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Compensation of Utility Current by PV APF and Fuzzy Logic Controller Combination

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***Abstract*—this paper has proposed a novel method for the improvement of power quality (PQ) in a nonlinear system using active power filter (APF). The proposed topic incorporates Photovoltaic (PV) system, MPPT controller, fuzzy controller, dc link capacitor, voltage source converter (VSC) and nonlinear load. The switching gate pulses for the APF are generated by fuzzy logic controller (FLC) technique depending on instantaneous power balance theory. By this technique total harmonic distortion (THD) in the utility current can be minimized within IEEE norms. The advantage of FLC is faster response, better efficiency, no need for accurate mathematical models, capable of dealing with imprecise inputs and managing with non-linearity. In this paper 3- phase 3-wire system under unbalanced and balanced load conditions with APF and FLC is implemented. MATLAB / SIMULINK is used to demonstrate the system and a comparison of THD values at certain load conditions is presented.**

***Key words:-* Photovoltaic (PV) , Incremental Conductance MPPT method , Instantaneous Power balance Theory , Active Power Filter , fuzzy logic controller.**

I.INTRODUCTION

At present, the usage of conventional non-linear loads in Electrical power system has started the exploration in PQ concern like voltage sag and swell, harmonics and fluctuations in voltage etc., Among all the issues, the dominant PQ problem is Harmonics. To lessen the harmonics in conventional way passive L-C filters are used and furthermore capacitors can be employed to enhance the PQ of ac loads. But the conventional passive L-C filters have some disadvantages like extensive size, resonance problem and fixed compensation. To relieve the harmonics problem effectively analysts have developed APF. In this paper, the grid connected PV associated with a nonlinear load having intermittent components as Boost converter to obtain the maximum power from PV, incremental conductance MPPT method and a dc/ac VSC which acts itself like APF. In this case distorted compensation capability to the utility has to be provided by the PV system, such that current absorbed/injected by the utility should be sinusoidal. So the percentage of harmonic compensation [1] can be analyzed by flexible control of dc/ac VSC.

The PV-APF combination is most efficient way to compensate the power factor and harmonics present in current and also infusing the energy produced by PV system with low THD. At night when the PV array is not operating or (no battery and no irradiance), the APF controller supply the load.

Active Power Filter (APF) is one of most effective ways of filtering the harmonics. The important aspect in the design of the APF is its controller part. The techniques involved in the design to obtain reference current of APF determine the efficiency of filter. With the advancement in different technologies has made the lowering of harmonics below 5% as stated by IEEE. Efficient ways of generating reference current is instantaneous

Power balance theory (p-q theory). Here all the parameters are processed instantaneously. FLC is incorporated, which can reduce the harmonics. The PV-APF can be operated in four modes. They are listed as follows

1. DQ-Current Mode- PV system is switched ON and MPPT is activated.

2. PV-APF Mode- PV and Utility or Grid supplies load and the APF performs its action.

3. APF Mode- PV system is switched OFF. The dc link capacitor and the utility sup lay the load and APF undergoes its regular action.

4. Utility Mode- just the utility supplies the load. In this paper THD value of utility current under certain load conditions is obtained. The PV-APF with FLC and instantaneous power balance theory is proposed.

II. MODELING OF PV ARRAY

A PV array of 100-KW has 330 solar power modules of SPR-305E-WHT-D type, the total array ha 66 strings of 5

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modules connected in series and associated in parallel. The operating conditions of PV array are 25oc temperature and irradiance or insolation (λ) of 1000w/m2.

In electrical analysis, the PV array can be modeled as a current source with constant magnitude. The equivalent electrical circuit of a PV array includes the basic elements such as diode, shunt resistance, series resistance and current source as shown in the figure (1). The parameters of a PV cell are Voc, open circuit voltage (at zero load current) and Isc, short circuit current (at zero load voltage) these are calculated by neglecting the leakage ground currents. By neglecting the small diode current and leakage current Voc can be calculated by the formula Vout+RsI, here Vout is the output voltage of PV array. The electrical equivalent circuit can be shown in figure(1).

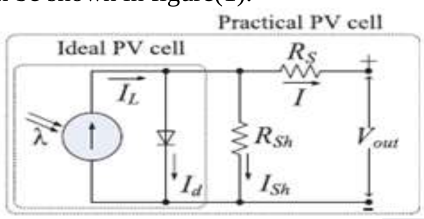

Figure 1. Electrical Equivalent circuit of a PV cell

The PV array generated current is I_L equals the output current I if the values of shunt current I_{sh} and diode current I_d are low. The shunt current I_{sh} is inversely proportional to R_{sh}, shunt resistance 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.[3]

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

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

The module current or Photo current I_L can be given as

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

Here, I_L: photo-current (A); K_i: short-circuit constant of cell at 25°C and 1000 W/m2; T: operating temperature(^oK); λ: solar irradiation (W/m2).
The diode current I_d is given

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

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

$$I_D = \frac{I_{sc}}{\left(\exp\left[\frac{V_{oc}Q}{N_s KT}\right] - 1\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

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

$$I_D = \frac{I_{sc}}{\left(\exp\left[\frac{V_{oc}Q}{N_s KT}\right] - 1\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5)$$

III. INCREMENTAL CONDUCTANCE MPPT METHOD

MPPT or Maximum power point tracking is algorithm is implemented to achieve maximum power at specific conditions from the PV panel. The PV output power depends on sunlight based irradiance, temperature and position of the panel. In addition to this it also depends on another component which is a result of voltage and current. By fluctuating these parameters the power can be maximized. The voltage at which PV produces maximum power is Maximum Power Point correspondingly as MPP we have $V_{amp}$and I_{max} in I-V characteristics as shown in the figure(2).

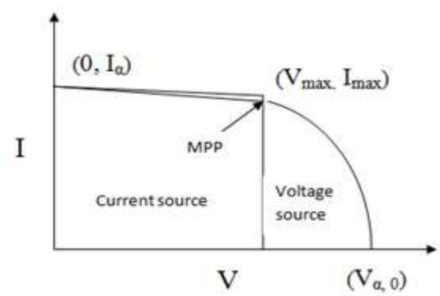

Figure 2. PV cell I-V characteristics

To find out the real working point in connection to MPP, this Incremental conductance method utilizes the derivate of the conductance di/dv. At MPP, slope of the tangent to P-V curve is zero [6]. This can be shown as

$$\frac{dP}{dv} = \frac{d(VI)}{dv} \qquad (6)$$

$$\frac{dP}{dv} = I + V\frac{dI}{dV} \quad (7)$$

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

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

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

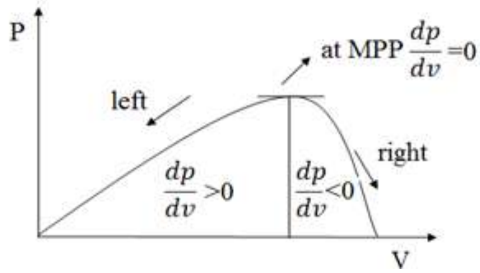

Figure 3. Incremental Conductance MPPT

From the instantaneous measurement of i and v, the following approximations are calculated

$$di=i(z)-i(z-1) \quad (11)$$
$$dv=v(z)-v(z-1) \quad (12)$$

So, this algorithm can obtain the change in voltage or power that leads to change in MPP by calculating i/v and di/dv at every instant. Once MPP has acquired, PV array is fixed at this point, unless di_p is noted the calculations are halted. This algorithm can decrement or increment the V_{PV} to trace another MPP. The efficiency of MPPT is determined by the speed tracking of MPP. The Incremental conductance method is proved to the best method with high efficiency at rapid changing climatic conditions.[5]

The MPPT can be 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 incremental conductance method can be represented in a flow chart in figure (4).

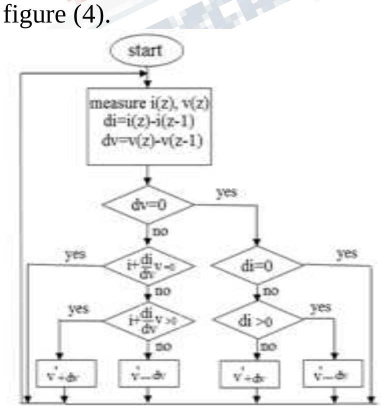

Figure (4). Flowchart for Incremental Conductance MPPT method

VI. CONCEPT OF INSTANTANEOUS POWER BALANCE THEORY

The voltage source inverter (VSI) has three phases consisting six IGBT's as switching devices and to minimize the current distortion an L filter is placed at output. Between the dc link and the utility VSI act like power controller. The DC/AC converter itself acts like APF by generating pulses to the switches in its circuit. In addition to this it eliminates harmonics, providing reactive power compensation and simultaneously infusing maximum power generated by PV units into system. Using instantaneous power theory the controller has been designed.

The power flow through the utility can be in two cases:
1. PV supplies its generated power to local nonlinear loads and its additional power to utility.
2. PV supplies a part of nonlinear load and the residual part is received from the utility.

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

$$P_{VSC} = \bar{P}_{VSC} + \tilde{P}_{VSC}$$
$$P_L = \bar{P}_L + \tilde{P}_L \quad (13)$$

$$Q_L = \bar{Q}_L + \tilde{Q}_L$$

The average component can be obtained from the fundamental component of nonlinear load current. The oscillating part is obtained from the negative sequence components and harmonics.

V. PV ACTIVE POWER FILTER

In the proposed method, initially the measured voltages of load are transformed to the α-β-o coordinates.

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

The instantaneous real power (P_L) and imaginary power

(Q_L) are to be calculated by using the Clarke Transformation.

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

Here load power average part will be supplied by the utility. The PV-APF combination supplies the real power oscillating part along with the imaginary power of the load. C_{VSC} the dc link capacitor, its voltage should be kept at (V_{VSC}^{ref}), reference value for this an additional amount of power is utilized which is $(\overline{P_{LOSS}})$ which is to be provided by the utility. The equations can be written as

$$\bar{P}_L + \tilde{P}_L = \bar{P}_{VSC} + \tilde{P}_{VSC} + \bar{P}_{UTI} + \bar{P}_{LOSS}$$
$$\bar{Q}_L + \tilde{Q}_L = \bar{Q}_{VSC} + \tilde{Q}_{VSC} + \bar{Q}_{UTI}$$
$$\bar{P}_{VSC} = \bar{P}_L - \bar{P}_{UTI} - \bar{P}_{LOSS}$$
$$\bar{Q}_{VSC} = \bar{Q}_L - \bar{Q}_{UTI} \quad (16)$$
$$\tilde{P}_{VSC} = \tilde{P}_L$$
$$\tilde{Q}_{VSC} = \tilde{Q}_L$$

The reference values for VSC are calculated from these equations

$$P_{VSC}^{ref} = P_L - \bar{P}_{UTI} - \bar{P}_{LOSS}$$
$$Q_{VSC}^{ref} = Q_L - \bar{Q}_{UTI} \quad (17)$$

If the $\bar{P}_{LOSS}$ is provided by the PV unit and the load imaginary part is supplied by the PV-APF then the equations are

$$P_{VSC}^{ref} = P_L - \bar{P}_{UTI} + \bar{P}_{LOSS}$$
$$Q_{VSC}^{ref} = Q_L \quad (18)$$

After calculating the reference powers for DC/AC VSC, by reverse Clarke transformation, the current reference values in 3-phases are calculated by these equations

$$\begin{bmatrix} I_{\alpha VSC}^{ref} \\ I_{\beta VSC}^{ref} \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} P_{VSC}^{ref} \\ Q_{VSC}^{ref} \end{bmatrix} \quad (19)$$

$$\begin{bmatrix} I_{aVSC}^{ref} \\ I_{bVSC}^{ref} \\ I_{cVSC}^{ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{\alpha VSC}^{ref} \\ I_{\beta VSC}^{ref} \end{bmatrix} \quad (20)$$

During APF controller [7] mode the PV is removed, the C_{VSC} connected to the converter supplies the load. The current references are calculated from $C_{VSC.}$

$$P_{VSC}^{ref} = \tilde{P}_L + \bar{P}_{LOSS}$$
$$Q_{VSC}^{ref} = Q_L \quad (21)$$

Here P_{loss} is to be infused by the utility. The Hysteresis control technique is employed to switch the IGBT switches in the VSC. The dc voltage regulation passes through FLC which filters out the harmonics in the dc capacitor voltage.

VI. FUZZY LOGIC CONTROLLER

The disadvantages of the traditional controllers like PI, PID has led for the research of Fuzzy logic controller (FLC). In FLC linguistic variables are developed rather than to develop mathematical models. Hence FLC is a robust system. Harmonic distortion can be reduced effectively by implementing FLC as a controller so that there is a chance for the enhancementof power quality of a system. In FLC, the theory of fuzzy set takes its fundamentals from human thinking.

In FLC of APF, the capacitor voltage at dc side is taken and then compared with the values of reference. The error derived at the n^{th} processing instant e=$V_{dcref} - V_{dc}$ and the change of error signal ce(n)= e(n)-e(n-1) are used as inputs for fuzzy system. FLC comprises of 4 stages: knowledge base, fuzzification, defuzzification and inference mechanisms [8].

FLC is characterized as follows:

1. For each ouput and intput seven fuzzy membership triangular functions are considered: negative small (NS), negative medium (NM), negative big (NB), zero (ZE), positive big (PB), and positive medium (PM), positive small (PS).
2. Impliction using Mamdani's 'min' operator.
3. Defuzzification using the 'Centroid' method.
4. The relation between the input variables to the output variables can be defined by rules of fuzzy rule base.

		Error(e)						
Change In Error c(e)		NB	NM	NS	ZE	PS	PM	PB
	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

Table 1. Fuzzy rule base

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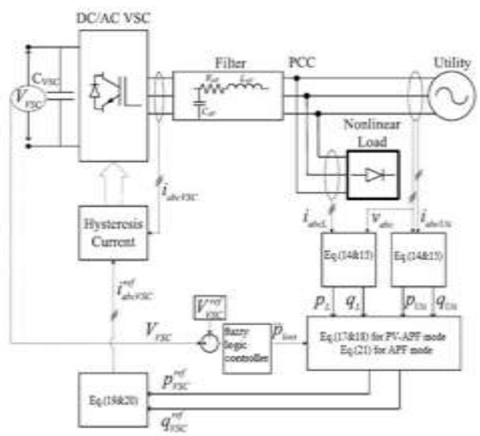
The hysteresis current control with fixed band is incorporated to get the switching the pattern by using these error signals. The firing pulses obtained are implemented to the VSC to minimise the error in current. This method is accurate and faster in response.

The FLC and hysteresis controller are implemented in the system and by using the power balance theory the switching pulses are generated to the APF as depicted in figure(5).



VI. SIMULATION RESULTS

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

Photovoltaic System	SPR-305E-WHT-D type have 330 solar modules 5 series and 66 parallel array Irradiance – 1000w/m² Output Voltage- 250V Maximum power – 100KW Output voltage at maximum power-274V
Boost Converter	f=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_{abcR} – 260V Frequency- 60Hz
Unbalanced non-linear load	3- phase diode rectifier Constant dc current – 450A 1-phase diode rectifier Constant dc current – 50A

The total simulation is carried in four modes for 0.75sec.They can be represented as

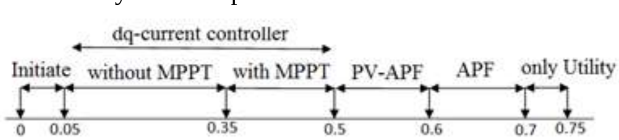


Figure (6). Operation modes of simulation

A. Performance of pv unit

An equivalent circuit for PV array is designed by the electrical equivalent PV model of fig(1) and it is analysed in MATLAB. By solving the I-V equation(1) I value can be obtained. The PV output power is depicted in figure (7). The PV output voltage is depicted in figure (8) and the Duty cycle is depicted in figure (9). In all these after the MPPT is activated the PV unit Power and voltage has increased.

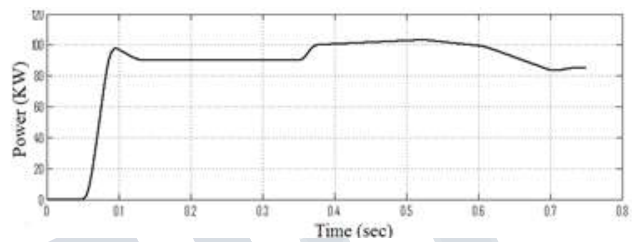


Figure (7).PV output power

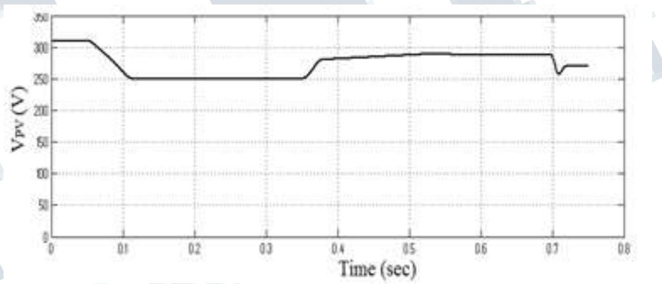


Figure (8). PV unit Output Voltage

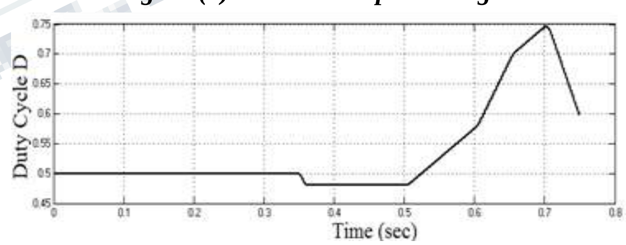


Figure (9). MPPT Duty Cycle

B.Active Power Filter Performance

The simulation is done on three phase three wire system with nonlinear load. Here as nonlinear load the diode rectifier can be incorporated. We have two cases such that under balanced load (utility supplies power) and unbalanced load (utility receives power) conditions. From these simulation utility currents, voltages and powers of load, utility, PV are taken as outputs. THD values of utility current in these four cases are calculated using FFT analysis.

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Case 1:

The natural diode rectifier consuming 450(A) dc current for three phases and 50(A) dc current for one phase is connected as load. The total load power demand is 130KW.

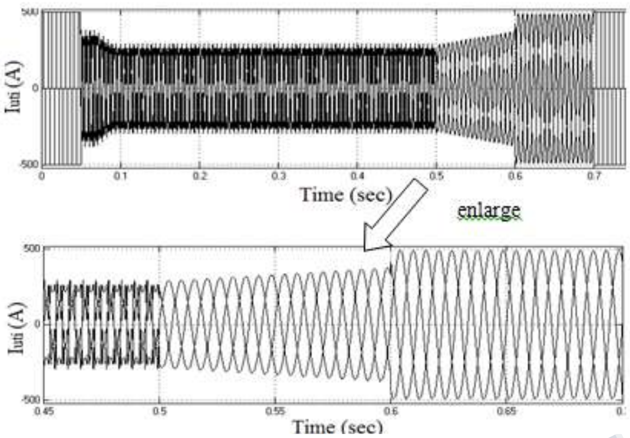

Figure (10).current waveform supplied by Utility

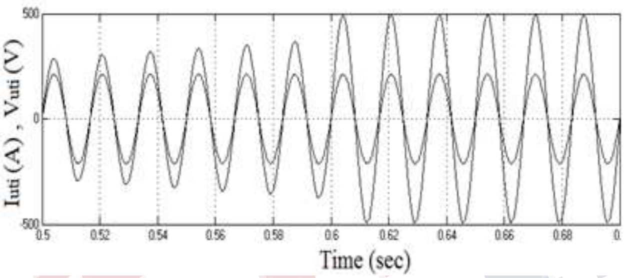

Figure (11). Voltage and current waveforms of Utility

When the Active Power Filter is performing its operation the voltage and current supplied by the utility are in phase as shown in figure (11). It shows that the APF with FLC is an accurate method for harmonic compensation [9] and making the utility power factor to unity

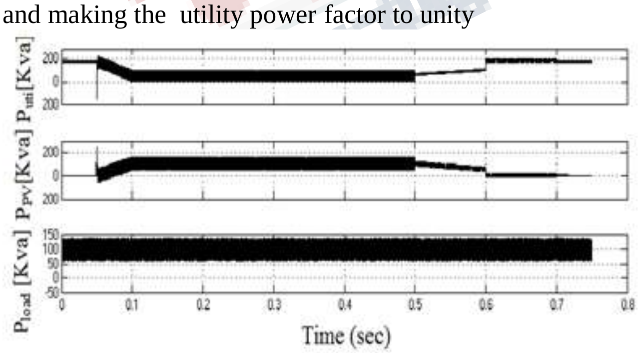

Figure (12). Under balanced load condition real power from the (a) utility, (b) PV unit, and (c) load ,.

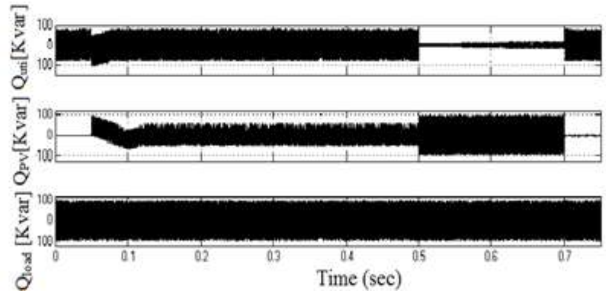

Figure (13). Under balanced load condition Imaginary Power from the (a) Utility, (b) PV unit, and (c) load,.

The simulation can be done in four modes at different time intervals as shown in figure(6).

1) dq-current mode: It is from 0.05s to 0.5s. During this the PV unit is switched ON and its MPPT is activated.

2) PV-APF mode: IT is from 0.5s to 0.6s. During this period PV and Utility both supply the load and active power filter is operated.

3) APF mode- It is from 0.6s to 0.7s. During this period PV is switched out from the system. The dc link capacitor connected to the APF is supplying the load.

4) Utility mode: It is from 0.7s to 0.75s. During this mode only the utility has to supply the load.

The THD of utility current in these four modes is analyzed by fast Fourier transform (FFT) as shown in figure(14), under balanced load conditions.

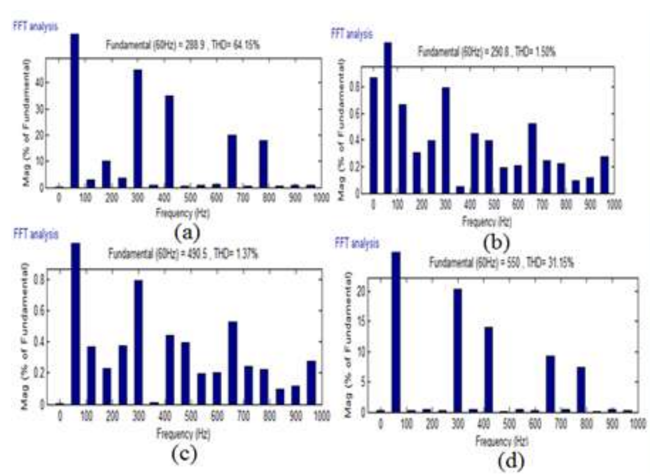

Figure (14). under balanced load condition, THD in four modes of PV system operation (a) dq-current mode, (b)

PV-APF mode, (c) APF mode, (d)Utility mode

CASE 2:

The load consumes dc current of 50(A) for a 3- phase rectifier and 50(A) dc current for 1- phase rectifier. Here the utility receives the power under this unbalanced condition

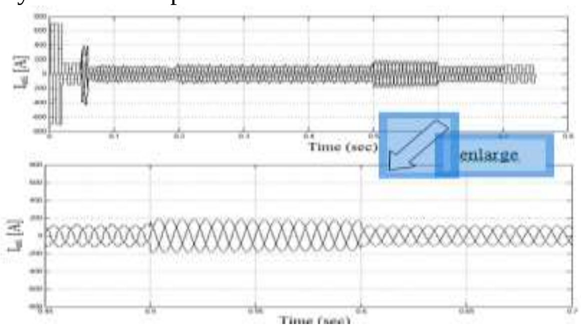

Figure (15). Current wave form received by Utility

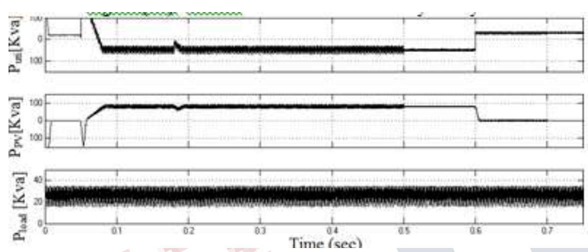

Figure (16). Under unbalanced load condition real power from the (a) utility, (b) PV unit, and (c) load.

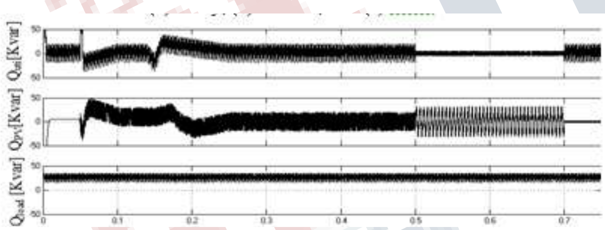

Figure (17). Under unbalanced load condition Imaginary power from the (a) utility, (b) PV unit and (c) load,

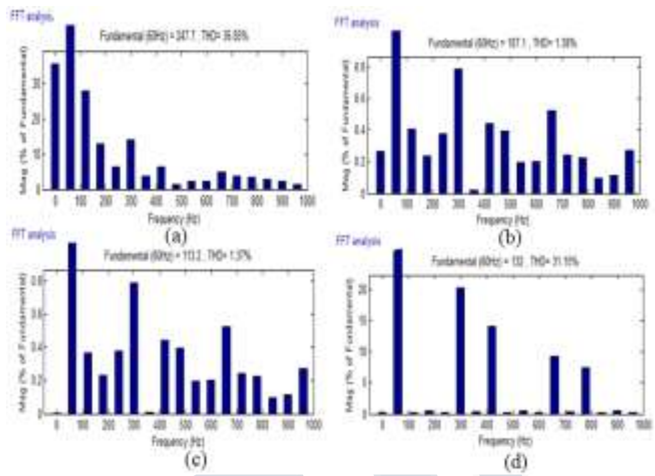

Figure (18). Under unbalanced load condition THD in four modes of PV system operation, (a) dq-current mode, (b) PV-APF mode, (c)APF mode, (d)Utility mode.

The THD of utility current in these four modes is analyzed by fast Fourier transform (FFT) as shown in figure(18), under balanced load conditions.

VII. CONCLUSION

In this paper, the PV-APF system with FLC is proposed at unbalanced and balanced load conditions. It proved that the photovoltaic system can be combined with the APF and FLC can effectively reduce the THD when it is connected to the grid or utility. The proposed topology has provided reactive power compensation and reduced harmonics and due to nonlinear load current. As a result utility current become sinusoidal and unity power factor is also achieved. As evident from the simulation studies that PV based shunt APF is effective for power conditioning applications. The THD of the current from utility after compensation is "1.37%" which is less than 5% required by the IEEE-519 standards limiting the THD in distribution networks.

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