient in supplying to load the constant voltage without phase jump. The complete mathematical model for the grid connected PV system is developed and simulated. The results verify that the proposed system is proficient to supply the local loads**.

Keywords - PV Solar Power Generator, DC-DC Boost Converter, PWM inverter, PLL, Constant Current Controller (CCC).

I. INTRODUCTION

The continuous increase in the electrical energy with the clean environment needs the decentralized renewable energy production. The increasing energy consumption may overload the distribution grid as well as power station and may cause the negative impact on power availability, security and quality. The only solution to overcome this problem is integrating the utility grid with the renewable energy systems like solar, wind or hydro. The grid[1] can be connected to the renewable energy system as per the availability of renewable energy sources. Recently the solar power generation systems are getting more attention because solar energy is abundantly available, more efficient and more environment friendly as compared to the conventional power generation systems such as fossil fuel, coal or nuclear. The PV systems are still very expensive because of higher manufacturing cost of the PV panels, but the energy that drives them -the light from the sun- is free, available almost everywhere and will still be present for millions of years, even all non-renewable energy sources might be depleted. One of the major advantages of PV technology is that it has no moving parts. Therefore, the PV system is very robust, it has a long lifetime and low maintenance requirements. And, most importantly, it is one solution that offers environmentally friendly power generation.

The disadvantage of the PV system is that it can supply the load only in sunny days. Therefore, for improving the performance and supplying the power in all day, it is necessary to hybrid the PV system into another power generation systems or to integrate with the utility grid. The integration of the PV system with the utility grid requires the PWM voltage source converter for interfacing the utility grid and results some interface issues [1]. A prototype current-controlled power conditioning system has been developed and tested. This prototype sources 20 kW of power from a photovoltaic array with a maximum power point tracking control. The disadvantage of this system is the need of high bandwidth current measurement transducers (dc to several times the switching frequency), and the need for relatively high precision in the reference signal generation. Hence, this increases the cost of the system [2]. The inverters suitable for the PV system are central inverters, string inverters, Module integrated or module oriented inverters, multi string PV inverter with new trends has been described in [3]. If these solar inverters are connected with the grid, the control of these inverters can be provided using the phase locked loop [4]. The need and benefits of the distribution technology has been presented [5-6]. Single-phase Grid connected PV inverters with the control has been described with its advantages and disadvantages [7]. The three-phase Photovoltaic power conditioning system with line connection has been proposed with the disturbance of the line voltage which is detected using a fast sensing technique. The control of the system is provided through the microcontroller [8]. Power electronic systems can also be used for controlling the solar inverter for interfacing the Solar Power Generation system with the grid [9-11]. The complete design and modeling of the grid connected PV system has been developed to supply the local loads [12-13].

978-1-4673-0766-6/12/$31.00 ©2017 IEEE

This paper proposes the modeling of the grid connected PV system with the constant current controller (CCC), which controls the solar inverter for interfacing the grid. The voltage level of DC voltage generated by the PV array is increased using the boost converter and then applied to the 3-ϕ, 2 level Solar inverter. The control of the solar inverter is provided through the constant current controller. This controller uses the Phase Locked Loop (PLL) and PI controllers. The PLL is used for tracking the phase angle of the grid voltage. The PI controller gains are chosen such that the CCC generates the pulses for solar inverter according to the grid voltage. The proposed model is able to supply the 2 MW resistive loads and 30 MW, 2 MVAr load the applicable criteria that follow.

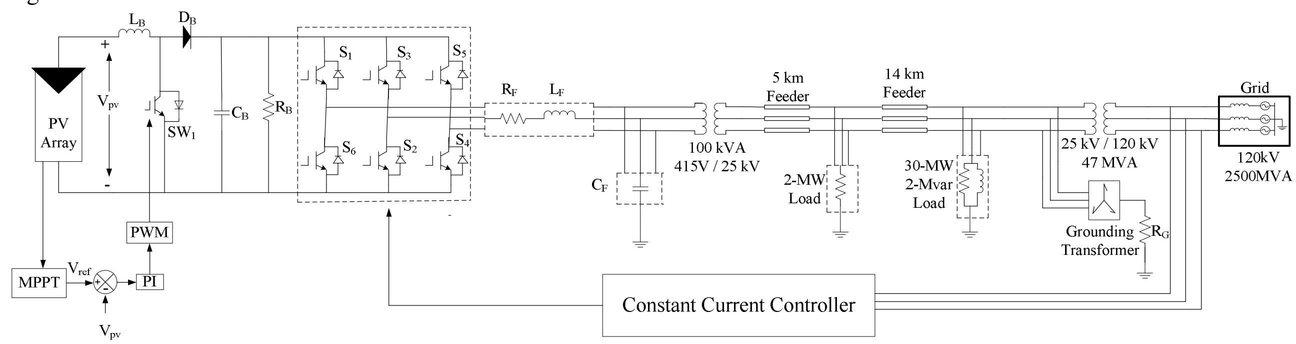

Fig.1 Configuration of the Grid integrated PV System

II. SYSTEM DESCRIPTION

Fig. 1 shows the configuration of the grid integrated PV system. The PV array is the combination of series and parallel connected PV module. Each PV module has series connected PV cell according to the voltage requirements. The MPPT technique is applied for operating the PV array at the maximum power point. The V_{ref} generated by the MPPT is the desired DC voltage of the PV array and compared with the actual voltage of the PV array. The error signal is processed by the PI controller for minimizing the error. That control signal is compared with the triangular waveform for obtaining the switching pulses for the switch SW_1. This arrangement controls the duty ratio for varying the load according to the MPPT. The boost converter stepping up the voltage level of the PV array.

The 2-level inverter is inverting the DC voltage 600 V into the sinusoidal AC signal 415 V. A constant current controller is providing the switching pulses to the inverter. This controller senses the phase angle of the grid voltage and generates the switching pulses such that the inverter can output the voltage with the same frequency of the grid voltage. If there is phase distortion in the grid voltage, this controller is able to track the distorted phase and controls the inverter to give the same output. The harmonics generated by the inverter is reduced by the 3-phase LC filter. For integrating the PV system into the grid the voltage level should be same. Hence the 100 kVA, 415/25 kV transformer is used.

The 120 kV, 2500 MVA utility grid is integrated with the solar system. The grid voltage level has been changed from 120 kV to the 25 kV using the step down transformer. The 30 MW, 2-MVAr load is connected at the grid side. At the distance of 14 km resistive load of 2 MW is connected. At the distance of 5 km solar system has been connected. The grounding transformer is used for the protection against fault. The fault current is grounded by the grounding resistance R_G.

III. MODELLING OF PV ARRAY

The Solar cells are the medium to convert solar energy into the electrical power. These cells are made up of semiconductor materials, when sun beam is absorbed with these material electrons emits and releases the current and thus electric power is produced. The equivalent circuit for obtaining the V-I characteristic of the PV cell is shown in the fig. 2.

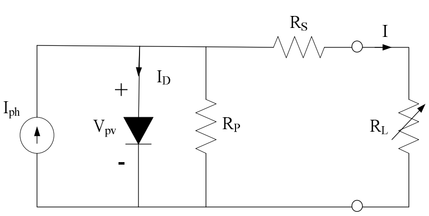

Fig. 2 Equivalent Circuit of a PV Cell

To obtain the desired high power numerous solar cells are connected in series and parallel. For the high voltage requirement cells are connected in series and for high current application cells are connected in parallel to form a panel. The group of these panels is known as PV array. The Mathematical modeling of the PV array can be given as:

$$I = N_P I_{ph} - N_P I_D \left[\exp\left(\frac{q}{kTA} * \frac{V_{pv}}{N_S}\right) - 1\right] \quad (1)$$

The diode reverse saturation current I_D varies with the temperature according to the following equation,

$$I_D = I_{rr} \left[\frac{T}{T_r}\right]^3 \exp\left(\frac{qE_G}{kA}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \quad (2)$$

The energy gap of the semiconductor used in the PV cell dependent on the temperature is given as:

$$E_G = E_G(0) - \frac{\alpha T^2}{T+\beta} \quad (3)$$

The photo current I_{ph} depends on the solar radiation and cell temperature as follows,

$$I_{ph} = [I_{scr} + K_i(T - T_r)]\frac{S}{100} \quad (4)$$

The PV power can be calculated using the following expression,

$$P = IV = N_P I_{ph}\left[\left(\frac{q}{kAT} * \frac{V}{N_S}\right) - 1\right] \quad (5)$$

Solar irradiation and temperature plays an important for predicting the behavior of the PV cell and effects of both the factors have to be considered while designing the PV system. The solar irradiation affects the output and the temperature affects the terminal voltage.

IV. Boost Converter and Its Control

The output voltage of the PV cell is very limited, which is very low for the application. The series and parallel combination also does not provide the required output. Hence the boost converter is necessary to enable the low voltage PV array to be used. A capacitor is also connected for reducing the high frequency harmonics between the PV array and boost converter. Fig. 3 shows the closed loop controller for boost converter.

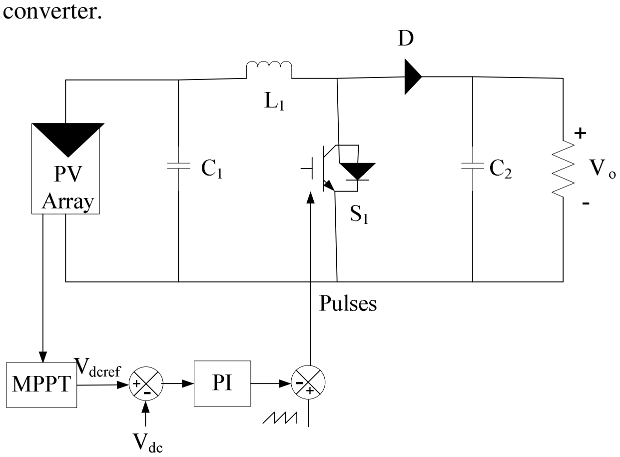

Fig. 3 Closed loop controller for boost converter

When the switch S_1 is in ON state, the inductor L_1 is charged from the voltage (V_{pv}) generated by the PV array and the capacitor C_1 discharges across the load. The duty cycle D is $\left(\frac{T_{on}}{T}\right)$ and $T = \frac{1}{f}$. The boost converter operates in CCM (Continuous Conducting mode).

The current supplied to the output RC circuit is discontinuous. Thus a large filter capacitor (C_2) is used to limit the output voltage ripple. The filter capacitor must provide the output dc current to the load when the diode D is in OFF state.

The control of the boost converter is provided through the PWM signal. The output of the filter which is the control signal is compared with the reference voltage. The PI controller attempts to minimize the error by adjusting the process control inputs. Then it is compared with the saw-tooth waveform to generate the PWM signal which is fed as gate signal to the IGBT switch. The control circuit regulating the reference voltage V_{dcref} , which is calculated by the MPPT techniques. Thus the PV array can be controlled by controlling the duty ratio for operating at the maximum power point.

V. Controller For Solar Inverter For Interfacing Grid

A solar or PV inverter is interfacing the utility grid. It also converts the variable direct current output of a photovoltaic (PV) solar panel into a utility frequency alternating current that can be fed into a commercial electrical grid. It is a critical component in a photovoltaic system and its control should be such that its output can interface the voltage of the utility grid. There are two basic control modes for the grid connected inverters. One constant-current-control and the other is constant-power-control. In this proposed model, the control of the solar inverter is provided through the Constant Current Controller using the 3-ϕ Phase Locked Loop (PLL). In constant current control, the inverter output currents are regulated to the reference grid current. Fig. 4 shows the switching model of the solar inverter.

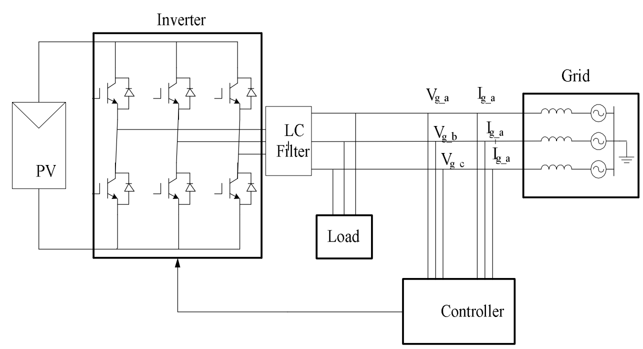

Fig.4 Switching Model of Solar Inverter

Fig. 5 shows the detailed block diagram of the constant current controller for generating the controlled switching pulses for the solar inverter such that the output voltage should be able to interface the grid. The 3-ϕ Phase Locked Loop calculates the phase angle of the utility grid and also gives the information about the frequency variation. According to the phase angle of the utility grid voltage, the constant current controller is modeled such that the controller is able to generate the switching pulses for solar inverter for tracking the phase of the grid voltage. The 3-ϕ grid current I_{g_abc} is converted into αβ variable using the Clarke transformation. The αβ variables are transformed into the dq variables. The current I_d and I_q are compared with the I_{dref} and I_{qref} for processing in the PI controller to minimize the errors. These signals are transformed into 3-ϕ signal using the inverse park's transform and then compared with the triangular waveform for generating the PWM switching pulse for the solar inverter. The V_{dc} and V_{dcref} is the DC link voltage of the PV array and expected DC voltage of the PV array.

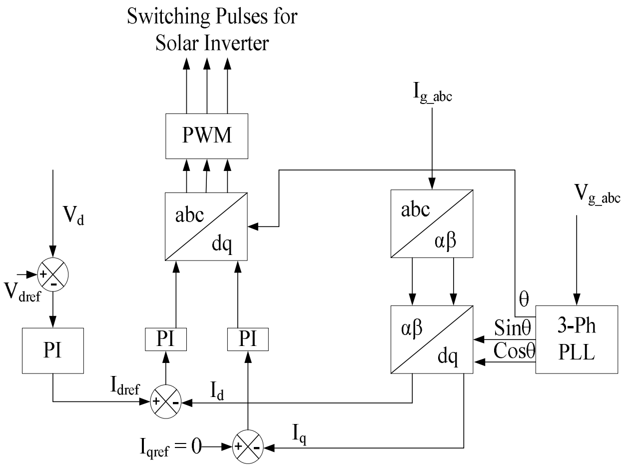

Fig. 5 Block Diagram of Constant Current Controller

VI. Results And Discussion

In this paper, the simulation model proposes a 120 kV, 2500 MVA grid integrated solar system. Fig. 6 shows the PV array power generation at various solar irradiations. The PV array delivering a maximum of 100 kW at 1000 W/m^2 sun irradiance. The PV array consists of 5 series connected modules per string and 66 parallel strings. There are 96 photovoltaic cells per module. Fig. 7 shows that the PV array generates voltage of about 321 V at 1000 W/m^2. The 0pen-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) of one module is 64.2 V and 5.96 A respectively. The voltage and current at maximum power for one module is V_{mp} =54.7 V and I_{mp}= 5.58 A respectively. The V-I and P-V curves are explaining the behavior of the PV array used in the proposed model.

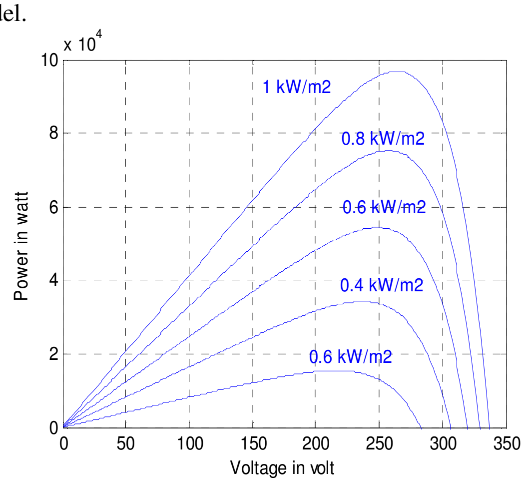

Fig.6 P-V Curve of the Solar Array

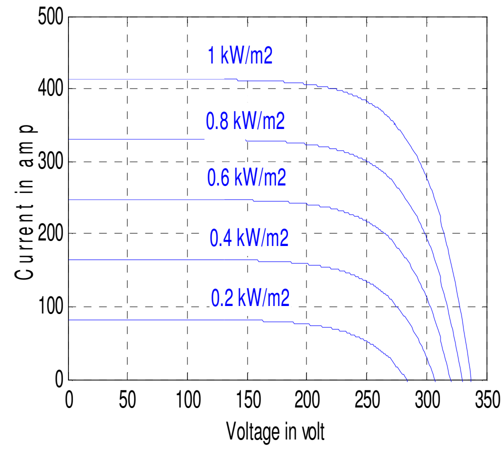

Fig. 7 V-I Curve of the Solar Array

The boost converter increasing voltage from PV natural voltage (300V DC at maximum power) to 600 V DC voltage. Switching duty cycle is optimized by the closed loop controller that uses the PI controller according to load variation. The DC voltage delivered by the DC converter is shown in the fig. 8.

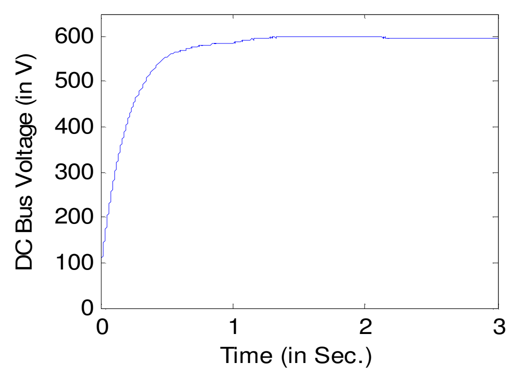

Fig. 8 DC voltage delivered by the Boost converter

The 2-level 3-phase voltage source inverter is converting the boosted DC voltage into sinusoidal AC voltage. The LC filter having the series inductance branch of 250 μH with internal resistance 0.002 Ω and 10-kvar capacitor bank is filtering harmonics produced by VSC. The combination of VSC and LC filter converts the 600 V DC voltage into the 415V pure sinusoidal AC voltage. Fig. 9 and fig. 10 shows the inverter output voltage before and after filtering respectively.

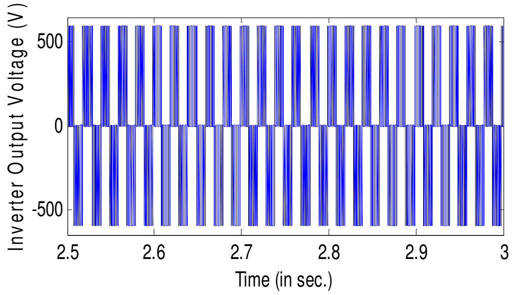

Fig. 9 Inverter output voltage before filtering

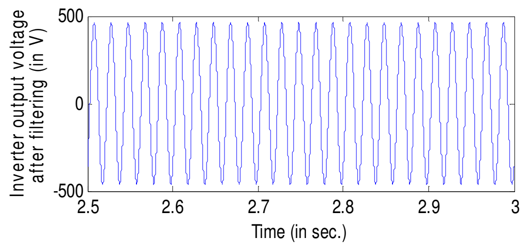

Fig. 10 Inverter output voltage after filtering

For integrating the modeled solar generation system into the utility grid there is need of stepping up the voltage level from 415V to 25 kV. There is 2 MW load is connected using the 5 km transmission line. Fig. 11 shows the load current for supplying the 2 MW load.

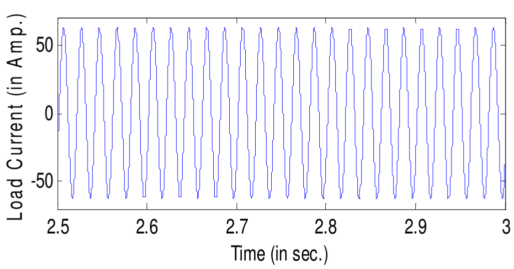

Fig. 11 Load current for supplying the 2 MW load.

Another 30 MW, 2 MVA_r load is connected using the 14 km transmission line. Fig. 12 shows the load current for supplying the load of about 30 MW, 2 MVAr. The grid voltage is stepped down from 120 kV to 25 kV. The grounding transformer is used for the protection against the faults. The grounding resistance is taken as 3.3 Ω.

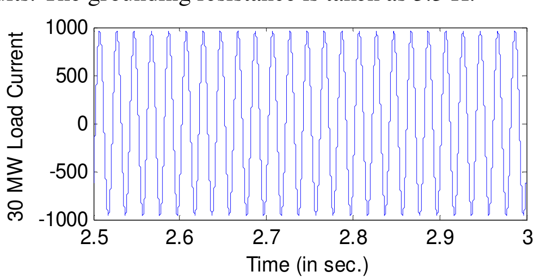

Fig. 12 Load current for supplying the load of about 30 MW, 2 MVAr

VII. CONCLUSION

For improving the energy efficiency and power quality issues with the increment of the world energy demand, the power generation using the renewable energy source is the only solution. There are several countries located in the tropical and temperature regions, where the direct solar density may reach up to 1000W/m^2. Hence PV system is considered as a primary resource. In this paper, the detailed modeling of grid connected PV generation system is developed. The DC-DC boost converter is used to optimize the PV array output with the closed loop control for keeping the DC bus voltage to be constant. The 2 level 3-phase inverter is converting the DC into the sinusoidal AC voltage. The control of the solar inverter is provided through the constant current controller. This controller tracks the phase and frequency of the utility grid voltage using the Phase-Locked-Loop (PLL) system and generates the switching pulses for the solar inverter. Using this controller the output voltage of the solar inverter and the grid voltage are in phase. Thus the PV system can be integrated to the grid. The simulation results the presented in this paper to validate the grid connected PV system model and the applied control scheme.

REFERENCES

[1] A. M. Hava, T. A. Lipo and W. L. Erdman. "Utility interface issues for line connected PWM voltage source converters: a comparative study", Proceeding of APEC'95, Dallas (USA), pp. 125-132, March 1995.

[2] L. J. BORLE, M. S. DYMOND and C. V. NAYAR, "Development and testing of a 20 kW grid interactive photovoltaic power conditioning system in Western Australia", IEEE Transaction, Vol. 33, No. 2, pp. 502-508, 1997.

[3] M. Calais, J. Myrzik, T. Spooner, V. Agelidis, "Inverters for single- phase grid connected photovoltaic systems – an overview", IEEE 33rd Annual Power Electronics Specialists Conference, Volume 4, 23-27 June 2002

[4] S. K. Chung, "Phase-Locked Loop for Grid connected Three-phase Power Conversion Systems", IEE Proceeding on Electronic Power Application, Vol. 147, No. 3, pp. 213-219, 2000.

[5] S. Rahman, "Going green: the growth of renewable energy", IEEE Power and Energy Magazine, 16-18 Nov./Dec. 2003.

[6] W.El-Khattam, M. M. A. Salma, "Distribution generation technologies: definition and benefits", Electric Power Systems Research, Vol. 71, pp. 119-128, 2004.

[7] S. Kjaer, J. Pedersen, F. Blaabjerg, "A review of single-phase grid connected inverters for photovoltaic modules", IEEE Transactions on Industry Applications, Vol.41, No.5, Sep/Oct 2005.

[8] J.-M. Kwon, K.-H. Nam, and B.-H. Kwon, "Photovoltaic power conditioning system with line connection", IEEE Transactions on Industrial Electronics, Vol. 53, No. 4, pp. 1048 – 1054, June 2006.

[9] J. M. Carrasco, L.G. Franquelo, J. T. Bialasiewicz, E. Galvan, R.C. Portillo-Guisado, M. A. Martin-Prats, J. I. Leon, N. Moreno-Alfonso, "Power electronic systems for the grid interation of renewable energy sources: a survey", IEEE Transaction on Industrial Electronics, Vol. 53, No. 4, pp. 1002-1016, 2006.

[10] F. Blaabjerg, R. Teodorescu, M. Liserre, A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems", IEEE Transaction on Industrial Electronics, Vol. 53, No. 5, pp. 1398-1409, 2006.

[11] Jing Li, Fang Zhuo, Jinjun Liu, Xianwei Wang, Bo Wen, Lin Wang, Song Ni, "Study on unified control of grid-connected generation and harmonic compensation in dual-stage high-capacity PV system", IEEE Energy Conversion Congress and Exposition, pp. 3336-3342, 2009.

[12] Seyed Hossein Hosseini, Mitra Sarhangzadeh, Mohammad B. B. Sharifian, Farzad sedaghati, "Using PV in distribution network to supply

local loads and power quality enhancement", International Conference on Electrical and Electronics Engineering,2009, pp. 249-253
[13] M. G. Molina, L. E. Juanico, "Dynamic modeling and control design of advanced photovoltaic solar system for distributed generation application", Journal of Electrical Engineering: Theory and Application (JEETA), Vol. 1, No. 3, pp. 141-150, 2010.