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Reduced Harmonics In 3-Phase Grid-Connected Solar, Fuel Cell, And Battery Systems Using Z-Source Inverter With Filter Integration

[1]Kishor Rachakonda, [2]Dr.K. KrishnaVeni, [3]Dr.J. Upendar

[1]Research Scholar, [2]Professor, [3]Assistant Professor

[1]Electrical Engineering,

[1]Osmania University, Hyderabad, India

ABSTRACT*:* This paper explores the reduction of harmonic distortion and variations in voltage in 3-phase grid-connected solar, fuel cell, and battery systems using a Z-source inverter (ZSI) integrated with harmonic filters. The hybrid system, combining solar, fuel cell, and battery energy storage, provides a reliable and sustainable power source for grid connection. However, harmonic distortions can arise due to the switching operations of inverters, affecting power quality and system performance. To address this, a harmonic filter is incorporated into the system design to significantly reduce harmonics. The integration of filters with the Z-source inverter mitigates harmonic problems, enhances the overall efficiency and also stability of the hybrid power system in grid-connected operations. The proposed system in reducing harmonic content and improving power quality under variations of solar insolation and loads with simulation results obtained using Matlab/Simulink.

***Index Terms* -** Photovoltaic, FC, Battery, Harmonics, Grid Connected.

I. Introduction

The power quality issues such as harmonic elimination, voltage sags, voltage increments, frequency deviations, and voltage magnitude are included in the management system. Due to increasing application of nonlinear loads in the distribution system power quality issues especially harmonics, are becoming a concern in power systems[1]. This is true in the low-voltage distribution network where electronic devices such as computers, compact fluorescent lamps, and many other appliances, are drawing harmonics currents from the grid. The voltage harmonics are directly related to the distribution system power quality may affect sensitive loads or communications system. To maintain good quality power, enforcing the adoption of stricter regulations on the nonlinear loads is necessary [2]. To limit the harmonics in the system is to adopt passive filters or active power filters. Hybrid filter constitute of active and passive filter with different structures are used. The passive filter such as probability of resonances and non-dynamic responses and also high cost of active filter, while using both the advantages of both of them with lower costs. Different structure of hybrid filter can be utilized in the power systems such as shunt passive filter and series active power filter with non-linear loads, shunt active and passive filter with non-linear loads, series active and passive filter parallel with non-linear load etc[]3-4].

In this study hybrid filter is constitute of a series active filter and a passive filter connected in parallel with the load. The control strategy is based on the Victorian theory dual formulation of instantaneous reactive power, so the voltage waveform injected by the active filter is able to compensate the reactive power and load current harmonics and to balance asymmetrical loads[5-7]. The proposed algorithm also improves the behaviour of the passive filter.Z Source Inverter (ZSI) with space vector pulse width modulation technique (SVPWM) in the DC bus to maintain the DC bus voltage level at a constant value. Hence high reliability, high efficiency, and low cost can be achieved. DC-DC boost converter is usually required when the dc source voltage is insufficient to supply the output voltage, resulting in a two-stage system with high cost and complicated control. The traditional CSIs have analogous limits[8-9]. A 3-ph hybrid filter is connected into the utility grid to compensate the reactive power and the load current harmonics, generated by the non-linear load. By using the vectorial theory, control strategy of hybrid filter dual formulation of instantaneous reactive power[10].

II. SYSTEM CONFIGURATION

The control scheme in the system configuration was described in detail in the previous section. Furthermore, the HS component, i.e., PV-FC, is connected to the DC bus through the diode to avoid reverse power flow. The BESS is connected by a bi-directional converter to the DC bus.

a) Z-Source Inverters:

Some of the limitations of VSI or CSI include; simultaneous buck-boost, interchange from voltage source to current source and vice-versa operation can't be achieved, severe affect due to EMI noise, resulting into reduced reliability. In order to get rid of these problems faced by VSI and CSI, use of Z-source inverter is another alternative to achieve power conversion. The structure of Z-source inverter is different from VSI or CSI, having an X-shaped impedance network. This topology offers an additional freedom of control with presence of shoot-through interval along with active state. The shoot-through state is undesirable in VSI in order to protect switching devices. The use of inductors in impedance network of ZSI enables safe shoot-through of inverter branch and boosting of voltage across the capacitor network.

Where D is the duty ratio and Vpv is the PV output voltage. The AC output voltage Vac of ZSI is expressed as:

$$V_{ac} = BmV_{PV} \quad \text{eq-1}$$

Where m is the modulation index and B is the boost factor given as:

$$B = \frac{1}{1-2D} \quad \text{eq-2}$$

During this process, the non-boost method of ZSI, the input PV power appears the capacitor through the current ripple is limited by the inductor. Further the power is kept constant by the capacitor to make the output voltage is sinusoidal. The shoot-through current through inductor linearly voltage increases across capacitor. The approximate value of capacitor is written as

$$C \geq \frac{DI_L}{2 f_s \Delta V_c} \quad \text{eq-3}$$

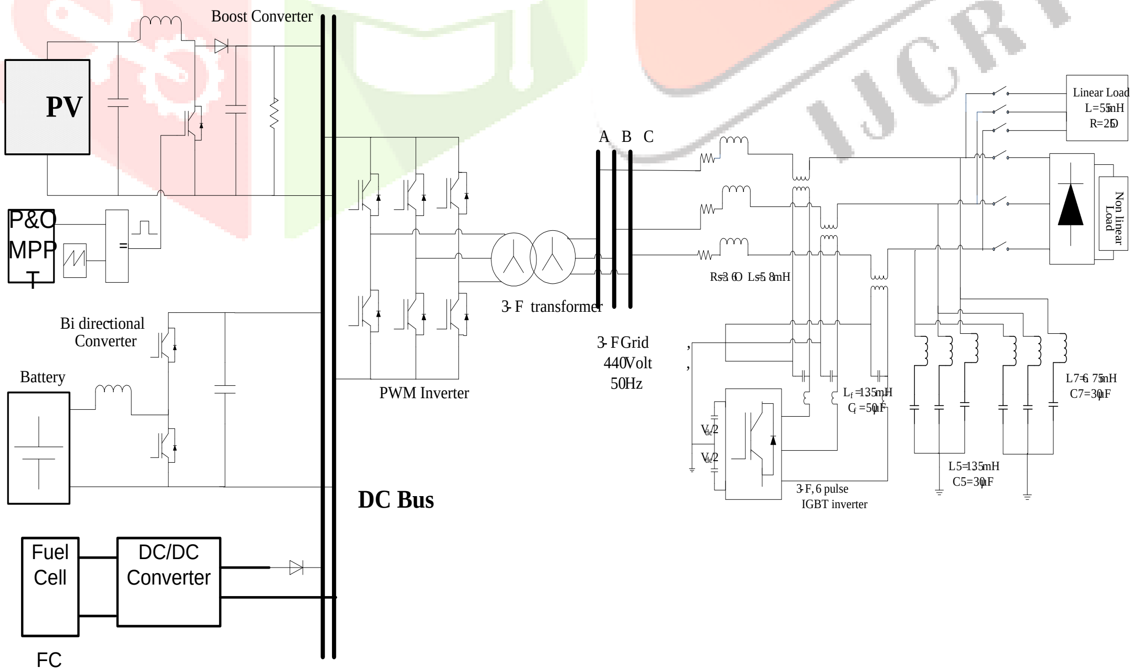
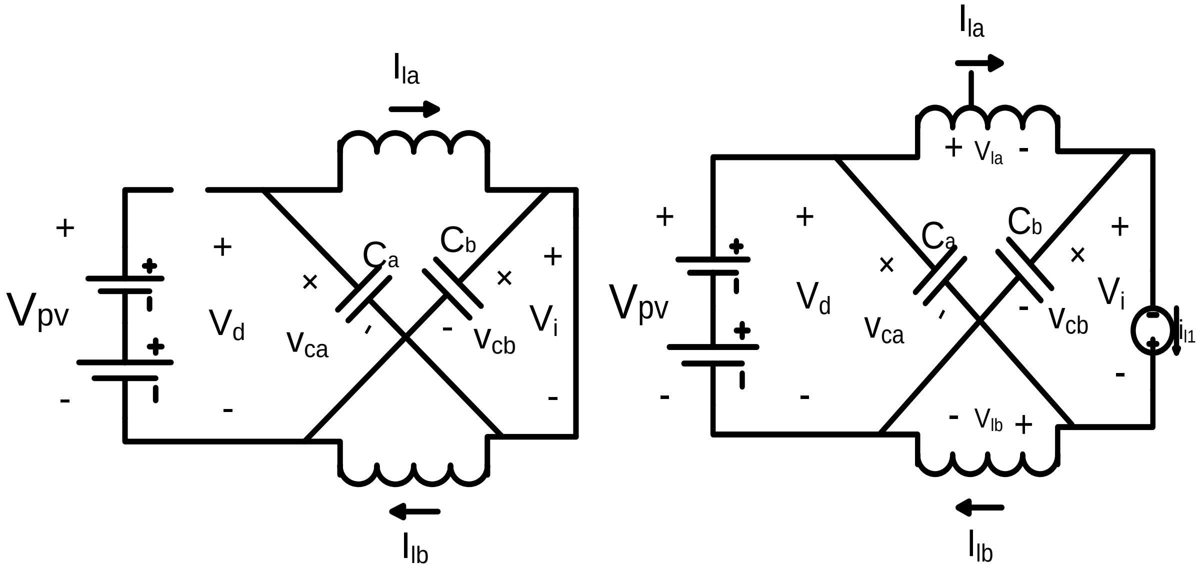


Fig.1 Circuit type I Hybrid System connected to grid



(a) (b)

Fig.2 Z-source inverter. Equivalent circuit of a) Active state b) shoot-through state

Mathematically voltage across the capacitor C_a and C_b are given as

$$V_{ca} = \frac{1-D}{1-2D} V_{PV}$$
$$V_{cb} = \frac{1-D}{1-2D} V_{PV} \qquad \text{eq-4}$$

Where D is the shoot-through duty ratio, IL is the average current of the Z-network inductor, fs is the switching frequency and is the value of capacitor voltage ripple at peak power. The ripple content in capacitor voltage is taken as 1-5%.

In the inductor maximum ripple of current occurs when maximum shoot-through takes place. In general, the maximum ripple current is taken in range 5-30%. The approximate design value for inductor is written as:

$$L \geq \frac{DV_c}{2 f_s \Delta I_L} \qquad \text{eq.5}$$

Where VC is the average capacitor voltage and is the value of inductor current ripple at peak power to certain value.

b) Hybrid Filter

i) Passive Filter: A passive filter is used to eliminate the current harmonics, when it is connected across the load.

ii) Active power Filter Compensation Strategy by Dual Instantaneous Reactive Power Theory:

The consumers receiving power supply from grid connected PV system face numerous PQ problems including harmonics and unbalance supply. The connections of nonlinear loads drawing nonlinear currents have led to deterioration in voltage quality. In order to achieve, improved signal waveform, the hybrid filter is basically formed by a series active filter and a passive filter connected in parallel with the load.

III. CONTROL STRATEGIES OF HYBRID SYSTEM

In this section, we aim at designing controllers that will be able to ensure:

(i) A global stability of closed loop system,

(ii) A perfect robust MPPT design. Specifically, the controller must enforce the PV voltage to track, as accurately as possible even in rapid change in solar cell temperature.

(iii) A unity PF in the grid; and suitable controller for hybrid filters to improve the Power Quality.

The hybrid filter basically formed by a series active filter and a passive filter connected in parallel with the load is proposed. (main paper). This theory is based on the Clarke transformation. Transformation from a-b-c coordinates to α-β coordinates is obtained as:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad \text{eq-6}$$

Transformation matrix of eq.4 is applicable for the current also. Instantaneous real power p and instantaneous reactive power q for 3- three wire system can be calculated as

$$p = v_\alpha i_\alpha + v_\beta i_\beta, q = v_\alpha i_\beta - v_\beta i_\alpha \quad \text{eq.7}$$

According to eq.5 and eq.6, these two powers can be expressed in the vectorial form by means of dot product

$$p = i_{\alpha\beta}^T v_{\alpha\beta}, q = i_{\alpha\beta\perp}^T v_{\alpha\beta} \quad \text{eq.8}$$

Now the voltage vector can be calculated based on eq.6 and eq.7, as

$$v_{\alpha\beta} = \frac{p}{i_{\alpha\beta}^2} i_{\alpha\beta} + \frac{q}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \quad \text{eq.9}$$

According to (eq.8) load voltage can be defined by

$$v_{L\alpha\beta} = \frac{p_L}{i_{\alpha\beta}^2} i_{\alpha\beta} + \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \quad \text{eq.10}$$

The compensation strategy is based on an ideal reference load which must be resistive, balanced and linear.

$$R_e = \frac{P_L}{I_1^2} \quad \text{eq.11}$$

Where I_1 is the rms value of the fundamental component of source current and PL is load average power which can be obtained by a Low pass filter. Voltage at the PCC in α-β coordinates can be obtained by

$$v_{PCC\alpha\beta} = \frac{P_L}{I_1^2} i_{\alpha\beta} \quad \text{eq.12}$$

Reference voltage for active filter is given by

$$v_{C\alpha\beta}^* = v_{PCC\alpha\beta} - v_{L\alpha\beta} \quad \text{eq.13}$$

the reference voltage for active filter can be calculated as

$$v_{C\alpha\beta}^* = \left(\frac{P_L}{I_1^2} - \frac{p_L}{i_{\alpha\beta}^2} \right) i_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta} \perp \quad \text{eq.14}$$

In case of unbalanced load, instead of using I_1, positive sequence fundamental component of source current I_1+is used for compensation strategy. Therefore, the reference voltage for unbalanced load is

$$v_{C\alpha\beta}^* = \left(\frac{P_L}{I_1^{+2}} - \frac{p_L}{i_{\alpha\beta}^2} \right) i_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta} \perp \quad \text{eq.15}$$

a) Space Vector PWM (SVPWM) Based VSI

SVPWM technology is widely used in inverters. For calculating the vectors of the SVPWM to generate the pulse wave of the VSI, the trigonometric function is involved and the sector selection is considered. For the rapid change in power electronics application, the accuracy of SVPWM is very high although the technique is complicated. the closed-loop control technique of a VSI using the SVPWM technique. Due to rapid development of control technique in power electronics, Space Vector PWM technique has one of the most important modulation techniques for 3-Φ inverters and rectifiers due to its easy to implementation, wide linear modulation range and less harmonic distortion features. The principle of Space Vector PWM technique for a three-phase ZSI, and then the implementation scheme of maximum boost control method based on SVPWM technique are used for hybrid power system.

As illustrated in Fig. 1, Va, Vb, and Vc are the output phase voltages of a three-phase ZSI. The switching variable frequency a, b, c, a′, b′ or c′, here when switch is on the transistor value s=1, then switch is off the transistor value is s=0. The relationship between the switching variable vector [a b c]T and the phase voltage vector [Va Vb Vc]T is written as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \text{eq.16}$$

The reference voltage vector of three-phase ZSI is obtained by mapping the desired three-phase voltages to the dq plane through the eq.16.

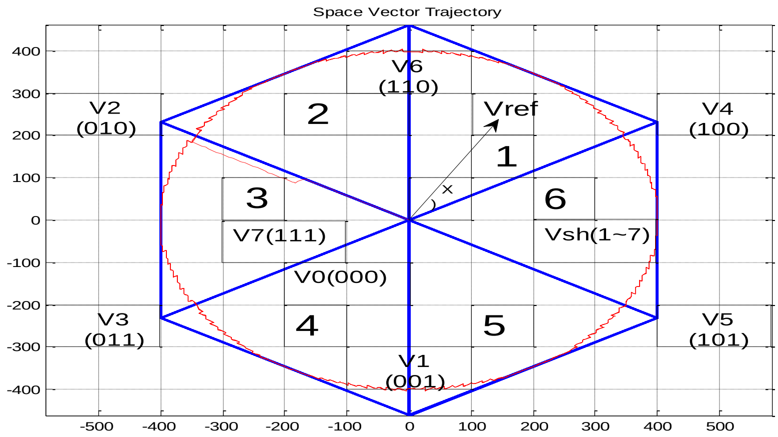


Fig. 3 Basic space vectors and sectors of three-phase ZSI

$$\vec{V}_{ref} = \begin{bmatrix} Vd \\ Vq \end{bmatrix} = T_{abc-dq} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{\sqrt{6}}{2} \hat{V}_{ph} \begin{bmatrix} \cos(\omega t) \\ \sin(\omega t) \end{bmatrix} \qquad \text{eq.17}$$

IV. HYBRID FILTERS COMPENSATION TECHNIQUE

A three-phase hybrid filter is connected into the utility grid to compensate the load current harmonics, generated by the non-linear load. Nonlinear loads such as power electronic converters; voltage regulators and the fluctuating loads are mainly responsible for the electrical pollution which includes the deterioration of electric power through the generation of harmonic voltages & currents. This degrades the performance of the overall system and the equipment connected at the end users and decrease the efficiency and life time of all the connected equipment. Passive filter is not suitable for variable loads. The active power filter improves the harmonic compensation features of the passive filter. The performance of both the PV system and Hybrid filter has been verified under different loading conditions in MATLAB/Simulink platform. The system and methods applied is very useful and efficient and independent on any change in the load. Hybrid filter not only compensates the reactive power required by the load but also improves the performance of the passive filter Control strategy of inverter including voltage regulator is shown in Fig. 5.8 where 3 phase voltage V_{abc} is first transformed from a-b-c to d-q co-ordinates using Park transformation which is represented by and V_{dq} is subtracted from the reference value of V_{dq}.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad \text{eq.18}$$

Error is passed through the PI controller and the controlled output is retransformed into a-b-c co-ordinates by using inverse Park transformation to get inverter voltage (Vabc_inv) which is further used to generate the pulses for the 3 -Φ PWM inverter through a PWM generator. Inverse Park transformation is represented by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \qquad \text{eq.19}$$

a) Control of Hybrid Filter

The control scheme for the hybrid filter is considered on the load side, the voltage vector and source side of the current vector are considered. The α-β component of the voltage and the current vector are obtained by α-β transformation. The real instantaneous power is obtained by the product of the α-β component of voltage and current, and the mean value is obtained with the help of a low-pass filter. The fundamental component of the current is obtained. A 3-VSI is implemented in the hybrid filter in the circuit real power demand by the load should be equal to the power supplied from the main and the power converter is assumed to be lossless; thus, the DC capacitor average voltage is maintained as a constant value. During the transient, such as a sudden change in load, power imbalance occurs. Therefore, the DC capacitor average voltage is reduced. At the same time, the current magnitude of the main supply should be increased to increase the real power supplied from the source. On the other hand, as the DC capacitor voltage rises, the source current must be decreased. In this context, the DC capacitor voltage reflects the information about the real power flow.

V. SIMULATION RESULTS AND DISCUSSION

The control scheme described in previous sections is implemented with the considered HPS as shown in Fig.1 in a MATLAB platform. All parameters (insulation, temperature variation, load connected to the system, etc.) are considered in the simulation and are shown.

The circuit configurations of the grid connected PV system are simulated in the Matlab /Simulink. The value ZSI network elements are as La=Lb= 2mH and Ca=Cb= 400μF. The 5th and 7th harmonic component of the source current is suppressed by the LC passive filter. The switching frequency is kept as 20 kHz for the IGBT switches. The comparative assessment between two circuit types for power quality improvement is carried out on different conditions of load and variation in solar intensity with/without hybrid filter. The nonlinear load consists of uncontrolled rectifier in shunt with the series combination of resistor and inductor. And linear load has series combination of 35Ω resistor and 50mH inductor.

Case 1: Linear and Non-Linear Balanced load without hybrid filter

In this case, a linear load which is series combination of 25Ω resistor and 55mH inductor and a non-linear balanced load of same value is connected and switched ON in a particular sequence. For the first 1 sec., only linear load is switched ON. Insolation level during this period is 950 W/m2. After 1 sec. only non-linear load is switched ON up to 2 sec and insolation level is kept at 1100 W/m2. After 2 sec. both the loads are switched ON with the insolation level of 1050 W/m2. Non-linear load consists of an uncontrolled rectifier with the series combination of resistor and inductor on the DC side. Total Harmonic Distortion (THD) of source current and Power factor has been shown as Simulation results with varying insolation and switching Loads along with the harmonic analysis for this case has been shown in Fig.5.

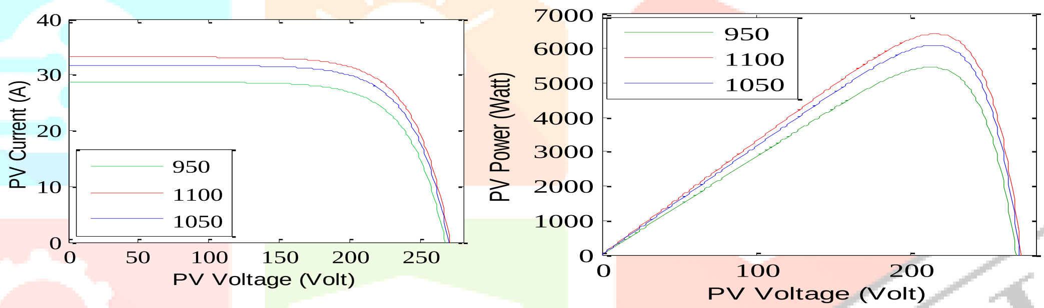
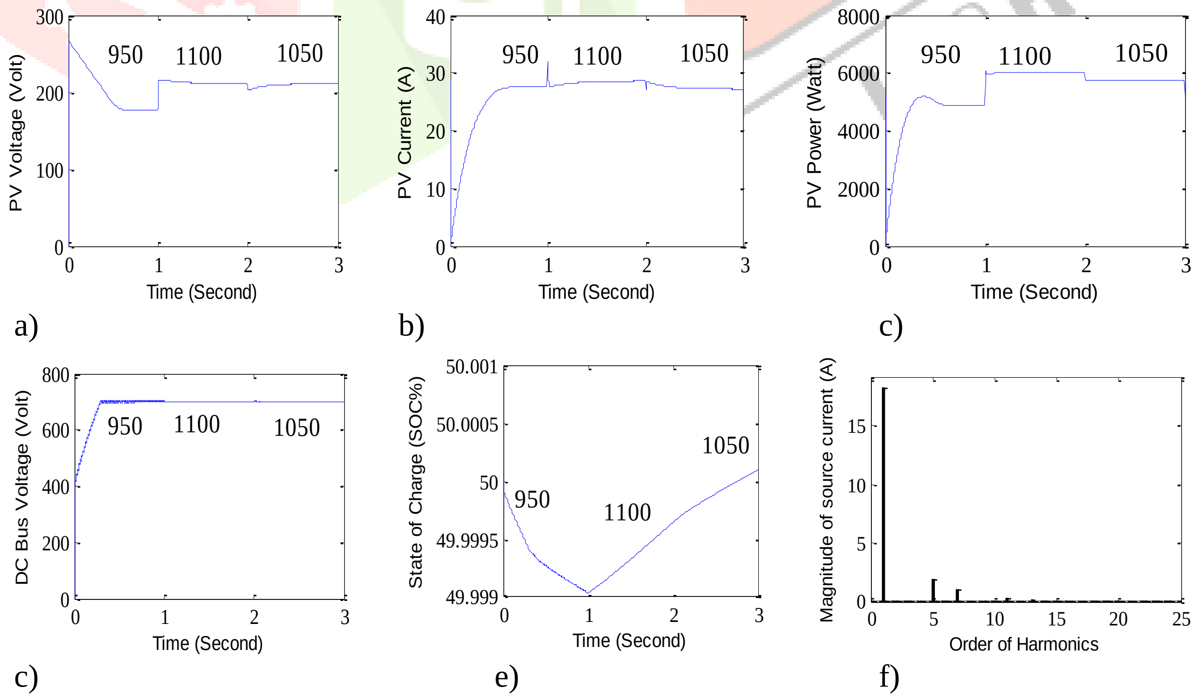
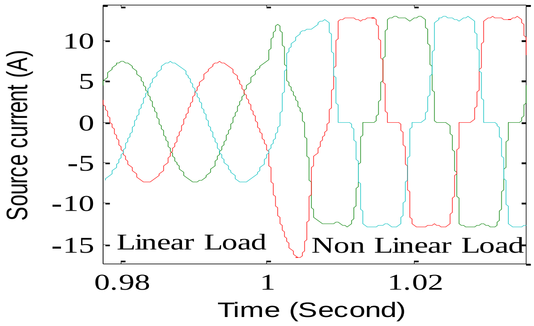
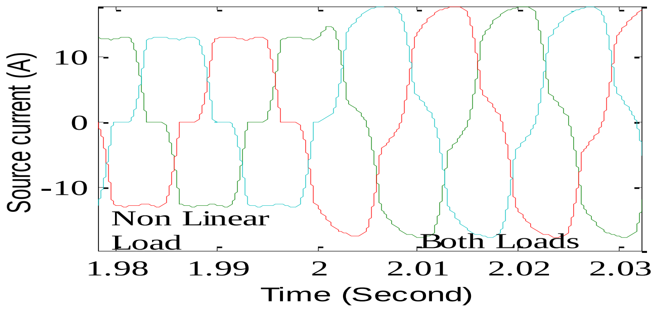


Fig.4 (a) I-V characteristics b)P-V characteristic





h)



i)

Fig.5 Case 1: Linear and Non-Linear Balanced Load without Hybrid Filter (a) PV voltage (b) PV current (c) PV power (d) DC bus voltage (e) SOC% of battery (f) (h) Harmonic analysis (g) Source current (h) Source current both loads

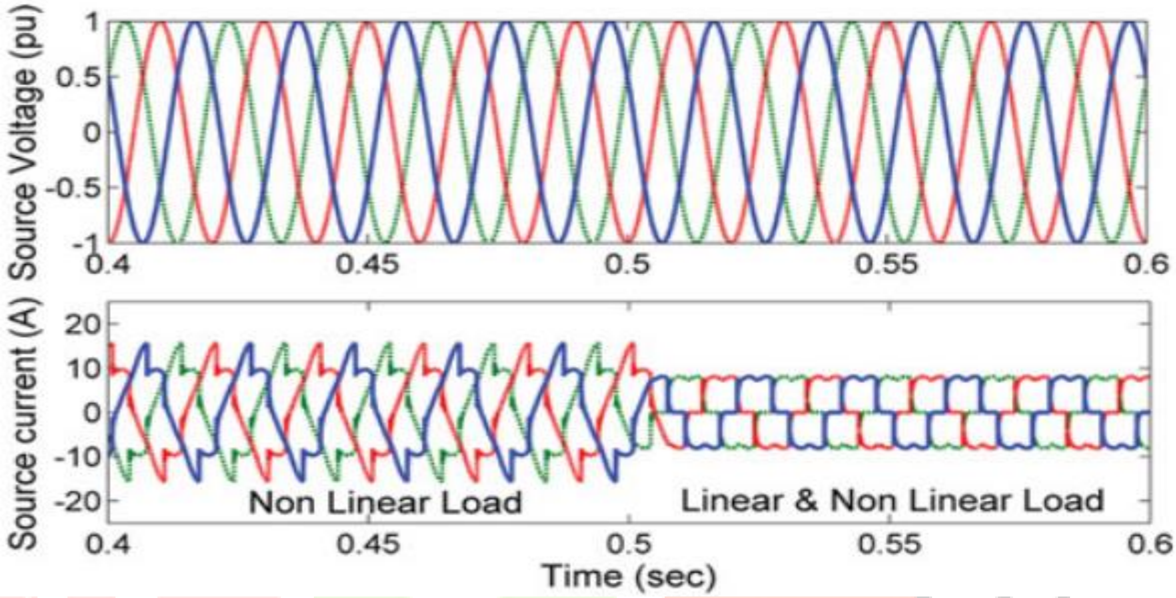
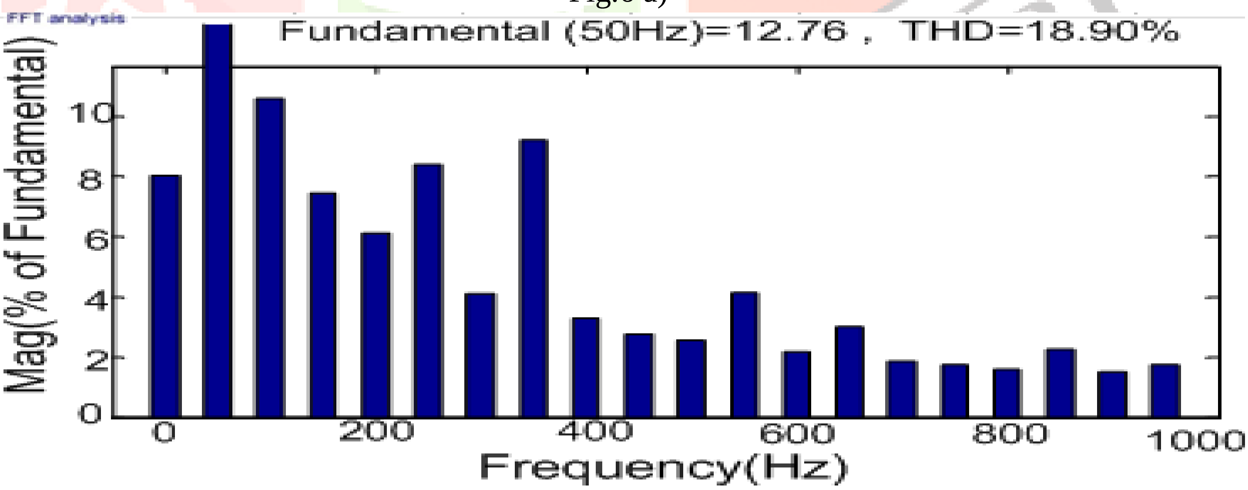
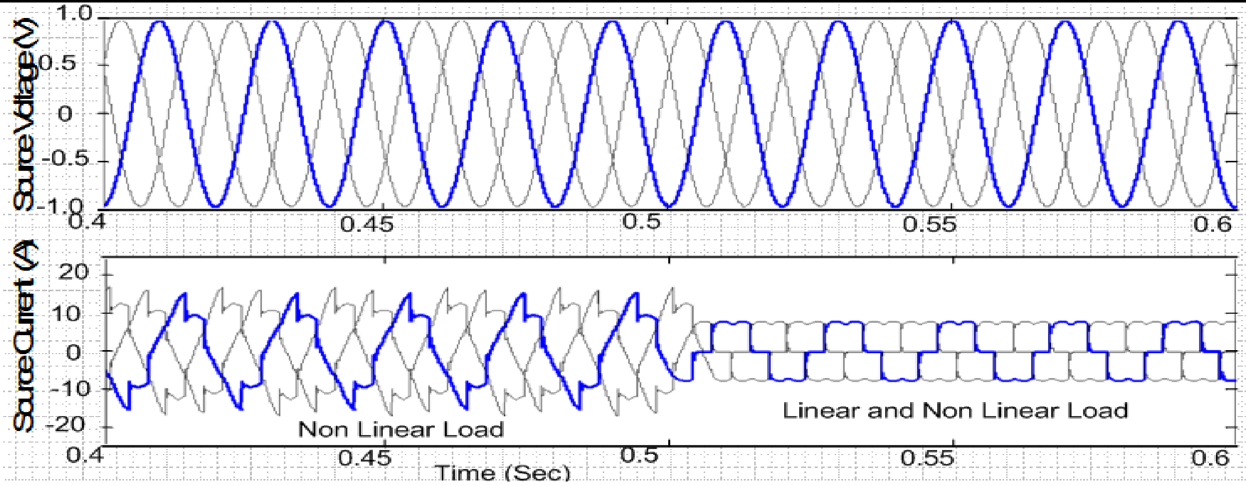


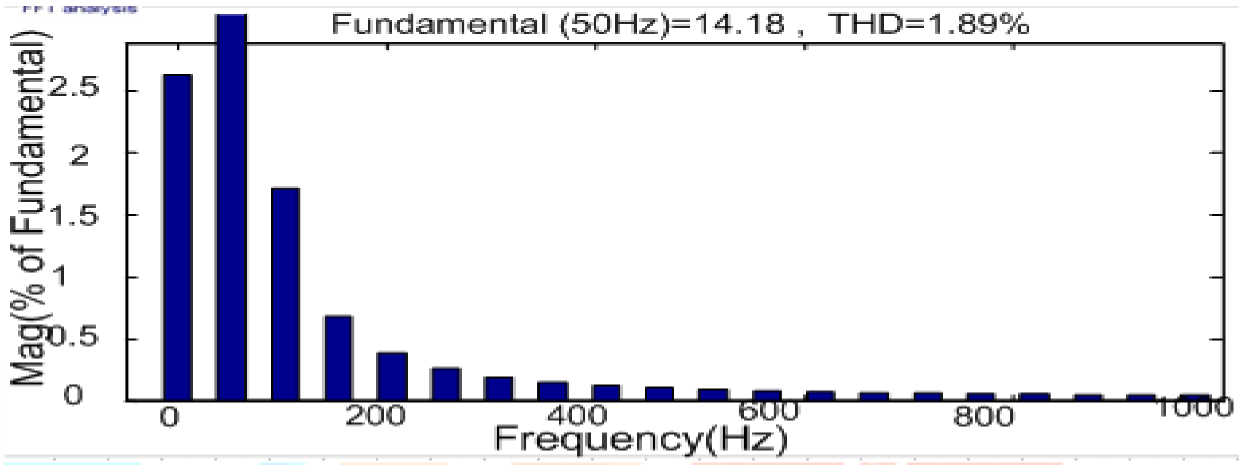
Fig.6 a)



b)



c)



d)

Fig. 6 (a) Source current and voltage of Case I, (b) THD plot without filter of phase *A* source current, voltage of Case II, (c) source current and (d) THD plot of phase *A* source current with filter.

Case 2: Linear and Non-Linear Balanced Load with Hybrid filter:

In this case, hybrid filter is connected with the same load and same switching pattern is applied as in case 1. PV characteristics and other PV parameters remain same as in previous case for all the cases. Reference voltage is first calculated with the help of eq.14 The source current THD decreases, which verifies the performance of connected power conditioning equipment. Power factor also improves. Furthermore, the harmonics spectrum during the linear load will remains unchanged for all the cases. Fig.6 shows the source current and harmonic analysis for this case.

VI.CONCLUSIONS

In a grid-connected HPS, PQ enhancement is carried out by suitable design of a hybrid filter. Qualitative analysis is carried out through a series of simulation results to demonstrate the superiority of its design for compensation of distorted signals retrieved at the PCC in the presence of various types of loads connected to it. Quantitative results for improvement of THD are shown in tabular form to support the simulation results. Further exploration of the backstepping technique is implemented for the MPPT design. The power management algorithm is also addressed to keep the DC bus voltage constant in a laboratory prototype has been built and tested, with non-linear load a rapid variation in temperature and radiation is taken for the PV system which further supports the effectiveness of the proposed control strategy.

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