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Design and Control of LCL Filter Interfaced Grid Connected Solar Photovoltaic System by Using Power Balance Theory

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Abstract: In this paper solar photovoltaic system connected to the utility grid is design and simulated. The utility grid and SPV system are coupled with current controlled voltage source (VSC) and LCL filter. LCL improves stability of the system .The system is controlled through power balance theory method. For grid synchronization and power control, control algorithm is required also requires power conditioning unit for smooth operation, Power balance theory (PBT) is used as control strategy. PBT is simple and can be achieved easily. The grid connected pv system consist of – Photovoltaic (PV), Incremental Conductance MPPT method, LCL filter, three phase utility grid, power balance theory. Source/grid voltages are used as reference for generating templates. This is the principle behind the algorithm implementation. In order to generate templates mathematical equations are required. Incremental conductance method is used for simplifying the implementation of the system the grid connected Photovoltaic system (PV) is connected to a non linear load having intermittent components as dc/dc. This system is capable of eliminating harmonics and compensating the reactive power.SPV array using indirect current control scheme. MATLAB/SIMULINK is used for demonstrate the system.

Keywords: Photovoltaic (PV), Incremental Conductance MPPT method, LCL filter, three phase utility grid, power balance theory.

I. INTRODUCTION

Solar power production and utilization is growing at faster rate. The solar production in India has reached almost 1.5GW capacity. With increase in consumption, it is challenge for any country to meet the demands. The PV system can interfaced with grid using inverter, as the output of the PV system is dc in nature. Inverter converts dc to ac. For grid synchronization and power control, control algorithm is required also requires power conditioning unit for smooth operation. LC filter is used as power conditioner to reduce ripples. LC is expensive for high power applications because of high value inductors. In order to reduce the cost we use LCL filter in place of LC filter. LCL improves stability of the system. Grid impedance has impact on stability of the system. So, special care needs to be taken while designing LCL filter. Various strategies are required for synchronization and power control. Synchronous reference frame theory (SRF) is one among various strategies. But SRF implementation is difficult because of PLL. So, Power balance theory (PBT) is used as control strategy. PBT is simple and can be achieved easily.

Source/grid voltages are used as reference for generating templates. This is the principle behind the algorithm implementation. In order to generate templates mathematical equations are required. Incremental conductance method is used for simplifying the implementation of the system the grid connected Photovoltaic system (PV) is connected to a non linear load having intermittent components as dc/dc converter to extract the maximum power using incremental conductance MPPT method and a dc/ac voltage source converter which acts itself as an Active power Filter. In this case the PV generators should provide the utility with distorted compensation capability, which makes current injected/absorbed by the utility to be sinusoidal. So the harmonic compensation function can be realized by flexible control of dc/ac voltage source converter.

This paper presents a comparison of THD value of the utility current in these four modes when the utility supplies and receives the power. The PV-APF combination with instantaneous power balance theory and fuzzy logic controller is proposed.

II. MODELLING OF PV DEVICES

A 100-KW PV array uses 330 solar power modules of SPR-305E-WHT-D type. The array has 66 strings of 5 series connected modules connected in parallel. The operating conditions of PV array are Temperature of 25^{o}c and irradiance or insulation (λ) of 1000w/m^2. The PV modules are represented approximately as constant current source in electrical analysis. The equivalent electrical

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circuit of a PV array including fundamental components of diode, series resistance, shunt resistance and current source is as shown in the figure.

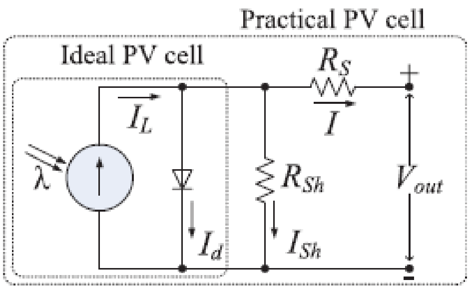

Figure 1: Electrical Equivalent circuit of a PV cell.

The parameters of a PV cell are open circuit voltage V_{oc} (at load current zero) and short circuit current I_{sc} (at load voltage zero). By neglecting the small diode current and leakage current $V_{oc} = V_{out}+R_sI$. The PV array generated current is I_L equal to the output current I if the values of diode current I_d and shunt current I_{sh} are low. The shunt current or leakage current I_{sh} is inversely proportional to shunt resistance R_{sh} , it's value varies from 200-300Ω. R_s represents the series resistance which is the internal resistance to the output current I, it's value varies from 0.05-0.10Ω. The efficiency of PV cell depends on the output current which is sensitive to the variations in R_s and R_{sh}.

The output current equation for a practical PV cell can be represented as show the equation below

$$I = I_L - I_d\left(e^{\frac{QV_{oc}}{AKT}} - 1\right) - \left(\frac{V_{out} + IR_s}{R_{sh}}\right) \qquad (1)$$

The module current or Photo current IL can be given as

$$I_L = \left(I_{sc} + K_i(T - 298)\right) \times \frac{\lambda}{1000} \qquad (2)$$

Here, I_L: photo-current (A); I_{sc}: short circuit current (A) ; K_i: short-circuit current of cell at 25°C and 1000 W/m2; T: operating temperature(°K) ; λ: solar irradiation (W/m2).

The diode current I_d is given as

$$I_d = I_D\left[\exp\left(\left[\frac{-QE_G}{AK}\right] \times \left[\frac{1}{T} - \frac{1}{T_{ref}}\right]\right)\right] \times \left[\frac{T}{T_{ref}}\right]^3 \qquad (3)$$

Here, I_D : diode saturation current ; Q : charge of an electron (1.6×10^{-19} C) ; A : ideality factor or diode emission factor (1.6) ; K : Boltzmann constant (1.38×10^{-23} J/°K) ; T: operating temperature(°K).

The diode saturation current I_D can be given as

$$I_D = \frac{I_{sc}}{\left(\exp\left[\frac{V_{oc}Q}{N_sKT}\right] - 1\right)} \qquad (4)$$

Here, I_{rs} : reverse saturation current of the diode; V_T : thermal voltage= $\frac{KT}{Q}$

The reverse saturation current can be given as

$$I_D = \frac{I_{sc}}{\left(\exp\left[\frac{V_{oc}Q}{N_sKT}\right] - 1\right)} \qquad (5)$$

III. INCREMENTAL CONDUCTANCE MPPT METHOD

MPPT or Maximum power point tracking is algorithm is used to extract maximum power from the PV panel under certain conditions. The output power of a PV is a function of solar irradiance , temperature and position of the panel. It is also a function of product of voltage and current. By varying these parameters the power can be maximized. The voltage at which PV produces maximum power is Maximum power point correspondingly at MPP we have V_{max} and I_{max} in I-V characteristics as shown in the figure.

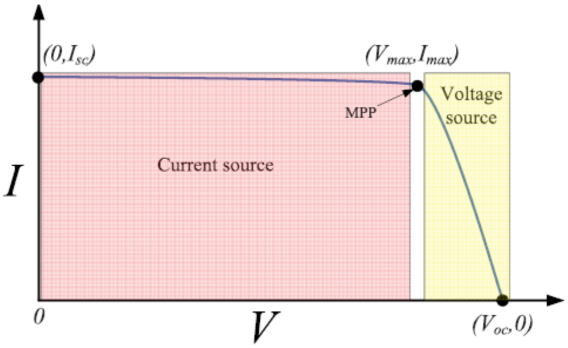

Figure 2: I-V curve of a PV cell.

In order to find out the position of the actual operating point in relation to MPP, this Incremental conductance algorithm uses the derivate of the conductance di/dv. It is based on the fact that the slope tangent of the characteristic p–v is zero in MPP.

$$\frac{dP}{dv} = \frac{d(VI)}{dv} = I + V\frac{dI}{dV} \qquad (6)$$

$$\frac{dI}{dV} = -\frac{I}{V} \qquad (8)$$

$$\frac{dI}{dV} < \frac{I}{V}\ ;\text{right} \qquad (9)$$

$$\frac{dI}{dV} > \frac{I}{V}\ ;\text{left} \qquad (10)$$

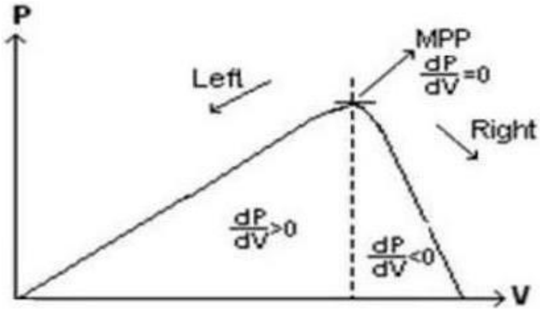

Figure 3: Incremental Conductance MPPT

When the operating point is located in the left side of the MPP, then i/v + di/dv > 0, whereas i/v + di/dv < 0 when the operating point is on the other side. From the instantaneous measurement of i and v, the following approximations can be done:

$$di = i(z)-i(z-1) \qquad (11)$$

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$$dv= v(z)-v(z-1) \qquad (12)$$

So, the algorithm can instantly calculate i/v and di/dv to calculate the direction of the perturbation leading to the MPP. Once MPP has been obtained, the operation of PV array is maintained at this point and the perturbation stopped unless a change in dI_{PV} is noted. In this case, the algorithm decrements or increments the PV array voltage V_{PV} to track a new MPP. The increment size determines how fast the MPP is tracked. The Incremental conductance method offers good performance under rapidly changing atmospheric conditions. The classic Incremental conductance algorithm requires the measurement of the PV array voltage V_{PV} and current I_{PV} in order to determine the correct perturbation direction.

IV. BOOST CONVERTER

The boost converter use an inductor and control the duty cycles for current through that inductor to provide the desired relation between input and output voltages. Duty cycle (D) is defined as the ratio of the time a switch is closed to its total operating time per cycle. The incremental conductance MPPT is used to calculate the duty cycle which is used as gate pulse for the IGBT switch in boost converter and makes it to operate in first quadrant. The three-phase grid-connected voltage source inverter has six IGBT as switching devices and an output L filter reducing the current distortion. The inverter must act as a power controller between the dc link and the utility. The DC/AC converter itself acts as an Active power filter by generating pulses to the switches in its circuit.

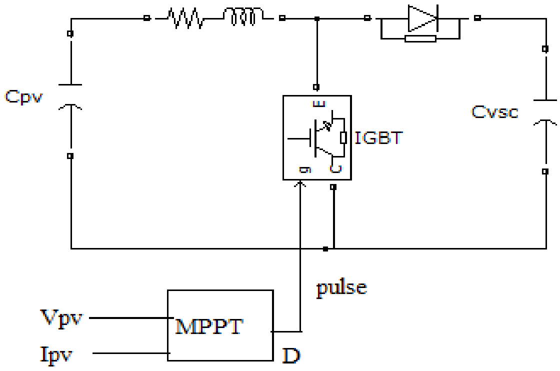

Figure 4: Boost Converter

It also provides harmonic elimination, reactive power compensation and simultaneously inject the maximum power generated by PV units. The controller is established based on instantaneous power theory, where all the parameters are calculated instantaneously.

In general, there are two cases of utility power flow:

1) PV supplies enough power for local nonlinear loads and injects its excess power to the utility.
2) PV supplies one part of nonlinear loads consuming and the other part of load power is received from the utility.

Under the harmonic voltages condition, instantaneous voltages contain two components; 1) Average component (superscript -) and 2) Oscillating component (superscript ~).

$$\begin{aligned} P_{VSC} &= \overline{P}_{VSC} + \widetilde{P}_{VSC} \\ P_L &= \overline{P}_L + \widetilde{P}_L \\ Q_L &= \overline{Q}_L + \widetilde{Q}_L \end{aligned} \qquad (13)$$

The average component derives from the fundamental component of nonlinear load current. The Oscillating part is derived from the harmonics and negative sequence components.

V. CONTROL STRATEGY IMPLEMENTATION

The proposed control method which is based on instantaneous power theory has been used for solving all the problems related to the power quality including source voltage harmonics, unbalanced voltages, voltage sag and swell. In the proposed approach, first the measured voltages of load are transferred to the α-β-o coordinates. By using the Clarke Transformation the instantaneous real power (P_L) and imaginary power (Q_L).

$$\begin{bmatrix} V_\alpha\ (I_\alpha) \\ V_\beta\ (I_\beta) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a\ (I_a) \\ V_b\ (I_b) \\ V_c\ (I_c) \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} P_L \\ Q_L \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad (15)$$

Here utility will inject the average part of the load power. The oscillating components of the real power and all the components of the imaginary power of the load are supplied by the PV-APF combination. In addition the dc link voltage regulator determines an extra amount of real power $(\overline{P}_{LOSS})$ that causes additional flow of energy to the dc link capacitor CVSC in order to keep its voltage around a fixed reference value (V_{VSC}^{ref}). That real power is fed from the utility. The equations can be given as

$$\begin{aligned} \overline{P}_L + \widetilde{P}_L &= \overline{P}_{VSC} + \widetilde{P}_{VSC} + \overline{P}_{UTI} + \overline{P}_{LOSS} \\ \overline{Q}_L + \widetilde{Q}_L &= \overline{Q}_{VSC} + \widetilde{Q}_{VSC} + \overline{Q}_{UTI} \\ \overline{P}_{VSC} &= \overline{P}_L - \overline{P}_{UTI} - \overline{P}_{LOSS} \\ \overline{Q}_{VSC} &= \overline{Q}_L - \overline{Q}_{UTI} \\ \widetilde{P}_{VSC} &= \widetilde{P}_L \\ \widetilde{Q}_{VSC} &= \widetilde{Q}_L \end{aligned} \qquad (16)$$

From these calculations we have to calculate the reference values for voltage source converter

$$\begin{aligned} P_{VSC}^{ref} &= P_L - \overline{P}_{UTI} - \overline{P}_{LOSS} \\ Q_{VSC}^{ref} &= Q_L - \overline{Q}_{UTI} \end{aligned} \qquad (17)$$

If the $\overline{P}_{LOSS}$ is supplied by the PV unit and the PV-APF combination compensates all the imaginary power of load demand is changed to

$$P_{VSC}^{ref} = P_L - \overline{P}_{UTI} + \overline{P}_{LOSS} \qquad (18)$$

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$$Q_{VSC}^{ref} = Q_L$$

After finding out the reference power for DC/AC VSC, using the reverse Clarke transformation, the reference current values in the three phases are generated as seen in the equations

$$\begin{bmatrix} I_{\alpha\,VSC}^{ref} \\ I_{\beta\,VSC}^{ref} \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} P_{VSC}^{ref} \\ Q_{VSC}^{ref} \end{bmatrix}$$

$$\begin{bmatrix} I_{a\,VSC}^{ref} \\ I_{b\,VSC}^{ref} \\ I_{c\,VSC}^{ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{\alpha\,VSC}^{ref} \\ I_{\beta\,VSC}^{ref} \end{bmatrix} \qquad (19)$$

The Hysteresis control technique is used to switch the IGBT switches in the voltage source converter by using these current references of voltage source converter. The dc voltage regulation passes through fuzzy logic controller which filters out the switching harmonics present in the dc capacitor voltage.

VI. SIMULATION MODEL OF THE SYSTEM

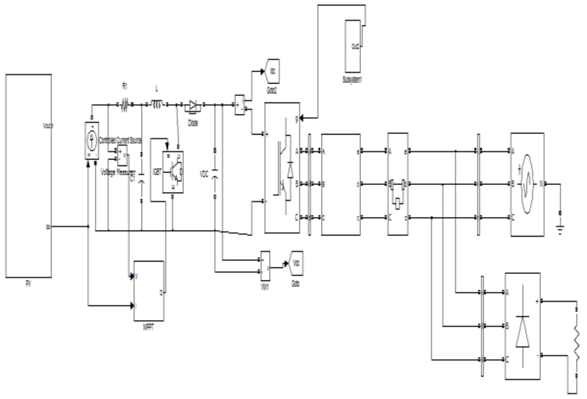

Figure 5: Simulation model of the system

Here we placed a ac voltage source as a grid it is connected to rectifier then its converts into AC and then AC signal passes through LCL filter, feeder which consist of LC components and finally its connected to a nonlinear load. In grid connected mode at PCC grid is connected but in islanding mode grid is disconnected

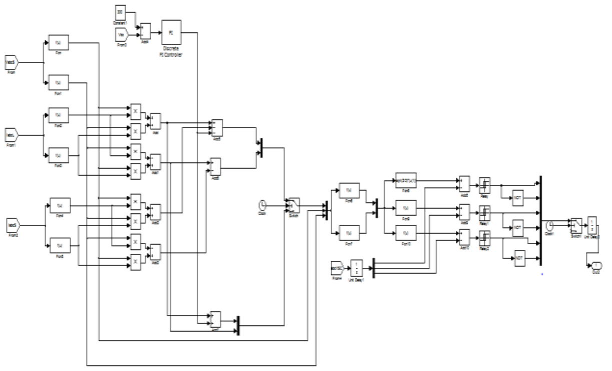

Figure 6: Control circuit

Fig.6. block diagram for control circuit by using inverter operation by using those equations we can set our reference values then by using PWM technique we can generate pulses and finally pulses given to gate terminal at universal bridge. Source/grid voltages are used as reference for generating templates. This is the principle behind the algorithm implementation. In order to generate templates mathematical equations are required. Incremental conductance method is used for simplifying the implementation of the system the grid connected Photovoltaic system (PV) is connected to a non linear load

VII. SIMULATION RESULTS

In this section, the analysis results will be verified by the time domain simulation results. The study system is constructed in MATLAB.

System Parameters in simulation

Photovoltaic System	4 series and 11 parallel array Irradiance – 1000w/m^2 Output Voltage- 250V Maximum power – 100KW Output voltage at maximum power-274V
Boost Converter	5 KHz Output Voltage- 500V
DC/AC VSC	DC link capacitor – 24000µF Active Power Filter (R_{AF} = 0, L_{AF}=0.2Mh) DC link Voltage V_{VSC} – 500V
Grid or Utility	Grid voltage V_{abcS} – 260V Frequency- 60Hz
Unbalanced non-linear load	3- phase diode rectifier Constant dc current – 450A 1-phase diode rectifier Constant dc current – 50A
Switching frequency	10kHz
LCL filter	Li=1.4mH,Lg=1.4mH,Cf=5uF
DC bus voltage	Vdc=800V
Grid voltage	VLL=415V

The total simulation can be done in four modes. They can be represented as

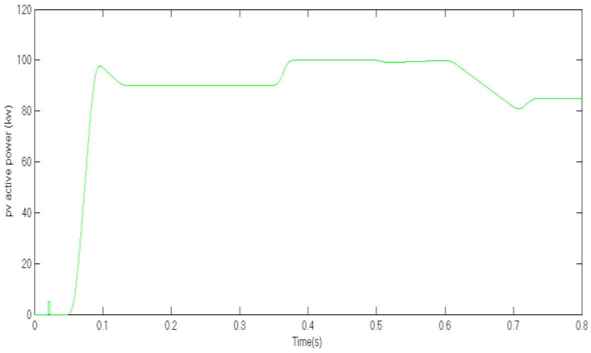

Figure 7: output power of pv during running time

The pv output is shown in above fig.7 without MPPT control dc/dc conveter uses constant duty cycle,pv power output could not reach maximum value as MPPT mode.after activating MPPT ,the MPPT has made the duty cycle changr from 0.5 to 0.45.

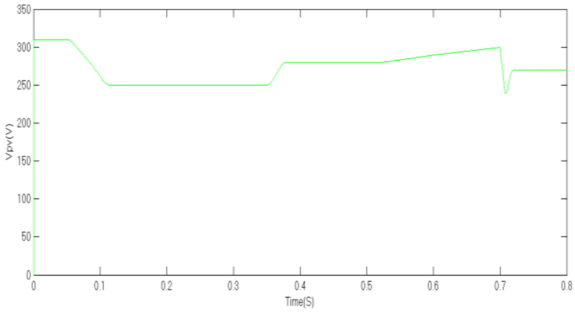

Figure 8: output voltage of PV unit

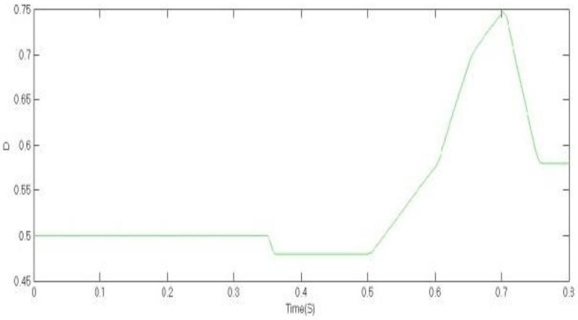

Figure 8 and figure 9: Duty cycle and VPV changed by MPPT. (a) Output voltage of PV unit. (b) Duty cycle of MPPT.

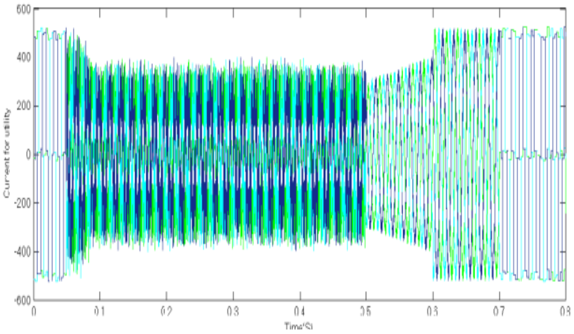

Figure 10: Utility supplied current waveform

The duty cycle running in PV-APF mode slightly increased to adapt to power dynamic response of compensation. The PV unit is switched out from the entire system and then the output active power is gradually reduced. In this duration, the nonlinear load is supplied by the utility. This six-ripple dc current brings higher fifth-order and seventh-order harmonics. If a three-phase-controlled rectifier load is used, the THDs increase while the commuted angles increase. In this case, both the PV unit and the utility should supply power to the load. The current from the utility is the most important point that should be considered in this paper and it is shown in Fig. 10.

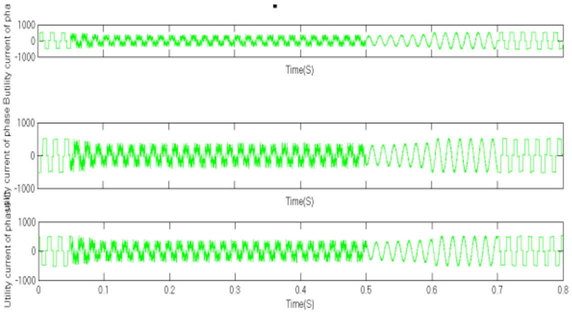

Figure 11: current from utility of three phases

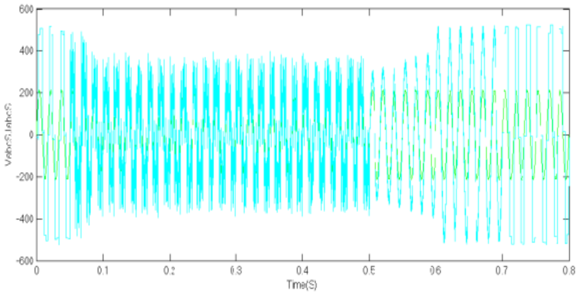

Figure 12: current from pv unit

Finally, in the mode while the PV unit is switched out of running system, and then only the utility supplies to nonlinear load, the THD is even lower than the dq-current mode . In APF mode and PV-APF mode, the even-order harmonics appear at higher magnitudes. As a result, when a PV unit run by conventional dq-current controllers is connected to the utility feeding a nonlinear load, the utility current suffers the highest THD values.

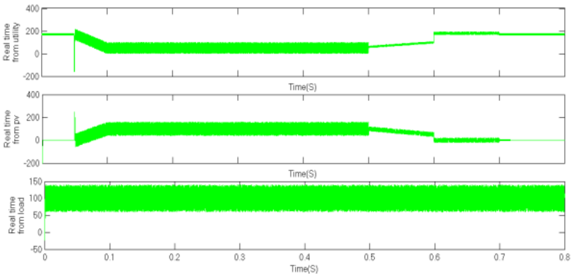

Figure 13.real power from the (a) utility (b) PV unit and (c) Load while the utility supplies power..

The instantaneous real power balance (p) among three parts, including the PV unit, the utility, and the local load is shown in Fig. 13.

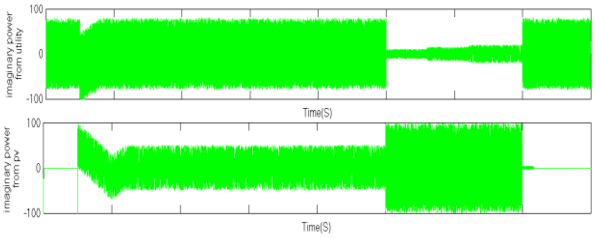

Figure 14: Imaginary power from the (a) utility
(b) PV unit and (c) load while the utility supplies power.

The instantaneous imaginary power balance (p) among three parts, including the PV unit, the utility, and the local load, is shown in Fig. 14

VIII. CONCLUSION

The LCL interfaced solar photovoltaic (PV) system is designed and simulated successfully using power balance theory algorithm. The desired results for evacuation of PV power are achieved and by providing compensating reactive power from PV system, grid is operated under unity power factor. It improves the power factor of the system. The grid connected system is investigated and analyzed under changed irradiance and load condition. The grid active and reactive power current references are generated by in phase and quadrature phase templates generation using the power balance theory. The system is investigated and analyzed for unbalanced load and non-linear load condition also. The performance of the system is maintained according to IEEE-519 standards for THD and under unbalanced and non-linear load conditions as the PV inverter generates the compensating current. This system does not require PLL as the synchronization is achieved through templates.

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