Performance Evaluation of 3-Phase Active Filter in Grid integrated PV System Employing Sinusoidal Current Control Strategy

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Abstract: - The basic aim of the electric power sector is to produce power as when required at the suitable sites, then transmitting and distributing the same to various load centers or end users, maintaining the quality (the frequency and voltage at a specified value) as well as reliability of electrical power at an economical price. The main objective of this chapter is to have a brief idea about various power quality issues with their improvement techniques and to learn the prospects of various methods of harmonic mitigation using Active filter (both series and shunt active filters), in a Grid connected PV system with a focus on sinusoidal current control strategy as a time domain control strategy based on instantaneous $pq-$ theory. Shunt Active Power Filter is implemented in the hybrid system to mitigate the harmonic current component as well as to recompense the imaginary or reactive power owing to their exact and reckless operation, whereas Series active filter takes care of voltage sags and swells due to source or load side disturbance. The strategy so implemented using MATLAB 2016A is to extricate sinusoidal current commencing from the source. The results have been analyzed in details explaining efficacy of the above control strategy. As the control strategy is a simple and effective, it has tremendous potential for application in the Distributed Generation oriented system. Further researches can be extended toward application machine learning techniques for the improvisation of control performance of the active power filters.

Key-Words: - Power Quality, Distributed Generators, Series Active filter (SAF), Shunt Active Power Filter (ShAPF), Sinusoidal Current Control Strategy, Custom Power Devices

1 Introduction

As the world looks forward to sustainable development, there has been increasing demand for clean energy sources with greater quality. It requires the power engineers to revisit the power quality issues, as they seem to have changed. Although substantial quantity of energy is generated, but it has become very difficult as well as challenging for power engineers to reconcile the rising expectation of getting high quality of power which is only possible by the mitigation of harmonics in power system specifically caused by nonlinear loads. In general good quality of power must have low interruption frequency, limited amplitude fluctuation along with less harmonic distortion, low flicker in the voltage at supply end, as well as less percentage of phase unbalancing and supply frequency fluctuation, etc. The lack of quality power

result in loss of production, damage to appliances, increase in power losses, interference with communication lines and many more.

Power quality puts the boundaries in the deviation levels of voltage, frequency and waveform shape of power supply for proper functioning of the equipment. Without these limitations according to the IEEE standard, equipment may mal-operate and may not produce desired output. Various causes and terms related to power quality issues are addressed by power engineers day by day. Some of the important terms related to Power Quality (PQ) has been described in [2] such as reactive power compensation, harmonic compensation, voltage regulation, harmonic pollution, etc.

Power quality issues are inevitable when numbers of DGs are connected. There is a close relation

between DG and power quality. Considering both supply side and load side, there are several DGs involved so as several loads and the power has to be transferred through a common distribution line. Therefore, proper coordination is required to be maintained from each source to satisfy the load pattern. Implementation of DGs will either enhance the PQ or deteriorate the service for end users which is a major concern now-a-days. As PQ is the combination of voltage and current, the quality of voltage can be considerably improved even with a slightest level of backup storage capacity implemented in the Series Connected Photo-Voltaic Distributed Generator (SPVG).

Among several PQ issues, the harmonics is considered to be the primary reason for poor PQ. Therefore, it is very essential to take into consideration, the rectification of the PQ problems and maintain the Total Harmonic Distortion (THD) within prescribed limits as per the IEEE standards [3]. So, for elimination of harmonics filters are an essential requirement.

On the basis of switching operation of filter elements, filters are classified as passive filters, which include manual switching of passive elements such as capacitor and inductors and active filters that include power electronic switching.

2 Active Power Filter (APF)

Focusing on the various active power filters (APFs) are conceivable substitute for minimizing effects arising due to non-linear loads on the power network which passages to recompense harmonics produced by nonlinear loads. To attain compensation aims, generation of reference signal is significant meant for the design purpose as well as in control purpose of active filters. Many control strategies has been realized, out of which the most effective is sinusoidal current control strategy for mitigation of the harmonics and also others PQ issues as generated due to unbalanced or unstable system owed to the non-linear loading condition [1].

So far the control aspect of APF has drawn lots of attention. Focusing on the digital filters, notch filters has been designed in [4] for damping out harmonics. Based on that both simulations and experiments have also been carried to prove the effectiveness of such filter that is able to produce required amount of lead or lag in phase around the resonant frequency for the stability of the system. In [5] selective filters such as harmonic selective filters have been used to

separate low frequency harmonic component from fundamental component. A comparison between another set of filters has been done in [6] i.e. Adaptive, Weiner and Kalman filters in which Kalman Filter is best among all to reduce THD by more than 50% and an extended Kalman filtering approach has been used in [7] for the frequency estimation due to the presence of noise, notch and harmonics in the system. Optimization techniques and algorithms used to enhance the performance of filters that includes Bee Colony Optimization, Fuzzy logic and Differential evolution, Unscented Kalman Filter (UKF), Particle Swarm Intelligence (PSI), Genetic Algorithm (GA) [8-10].

Advantages of active filter are it can remove all types of harmonic currents from the sensitized non-linear loads, i.e., for lagging loads, it can compensate reactive power factor and moreover it can behave as a damping resistor to prevent from harmonic resonance. Also the capital cost of active filters is low as it requires reduced ampere rating.

2.1 Shunt Active Power Filter (ShAPF)

Shunt active filter (ShAPF) is connected in parallel comprising of non-linear load whose harmonic currents are required to be compensated. The principle of operation of ShAPF is based on production of current harmonics equal in magnitude but in phase opposition i.e. 180˚ to the harmonics present in the grid. ShAPF along with compensating reactive power also mitigates harmonics and distortion [11-12]. ShAPF have more benefits in comparison to Series Active Filters (SAF) on the basis of their form and function.

Coming over the applied control techniques, in [13] the control technique of the ShAPF has been developed consisting of two current inside loops and a DC-bus voltage outside loop. Since, Lyapunov function is used to solve any problem due non-linearity so, in [14], the control strategy based on Lyapunov function has been used along with the ShAPF. The experimental validation of the ShAPF system has been done using a DS1104 DSP of d-SPACE and tested for different condition of operation. Again in [15-16] another experimental verification has been done for ShAPF consisting of dual parallel topology based APF where 110-V, 50-Hz mains providing power to a 3 kW load has been considered.

Shunt active filter (ShAPF) is connected across comprising of non-linear load whose harmonic

currents are required to be compensated. The principle of operation of ShAPF is based on production of current harmonics equal in magnitude but in phase opposition i.e. 180˚ to the harmonics present in the grid. ShAPF along with compensating reactive power also mitigates harmonics and distortion [17-18].

Configuration of ShAPF

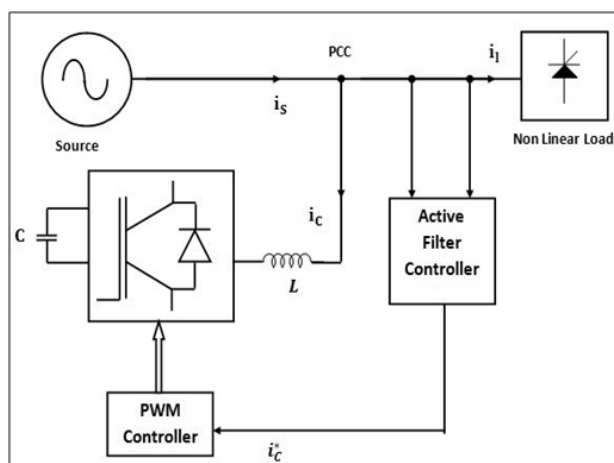The schematic diagram of ShAPF has shown in figure 1.1.

Fig. 1 Schematic Diagram of ShAPF

The figure 1 consists of two components, i.e., PWM converter and active filter controller.

A PWM converter, mainly accountable to process power and synthesize the compensating values of current which has to be drained from the network. Active Filter controller is accountable for processing signal and to define the real time instantaneous compensating current values, which is passed on continuous manner to the PWM converter section. Generally ShAPF works in a closed loop method. It sense current that flows through load, and computes the instant values of the compensating/shunt current reference value i_c^* for the PWM converter section. Either voltage source converter (VSC) or current source converter (CSC) can be used in ShAPF. CSC can be used for its robustness but in today's scenario shunt active filter that are used in commercial purpose almost uses VSC owing to its higher efficiency, initial cost is low as compared to CSC and reduced physical dimensions. It must be distinguished that, no supply is given to the converter, simply an energy storing component (capacitor for voltage fed converter or inductor for current fed converter) is linked at dc end of the

converters because shunt active power filter should perform like a compensator. In supplement, the exchange of average energy should remain zero among the power filter and the power system.

2.2 Series Active Filter (SAF)

The filtering characteristics of shunt passive filter depend on the source impedance (inductive in nature), high the source impedance, better is the filtering characteristics. However, the source impedance should be insignificant at the fundamental frequency to reduce the fundamental voltage drop appreciably which can be fascinated by the insertion of active impedance in series with the ac source. The active impedance can be realized by the series active filter (SAF) through the voltage source PWM inverter.

The SAF acts as controllable voltage source whereas ShAPF acts as a controllable current source. Both of these designs are executed desirable with VSI, with a capacitor acting as a dc bus.

The SAF is connected in series with the power supply and is used as a voltage booster. It compensates for voltage as a constant voltage source (CVS) [19]. A single-phase SAF has been developed based on SPMC. It has been designed in such a manner that it can operate bidirectional without any use of dc capacitor and additionally its implementation is simpler in terms of hardware control [20]. The SAF is usually used to solve any deviation in voltage and other PQ related issues. They are more competent than shunt compensators as they are able to compensate current issues.

Configuration of SAPF
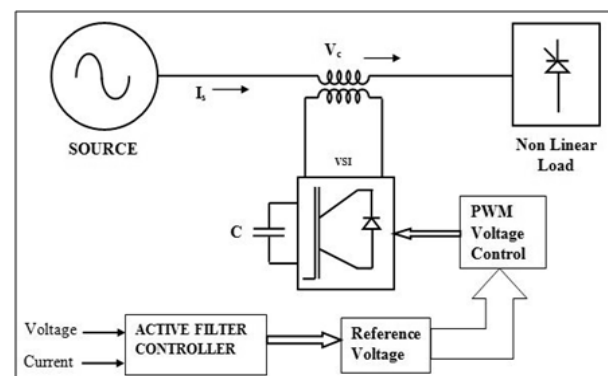
The schematic diagram of SAPF has shown in figure 2.

Fig. 2 Schematic Diagram of SAF

The figure 2, consists of which consists of two components, i.e., PWM voltage control and active filter controller.

The basic series active filter voltages are synthesized by the converter with a common dc capacitor. The reference voltage for this converter is calculated by the "active filter controller" as shown in figure 2 which has the input signal as load voltage and load current (same as source current).

A PWM voltage controller will be processing power and synthesize the compensating values of voltage to be drained from the network. Active filter controller will be processing signal to define the real time instant compensating voltage values to be passed on continuous manner to the PWM converter. The SAF works in a closed loop method sensing the voltage and computes the instant values of the compensating/series voltage reference value v_c^* for the PWM controller. A voltage source inverter (VSI) has been used in SAF due to its higher efficiency, low initial and compact size. It is acclaimed without any supply rather associated with a capacitor as an energy storing component linked at dc end of the converters for SAF to perform like a compensator. In supplement, the exchange of average energy should remain zero among the power filter and the power system.

3 CONTROL STRATEGY of AFs

The design of the controller for AFs is not so easy when applied in power system as the supply voltage itself is already unbalanced and/or distorted. The aspects of compensation for the active filter may be determined by the control algorithm as enforced in the AF controller.

The 3-φ Four-Wire system recognizes all line currents to be sovereign unlike 3-φ 3-Wire system where both of them are autonomous, i.e., for 3-φ 4-wire system, $i_a, i_b, i_c,$ are independent to each other whereas for 3-φ 3-wire system, among the three currents two of them are independent. There are several reasons for considering 3-φ 3-wire system. One of the major advantage is the easiness of controlling the line current harmonic values in pq – reference frame, which simply converts 3-φ 3-wire currents and voltages into 2-φ mutually independent quantities, so that easier control is possible in pq – domain.

The design of the controller for APFs is not so easy when applied in power system as the supply voltage itself is already unbalanced and/or distorted. The aspects of compensation for the active filter may be determined by the control algorithm as enforced in the APF controller.

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There are several reasons for considering 3-φ 3-wire system. One of the major advantage is the easiness of controlling the line current harmonic values in pq – reference frame, which simply converts 3-φ 3-wire currents and voltages into 2-φ mutually independent quantities, so that easier control is possible in pq – domain.

- A steady instantaneous source active power
- A sinusoidal source current
- The minimum supply RMS current which transfers energy to load with less loss in the transmission line, i.e., the corresponding source current and voltages are proportional.

For non sinusoidal as well as irregular supply voltages, compensation of load current is carried by the ShAPF assuring for a single optimal compensation only. Hence, according to the choice of preferences the design of the controller for a ShAPF is made which is the major cause of inferring sinusoidal current control strategy.

4 Sinusoidal Current Control (SCC) Strategy

Sinusoidal current control (SCC) strategy is based on Instantaneous power theory, which is based upon the transformation from abc – frame to $\alpha\beta0$ – frame. But the reason for not adopting control in abc – reference frame is that in 3-φ system the 3-phases are mutually dependent on each other, so independent control of the quantities is difficult. To make the control simple, 3-φ quantities are converted into 2-φ mutually independent quantities, so that easier control is possible in pq – domain, which is a stationery reference frame as proposed by H. Akagi. The purpose for choosing this control strategy is its simplicity in implementation. So far several applications on this strategy have been seen

in different literatures. For a system with multiple renewable energy systems integrated, implementing a robust control becomes cumbersome, as the control of renewable itself requires a lot of complexities.

The control involves 3-φ quantities first converted into 2-φ quantities. Then these 3-phase quantities are used to evaluate the instantaneous powers in time domain, both instantaneous active as well as reactive power can be estimated. By using low pass filter, the harmonic power can be extracted, which can be used to generate the compensating current once the zero sequence power is known. The neutral point clamped capacitor voltage can be used to evaluate the zero sequence power. Hence the above mentioned method is termed as sinusoidal current control (SCC) strategy as the compensating current is sinusoidal in nature.

Advantages of pq – Theory over all other compensating theory are it can be valid for both steady state as well as transient state. Instantaneous power can be defined on $\alpha\beta0$ – frame i.e. in three phase form. So, three phase system can be considered as a single unit but not the addition of three individual 1-φ circuits. abc – frame to $\alpha\beta0$ – frame transformation is also known as Clarke transformation.

For appropriate expression, zero sequence power, p_0 is expressed in terms of $\alpha\beta0$ – frame of reference, as the instantaneous Watt power, p and instantaneous VAR power, q are known from the instantaneous power theory.

Mathematically:

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} - - - - - - (1)$$

Here, the 3-φ instantaneous active power is defined by both instantaneous active power with the instantaneous zero sequence power. In case of 3-φ 3-wire (3P3W) system, instantaneous zero sequence power does not exist so for this type of system, $P_{3-\phi}$ can be treated as p only. But for 3-φ 4-wire (3P4W) system it may be noted as follows:

$$P_{3-\phi} = v_a i_a + v_b i_b + v_c i_c = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 = p + p_0 - - - - - - (2)$$
But for 3-φ 3-wire system,
$$P_{3-\phi} = v_\alpha i_\alpha + v_\beta i_\beta - - - - - - - - - - - - - - - - - (3)$$

Whereas,

$$p = \underbrace{\overline{p}}_{\substack{\text{Average Value} \\ \text{of the Active Power}}} + \underbrace{\widetilde{p}}_{\substack{\text{Oscillating Component} \\ \text{of the Active Power}}} - - - - - - - (4)$$

From (4), it can be observed that instantaneous active power can be divided into two parts i.e. $\overline{p}$ and $\widetilde{p}$, where $\overline{p}$ is referred to the average value or dc value of active power which implies total energy transfer in the system and $\widetilde{p}$ defines the oscillating component of active sequence power and the instantaneous imaginary power can be defined as:

$$q = v_\beta i_\alpha - v_\alpha i_\beta = \frac{1}{\sqrt{3}} \left(v_{ab} i_c + v_{bc} i_a + v_{ca} i_b \right) - - - - - - - (5)$$

Where, i_a, i_b, i_a and v_a, v_b, v_c are the instantaneous current and voltage in abc – frame, whereas i_α, i_β, i_0 and v_α, v_β, v_0 are the instantaneous current and voltage in $\alpha\beta0$ – frame.

As the converters used now a days are basically acts a non-linear load, the energy flow between the systems has a boundary condition. Comparing to the response of the converter and the generation of harmonic components and reactive power with the conventional approaches the analysis of different type of power is not sufficient using average or rms value as variables. So in a nonlinear circuit, time domain analysis has to be carried out for analysis of energy flow [21].

A 3-φ sinusoidal voltage which consists of only positive and zero sequence voltages are considered for the realization of zero sequence power. Symmetrical component in frequency domain only is applicable for steady state operation. Hence it can be converted into time domain for analysis of both steady state and transient state. For voltage, (6) is used as follows:

$$\left. \begin{array}{l} v_a = \sqrt{2}V_+ \sin(\omega t + \theta_{v_+}) + \sqrt{2}V_0 \sin(\omega t + \theta_{v_0}) \\ v_b = \sqrt{2}V_+ \sin(\omega t - \frac{2\pi}{3} + \theta_{v_+}) + \sqrt{2}V_0 \sin(\omega t + \theta_{v_0}) \\ v_c = \sqrt{2}V_+ \sin(\omega t + \frac{2\pi}{3} + \theta_{v_+}) + \sqrt{2}V_0 \sin(\omega t + \theta_{v_0}) \end{array} \right\} - - - - - (6)$$

Whereas (7) used for current is as follows:

$$i_a = \sqrt{2}I_+ \sin(\omega t + \theta_{i_+}) + \sqrt{2}I_0 \sin(\omega t + \theta_{i_0})$$
$$i_b = \sqrt{2}I_+ \sin(\omega t - \frac{2\pi}{3} + \theta_{i_+}) + \sqrt{2}I_0 \sin(\omega t + \theta_{i_0})$$
$$i_c = \sqrt{2}I_+ \sin(\omega t + \frac{2\pi}{3} + \theta_{i_+}) + \sqrt{2}I_0 \sin(\omega t + \theta_{i_0})$$
$$------(7)$$

In order to obtain zero sequence components, the above equation is required to be converted into αβ0-frame by using Clarke transformation. For voltage, (8) is used as follows:

$$v_\alpha = +\sqrt{3}V_+ \sin(\omega t + \theta_{v_+})$$
$$v_\beta = -\sqrt{3}V_+ \sin(\omega t + \theta_{v_-})$$
$$v_0 = +\sqrt{6}V_0 \sin(\omega t + \theta_{v_0})$$
$$--------(8)$$

Whereas (9) used for current is as follows:

$$i_\alpha = +\sqrt{3}I_+ \sin(\omega t + \theta_{i_+})$$
$$i_\beta = -\sqrt{3}I_+ \sin(\omega t + \theta_{i_-})$$
$$i_0 = +\sqrt{6}I_0 \sin(\omega t + \theta_{i_0})$$
$$--------(9)$$

From (8) and (9), the instantaneous zero sequence power can be obtained as:

$$p_0 = 3V_0I_0 \cos(\theta_{v_0} - \theta_{i_0}) - 3V_0I_0 \cos(2\omega t + \theta_{v_0} + \theta_{i_0})$$
$$= \bar{p}_0 + \tilde{p}_0 ----------------(10)$$

So the instantaneous zero sequence power can be divided into two parts which consists of average power and oscillating component of power which is at double the line frequency. Here $\bar{p}_0$ is unidirectional energy flow as conventional active power and $\tilde{p}_0$ represents the oscillating component whose average value is zero. Interesting fact about zero sequence power is $\bar{p}_0$ cannot be obtained alone without the oscillating component $\tilde{p}_0$. Hence the total zero sequence components always associated with both average as well as oscillating component.

In the case of *pq*-theory, the instantaneous power so obtained is in time domain without consideration of the *rms* value of voltage and current. It also comprises of conventional frequency-domain concept for which the theory is not the contradictory theory rather it is the complementary theory in frequency domain.

The instantaneous zero sequence power components in the fundamental voltage and current or in harmonics do not add any impact on instantaneous real power and imaginary power. The total instantaneous active power is always same as the

addition of instantaneous true power and instantaneous zero sequence power which includes both average and oscillating components. The instantaneous reactive power reveals the energy exchanged between system even in the harmonic and unbalance condition.

The physical significance of instantaneous power in αβ0-frame has been illustrated in figure 3.

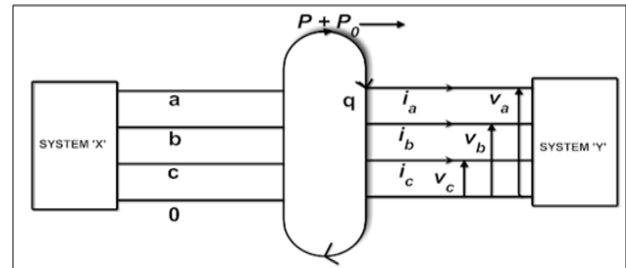Fig. 3 Physical significance of instantaneous power in $\alpha\beta0 - \text{frame}$

$p + p_0 \rightarrow$ Total Instantaneous power flow in unit-time.

$q \rightarrow$ Power exchange between three phases without any transfer of energy

The figure 1.3 shows the total instantaneous active power flow and instantaneous reactive power flow in between the two systems, i.e., source and load for a power distribution system. Imaginary power shows the energy exchanged between the phases not the energy transferred from one phase to other phase. The active and reactive current components are derived from the instantaneous *abc* voltages and currents are represented as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \underbrace{\frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix}\begin{bmatrix} p \\ 0 \end{bmatrix}}_{ActivePart} + \underbrace{\frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix}\begin{bmatrix} 0 \\ q \end{bmatrix}}_{ReactivePart} -----(11)$$

With the use of Inverse Clarke Transformation *abc* real and imaginary current may be obtained as follows:

$$\begin{bmatrix} i_{a_{(p)}} \\ i_{b_{(p)}} \\ i_{c_{(p)}} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\frac{(v_\alpha i_\alpha + v_\beta i_\beta)}{v_\alpha^2 + v_\beta^2}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} -----(12)$$

And

$$\begin{bmatrix} i_{a_{(q)}} \\ i_{b_{(q)}} \\ i_{c_{(q)}} \end{bmatrix} = \left(\frac{v_{ab}i_c + v_{bc}i_a + v_{ca}i_b}{v_{ab}^2 + v_{bc}^2 + v_{ca}^2}\right)\begin{bmatrix} v_{bc} \\ v_{ca} \\ v_{ab} \end{bmatrix} -------(13)$$

Where v_{ab}, v_{bc}, v_{ca} are the line voltages which can be obtained as follows:

$$v_{ab} = v_a - v_b, v_{bc} = v_b - v_c, v_{ca} = v_c - v_a$$

Also $i_{a_{(p)}}, i_{b_{(p)}}, i_{c_{(p)}}$ and $i_{a_{(q)}}, i_{b_{(q)}}, i_{c_{(q)}}$ are the real and imaginary current components which generate real and imaginary power respectively.

The line voltage does not contain any zero sequence component as: $v_{ab} + v_{bc} + v_{ca} = 0$

As the line voltage is free from zero sequence components, hence (12) and (13) can be re-written as:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} i_0 \\ i_0 \\ i_0 \end{bmatrix} + \begin{bmatrix} i_{a_{(p)}} \\ i_{b_{(p)}} \\ i_{c_{(p)}} \end{bmatrix} + \begin{bmatrix} i_{a_{(q)}} \\ i_{b_{(q)}} \\ i_{c_{(q)}} \end{bmatrix} - - - - - - - - - (14)$$

Among the two classifications of instantaneous power theory, one of them has already been described, i.e., instantaneous pq-theory. The other one is instantaneous abc-theory where use of Clarke transformation (abc-to $\alpha\beta 0$-transformation) is avoided. In this process instead of calculating real and imaginary power, active and non-active current may be calculated from abc phase voltage and currents.

4.1 SCC Strategy for ShAPF

There is an obvious question raised for selection of the ShAPF, numerous reasons can be cited which can be broadly reasoned as:
- Complexity of control in case of other compensators which require additional components.
- Cost effective control for low and lab-scale applications.

Apart from the above the complexity in tuning of filter components may also be reduced by the ShAPF which is applied to 3-φ 3-Wire system performing harmonic current suppression, reactive power compensation and power factor improvement.

M. Aredes et al. proposed ShAPF design for 3-phase 4-wire for unbalanced system [22], where application of $\alpha\beta 0$-has been considered in the presence of inverters and capacitors. They have used $\alpha\beta 0$-components of voltage and current for calculation of power to be compensated as well as zero sequence power which is lost due to unbalancing. This method is very basic for design of

ShAPF but it needs further advancement for better performance. Cavallini et.al [23] has proposed unity power factor (UPF) control strategy which is based on the method of line currents to fit the voltage waveform, by keeping the instantaneous real power equal to its mean value. The disadvantage of the proposed control strategy is observed as it is not particularly significant for the lower values of THD.

Based on various studies on different control approach for ShAPF and after observing their drawbacks, the proposed work has been carried out with a simple and old control strategy based on Instantaneous pq-theory on ShAPF has been shown in figure 4, which represents the basic control strategy for the system block diagram of a 3P3W ShAPF for compensation of current.
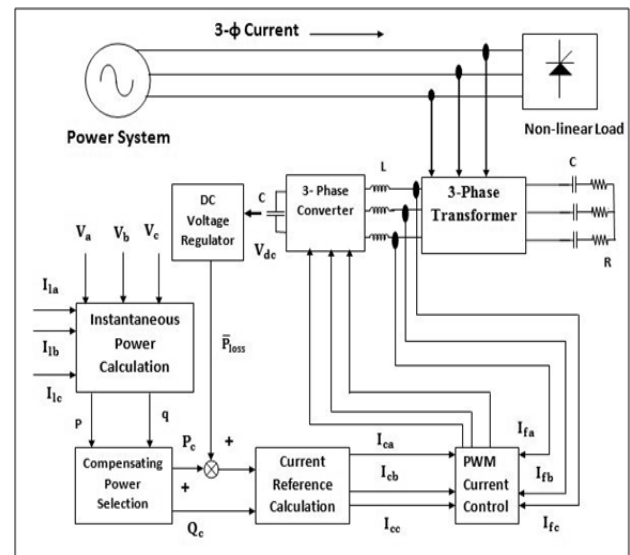

Fig. 4 Basic Control Strategy of 3-Phase 3-Wire ShAPF

The instantaneous power calculation block calculates the instantaneous power and the instantaneous active power are passed through high-pass filter to get the harmonic power. The compensating power selection block adds the line losses to the harmonic active power to obtain the active power to be compensated. The reactive power is obtained from the instantaneous power calculation block. These two are used for current reference calculation, which in turn is fed to PWM generator to generate firing pulses for shunt inverter. Input for the control block meant for calculation of the instantaneous power is the phase voltages at the PCC and the line currents of the nonlinear load to be compensated, i.e., a discriminated compensation characteristic for ShAPF, that performs as an open circuit for harmonic currents as produced by the

other nearby non linear loads. The current references are calculated using equations (11-14).

The ShAPF is the most familiar active filter for load current compensation. As quoted earlier, the ShAPF may support harmonic damping along the power line to evade the *harmonic propagation* as ensued due to harmonic resonance of the series inductors and shunt capacitors in power factor correction.

There are the following four functional control blocks in the active filter controller:

• Calculation of instantaneous power

• Selection of power compensation

• DC Voltage regulator

• Calculation of current reference

The instantaneous power of the non-linear load is measured by the instantaneous power calculation block. As per the pq – Theory, the real and imaginary powers exist, due to non existence of the zero-sequence power. The performance of the ShAPF is evaluated by the compensating power selection block, i.e., part of the real and imaginary power of the nonlinear load is selected which to be compensated by the ShAPF.

Furthermore, an extra amount of *real power* (p) is measured by the dc voltage regulator ensuing an additional energy flow to or from the dc capacitor for maintenance of voltage about a constant reference. This real power ($\bar{p}_{loss}$) is supplemented with the compensating real power (p_c), all together along with the compensating imaginary power (q_c) make its way to the block for the calculation of the reference current for evaluation of the instantaneous compensating reference current from the compensating powers and voltages. The structure of the control block diverged marginally from the earlier mentioned three control strategies.

The power circuit of the ShAPF is a 3-φ voltage source converter (VSC) constructed with IGBTs and series diodes. The PWM current control pressurizes the VSC to operate as a controlled *current* source. To prevent high $\frac{di}{dt}$ the interconnection of VSC with the power system is fashioned with an inductor (*commutation inductor* or *coupling inductor*) in series. For few cases, the leakage inductance of a usual power transformer sufficient to afford $\frac{di}{dt}$ limitation which removes the series inductor. In that case, a small passive filter, depicted with R and C, for filtration of the current ripples about the switching frequency must be equipped at the primary end of the transformer.

The ShAPF based on pq – Theory is applicable to both 3-φ 3-Wire circuit as well as 3-φ 4-wire circuit. A 3P3W control has been explained for system without neutral.

The constant instantaneous power control strategy assures the supply delivers one part of the power ($\tilde{p}$). As per the pq – Theory, the constant instantaneous watt power may be drawn from the supply so as the ShAPF will compensate the oscillating volt-amp power ($\tilde{p}$). Furthermore, the compensated RMS current is diminished through the compensation of the total reactive power, $q = \bar{q} + \tilde{q}$ of the load. There is no zero-sequence power for the concerned 3-φ 3-Wire system. Due to harmonics as well as irregularity in supply, the compensated current is non-sinusoidal assuring constant real power (p) to be drawn from the source which will be more interesting with no real-power swinging among the source and the desired load.

The sinusoidal current control strategy for ShAPF, was the first ever strategy established with the pq – Theory, and is introduced by Akagi et al. in 1983. Later on other two strategies, Constant power control strategy and Fryze current control strategy were developed. The ShAPF must be set up very much near to the nonlinear load so that it may draw a fixed instantaneous power from the supply as well as compensate the oscillating real power ($\tilde{p}$). The ShAPF must be supplied with a part of oscillating instantaneous active load current in a 3-φ system without neutral which results a zero powered zero-sequence component. The optimal power flow provided by shunt current compensation has been illustrated in figure 5.
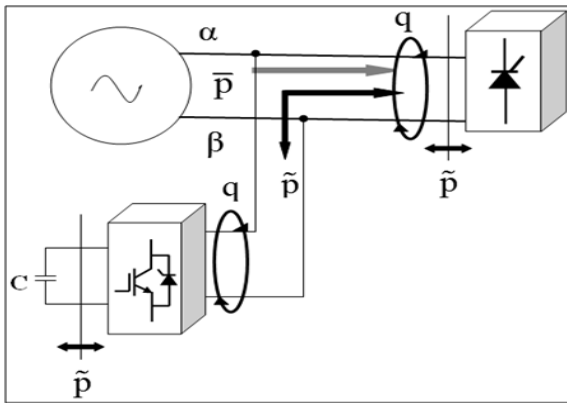
Fig. 5 Optimal Power Flow Provided by Shunt Current Compensation

A very large dc capacitor acting as an energy storage element or a dc source (a battery) must be connected to the active filter to absorb energy in long run without leading to overvoltage in dc capacitor which must be releasing equal energy in the subsequent semi cycle. To make it simpler the capacitor is replaced with an ideal dc voltage removing the dc voltage regulator generating $\bar{p}_{loss}$ during simulation. The dc voltage fluctuations due to low frequency, the oscillating power of the load must meet with an energy storage element (dc capacitor) in the ShAPF.

The signal $\bar{p}_{loss}$ is calculated by the dc voltage regulator pressurizing the ShAPF either to draw or inject real power to withstand the low frequency variation of dc voltage supplemented with the compensated power $-\tilde{p}$ or the load comprising the compensating reference current. Even the low cutoff frequency in extracting $\tilde{p}$ attempts to compensate low frequency components as exist in the real power of the load, the signal $\bar{p}_{loss}$ neutralizes the low frequency dc voltage variation. Hence $\bar{p}_{loss}$ restricts the rectification of low frequency components in $-\tilde{p}$ when both combines. Actually, here $\bar{p}_{loss}$ compensates the losses as well restrains the fluctuation of dc-voltage due to low-frequency components in $-\tilde{p}$.

Undoubtedly, the instantaneous power concept or theory practices a precise effective base for design of regulators (controller) for the power filter. The illustration of the control block of Active Filter Controller for sinusoidal current control technique can be seen in figure 6.
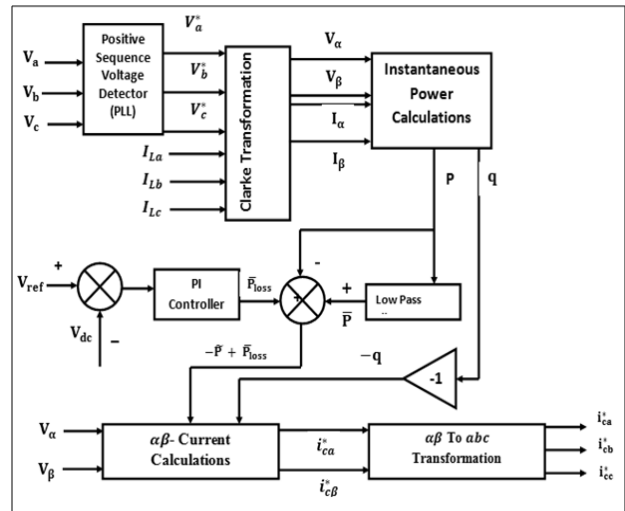

Fig. 6 Control block of sinusoidal current control strategy with 3-φ ShAPF

• *Positive sequence voltage detector:*

At load terminal the value of three phase voltage mainly consists of Positive Sequence Component. If there will be either negative sequence or Zero Sequence component then three phase voltage can be unbalanced and may also comprise harmonics from other components.Thus it is necessary to determine fundamental positives sequence voltage for this Sinusoidal current control technique and it is possible through positive voltage detector.

• *Phase-Locked-loop (PLL) circuit:*

The power network deliberately records the elemental components of frequency of the system voltages under consideration. This synchronizing circuit automatically defines the system frequency with the phase angle of positive sequence component of input signal.

• *Instantaneous Power Calculation Block:*

This block computes the instantaneous values of power of the passive load/nonlinear load.

• *Compensating Power Selection Block:*

This block selects some portion of real and imaginary power of the given nonlinear load which is to be compensated by the power filter.

• *DC Voltage Regulator:*

DC Voltage Controller defines a supplementary quantity of active power for which an extra energy

flows into the capacitor for keeping its value of voltage around a static reference value.

- *Compensating Current Reference Calculation Block:*

This block helps in defining the instantaneous value of compensating or shunts current reference from compensating voltages and powers.

Three phase instant voltages and currents phases of balanced or unbalanced source in the abc – reference frame is converted into instant voltages and currents on the $\alpha\beta 0$ – axis [28]. It can be noted that the instantaneous phase voltages V_a, V_b, V_c corresponding to $(V+1)$ phasor component of the fundamental positive-sequence voltage are transformed into the $\alpha\beta$ – coordinates by using the Clarke transformation block. Then, the set two phase component ($\alpha\beta$ – component of both current and voltage) are used for calculating active and reactive power (instantaneous powers) and also used for calculation of two phase compensating current. The compensating powers that is oscillating portion of real power ($\widetilde{p}$) and the total imaginary power, q are also used in the current calculation block in order to determine exactly all $\alpha\beta$ – components of currents in the load current that generates $-\widetilde{p}$ and q with $(V+1)$.

The three phase voltage can be converted into two phase voltage by means of Clarke transformation as shown in matrix form and this two phase voltage further participate in power ccalculation module in order to determine both active and reactive power along with two phase current i_α, i_β.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v'_a \\ v'_b \\ v'_c \end{bmatrix} -------(15)$$

Similarly, 3-φ line current scan be converted into two phase by using Clarke Tranformation it also help in determining real and imaginary power along with two phase voltage (v'_α, v'_β).

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} -------(16)$$

The benefit of implementing the Clarke transformation is that it converts 3-phase system into 2-phase system and allows independent control in two phases. Three instant powers that is zero-sequence component, the active component p, reactive component q the instant phase voltages and line currents can be represented in matrix format as shown below:

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v'_\alpha & v_\beta \\ 0 & v_\beta & -v'_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} --------(17)$$

From matrix active and reactive power is given as follow:

$$p = v'_\alpha . i_\alpha + v'_\beta . i_\beta -----------(18)$$
$$q = v'_\beta . i_\alpha + v'_\alpha . i_\beta -----------(19)$$

The block diagram of Sinusoidal Current Control Strategy epitomizes the entire algorithm of the controller for 3P3W ShAPF which compensates the oscillating real power as well as the imaginary power of the load (constant instantaneous power control strategy). Later the effect of the low-pass filter dynamic and the PI-Controller in the dc voltage regulator can be addressed transients.

According to the shunt current compensation, the real power of the nonlinear load must constantly be measured and is separated into average ($\overline{p}$) and oscillating ($\widetilde{p}$) parts instantaneously leads to equation (20).

$$p_c = \widetilde{p} = p - \overline{p} ------------(20)$$

In a true exercise, the separation of $\widetilde{p}$ from p can be realized through a block called *selection of the powers to be compensated* by a low pass filter with careful selection of cutoff frequency due to implicit dynamics lead to compensate errors during transients.

The total imaginary power to be compensated is:

$$-q = -\overline{q} + \widetilde{q} -----------(21)$$

The cause of appending a minus sign is same as explained earlier for compensation of the real oscillating power. Contrarily to compensate $-\widetilde{p}$, for

the compensation in the above equation does not need any energy storage elements.

In the above equation a minus sign has been appended with the real power to match with the direction of current as endorsed in the figure 4. For the load and the current for active filter, the usual load current convention is followed. If the current drawn by ShAPF particularly produces $-\tilde{p}$ of the load, then the power system is meant to supply the fixed part of the real power ($\bar{p}$) of the load. To compensate the oscillating flow of energy ($-\tilde{p}$), the dc capacitor of the PWM converter must be sufficiently large to store energy, for less voltage variations, but the PWM converter (a boost type) may lose its controllability with the lower peak dc voltage than that of the ac voltage.

Part of oscillating instantaneous active current on α-axis is:

$$i_{\alpha\bar{p}} = \frac{v_\alpha}{v_\alpha^2 + v_\beta^2}(-\tilde{p}) - - - - - - - - - - -(22)$$

Part of oscillating instantaneous active current on β-axis is:

$$i_{\beta\bar{p}} = \frac{v_\alpha}{v_\alpha^2 + v_\beta^2}(-\tilde{p}) - - - - - - - - - - -(23)$$

As expected, the ShAPF may be further optimized by further filtration of the compensated load current producing imaginary power as well as compensates the instantaneous reactive currents $i_{\alpha q}$ and $i_{\beta q}$.

Part of instantaneous reactive current on α-axis is:

$$i_{\alpha q} = \frac{v_\beta}{v_\alpha^2 + v_\beta^2}(-q) - - - - - - - - - - - -(24)$$

Part of instantaneous reactive current on β-axis is:

$$i_{\beta q} = \frac{-v_\alpha}{v_\alpha^2 + v_\beta^2}(-q) - - - - - - - - - - - -(25)$$

The ShAPF assures about the drawing of average real power, $\bar{p}$ of the load compensating the oscillating real and imaginary power from the power system. Hence, the *constant instantaneous power control strategy* contributes optimum compensation from power flow end, even under improper and irregular supply.

As specified earlier, the dc voltage regulator must be supplemented with the control strategy in a real time implementation (as shown in figure 4). Literally, a limited quantity of average real power ($\bar{p}_{loss}$) must constantly be drawn to support the switching and ohmic losses in the PWM converter, else it's mandatory to be supplied by the dc capacitor by continuous discharging. The power converter (boost converter) of the ShAPF assures the controllability of the PWM current control.

The compensating currents of the ShAPF and the supply current come as sinusoidal due to the compensation for $\tilde{p}$ and $\tilde{q}$ which will be in phase with the voltage due to the compensation for $\bar{q}$. Here, the elemental positive sequence component of the load current (I_{+1}) may generate the fixed real power which is the major achievement of this control strategy additionally which must be remarked as an important attribute of the compensation strategy implemented in figure 6. For supply irregularities, the compensated current will be non-sinusoidal and constant real power is drawn.

DC Voltage Controller defines an additional quantity of active power that causes an extra drift of energy to the capacitor for keeping its value of voltage around a static reference value as shown in the figure 4. Very small quantity of average active power p_{loss} is drained in continuous manner from the power network for supplying switching loss plus ohmic losses in the converter section or else, the same energy would be provided by dc link capacitor connected across converter which would discharge at continuous manner.

In real time operation, the separation of active and reactive power is analysed by a low-pass filter. Reference currents $i_{ca}^*, i_{cb}^*, i_{cc}^*$ for switching of PWM inverter is set up from Inverse Clarke Transformation. The switching scheme of IGBT's is set up by relating the reference currents and continuously sensing the currents from lines. The $\alpha\beta$ – current may be calculated as follow:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_\alpha'^2 + v_\beta'^2} \begin{bmatrix} v_\alpha' & v_\beta' \\ v_\beta' & -v_\alpha' \end{bmatrix} \begin{bmatrix} -p + \bar{p}_{loss} \\ q \end{bmatrix} - - - - - - -(26)$$

These two phase compensating currents are two phase currents which are then converted into three phase currents by means of inverse Clarke transformation.

$$\begin{bmatrix} i^*_{c_a} \\ i^*_{c_b} \\ i^*_{c_c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \dfrac{1}{\sqrt{2}} & 1 & 0 \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} \\ \dfrac{1}{\sqrt{2}} & -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{c_0} \\ i^*_{c_\alpha} \\ i^*_{c_\beta} \end{bmatrix} ---------(27)$$

The current references may be used to generate firing pulses for the PWM inverter. [29]

4.2 SCC Strategy for SAF

As there is a question over the selection of the SAF, then various reasons can be broadly listed as:
• It is hard to comprehend a large-rating PWM converter with swift current respond and low loss in compensating the harmonic components with high efficiency as in the main circuit of ShAPF.
• Injected currents by ShAPF may flow into the capacitors connected on the power system.

Apart from the above, SAF compensates the current distortions resulted due to non-linear loads with an appointment of high impedance path (by generating a voltage of same frequency as that of the current harmonics to be waived) enforcing the high frequency current to pass through the passive filter in parallel.

Based on the above discussions the proposed work is once again carried out with the simple control strategy on instantaneous pq – theory on SAF, which is applied on a 3P3W system. The basic block diagram of a 3P3W SAF for compensation of voltage is illustrated in figure 7.
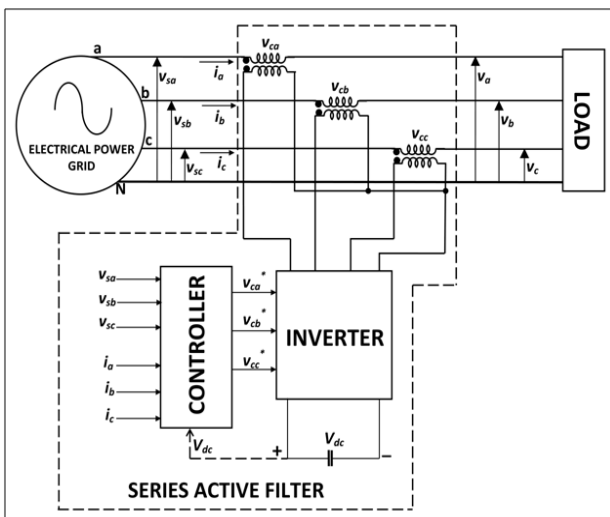
Fig. 7 Basic block diagram of 3-P-3-W Series Active Filter

SAF is for compensation of voltage. The input for the control block meant for calculation of the

instantaneous power is the phase voltages at the PCC and the line currents of the nonlinear load to be compensated, i.e., a discriminated compensation characteristic for ShAPF, that performs as an open circuit for harmonic currents as produced by the other nearby non linear loads.

Assuming no zero-sequence current, the relation among the source voltage, load voltage and active filter voltage is given by,

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{Ca} \\ v_{Cb} \\ v_{Cc} \end{bmatrix} ------------(28)$$

The basic SAF voltages are synthesized by three single-phase converters with a common dc capacitor. The reference voltage for these converters is calculated by the "Active Filter Controller (AFC)" as shown in the figure 7, which has as input signals the load voltages and currents (equal to the source currents). Here the voltages are calculated by the dual pq – theory (assumed as the currents, and the real and imaginary powers are known and the voltage components should be calculated in case of presence of series voltage compensation which is the dual of shunt current compensation) as given in (29):

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} i_0 & 0 & 0 \\ 0 & i_\alpha & i_\beta \\ 0 & -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} ---------(29)$$

From the above equation, the oscillating real power $\tilde{p}$ and the oscillating imaginary power $\tilde{q}$, where the zero sequence powers $\bar{p}_0$ and $\tilde{p}_0$ are assumed to be zero due to zero-sequence current. With these oscillating powers, the instantaneous voltages to be injected by the SAF for load harmonic voltage compensation by using:

$$\begin{bmatrix} v^*_{C\alpha} \\ v^*_{C\beta} \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} ---------(30)$$

A certain amount of $\Delta \bar{p}$ should be added to $\tilde{p}$ with an objective to compensate the losses like ShAPF. The reference voltages v^*_{Ca} and v^*_{Cb} can be converted to the abc – reference by:

$$\begin{bmatrix} v^*_{Ca} \\ v^*_{Cb} \\ v^*_{Cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v^*_{C\alpha} \\ v^*_{C\beta} \end{bmatrix} - - - - - - - - (31)$$

The SAF generates the voltages mentioned in (31) for the harmonic voltage compensation in the load producing oscillating active and reactive power at the load end. This approach confirms the voltage from the source side have purely sinusoidal waveforms. The Control block diagram of the series active filter has been illustrated in figure 8.
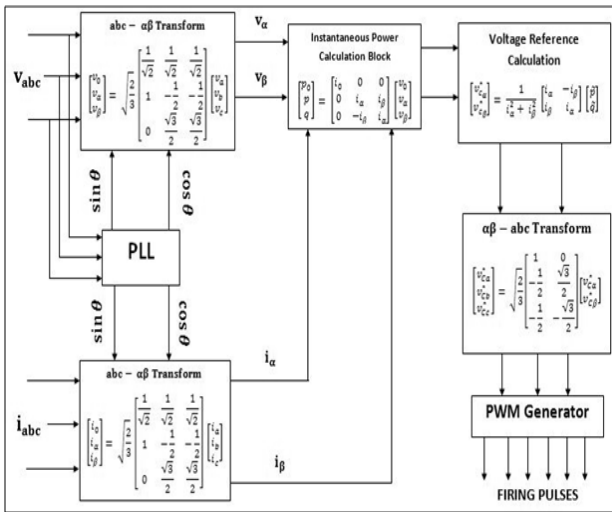
Fig. 8 Control Circuitry of Series Active Filter

The voltage v^*_{Cabc} are the voltage that needs to be obtained to compensate the harmonic component of load, which produce the oscillating real and reactive power. The source and load voltages thus obtained are purely sinusoidal in nature.

You can see the figure 9 illustrating the detailed modelling of grid connected renewable system.
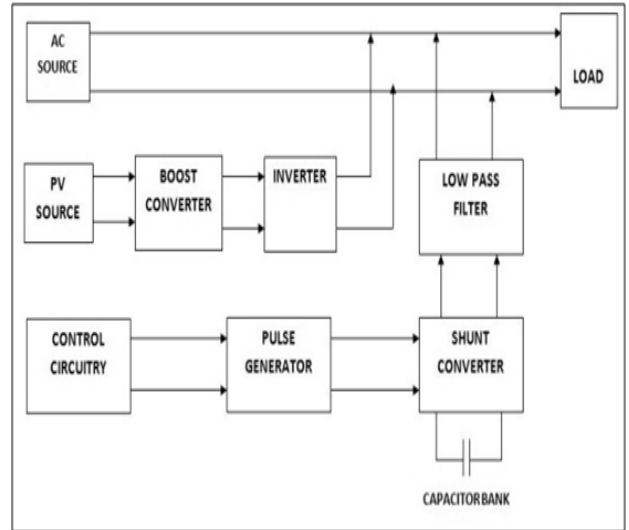
Fig. 9 System Block Diagram for ShAPF

It is a PV-system integrated to grid. ShAPF integrated to the system that is implemented to take care of power quality related issues and to inject grid as well as load desired power. It consists of a PV system whose voltage is stepped up by a boost converter. This voltage is fed to the inverter then it feeds the load and the grid.

The figure 10 illustrates the SAF based detailed modelling of grid connected renewable system.
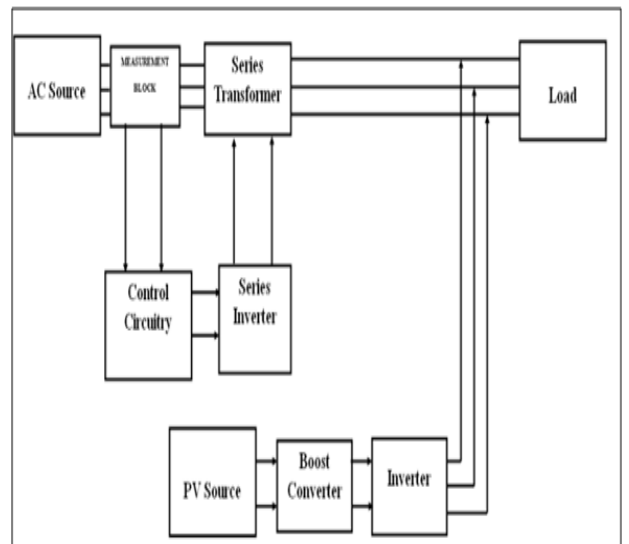
Fig. 10 System Block Diagram for SAF

The SAF integrated to the system that is implemented to take care of power quality related issues and to inject grid as well as load desired power. It consists of a PV system whose voltage is stepped up by a boost converter.

5 Simulation Analysis

To verify the effectiveness of the proposed sinusoidal current control strategy through ShAPF and SAF the simulation was carried out on a 3P3W system for non-linear load. The proposed strategy was simulated using MATLAB/SIMULINK 2016a with a system having Intel Core i5 processor with clock frequency 2.4 GHz, 8 GB RAM. The analysis of both ShAPF and SAF was carried in different environments.

A. Shunt Active Power Filter

The analysis of ShAPF is performed in two different environments which are given below:
1. Study of Operation of ShAPF for a 3-φ 3-wire (3P3W) System with passive non-linear load condition.
2. Study of Operation of ShAPF for a hybrid system of PV-grid with constant irradiance condition.

The non-linear load parameters for ShAPF can be seen in Table 1.

TABLE 1
LOAD PARAMETERS

Item	Value	
	Case – A	Case - B
Resistance	60Ω	10Ω
Inductance	0.15mH	---------
Grid Voltage	2 kV	230 V (RMS)
DC Link Capacitance	10000μF	200μF
PV Voltage	----------	104V

I. ShAPF For a 3-φ 3-wire (3P3W) System with Non-linear Load Condition:

The simulation was carried out for the system model illustrated in figure 9.

The figure 11(a) represents the performance of source voltage considering the ShAPF. This ShAPF is resulting source voltage characteristic in phase.
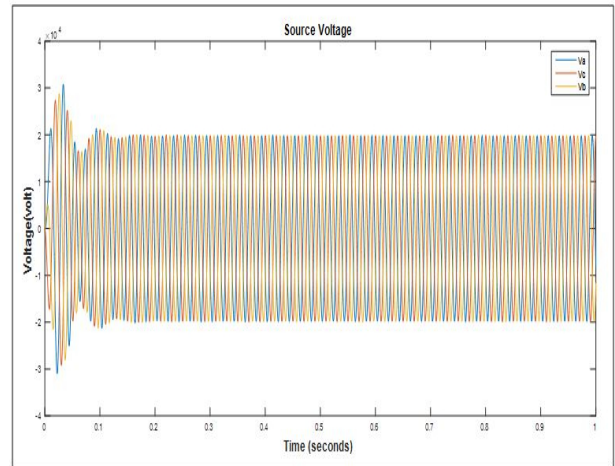
Fig.11 (a) Source Voltages

The figure 11(b) presents the performance of the source current of a 3φ3W system.
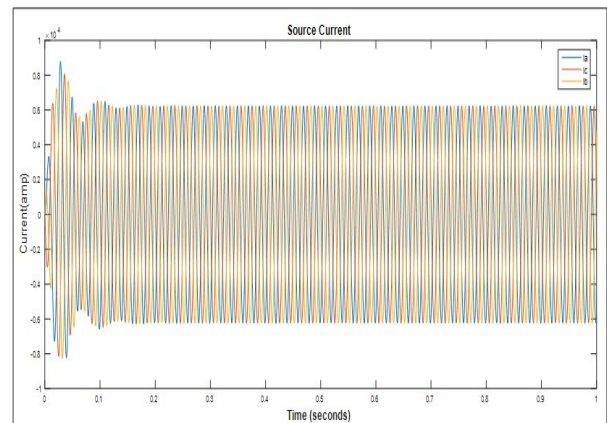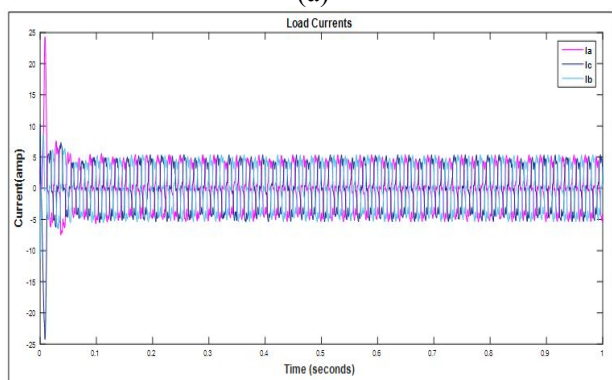

Fig. 11(b) Source Currents

The system was tested with a voltage source of 2000V Peak. With the introduction of shunt active filter the source current waveform is obtained with peak amplitude 600A. These waveforms disclose about the compensation of ShAPF for the disturbances at source end.

The figure 12 illustrates the load end parameters.
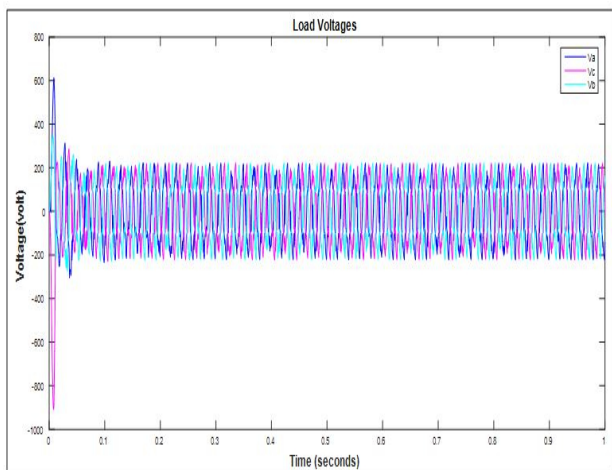
(a)

(b)

Fig. 12: Load End Parameters: (a) Load Voltage, (b) Load Current

Due to nonlinear load (rectifier circuit using RL) the load voltage and load current were distorted and unbalanced in absence of compensation, but applying sinusoidal current control strategy, both the load voltage and load current become balanced and smooth as shown in the figure 12(a) and 12(b) which shows the performance of load voltage and load current of 3-φ 3-wire system.

The figure 13 represents compensating waveforms of ShAPF where the figure 13(a) shows waveforms of the shunt voltages, whereas the figure 13(b) shows waveform of the shunt currents.
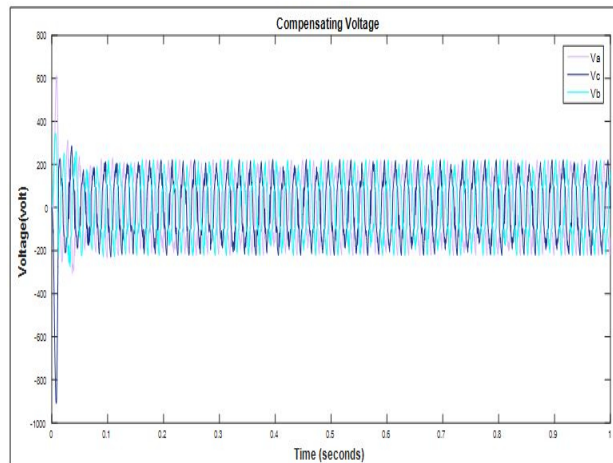
(a)
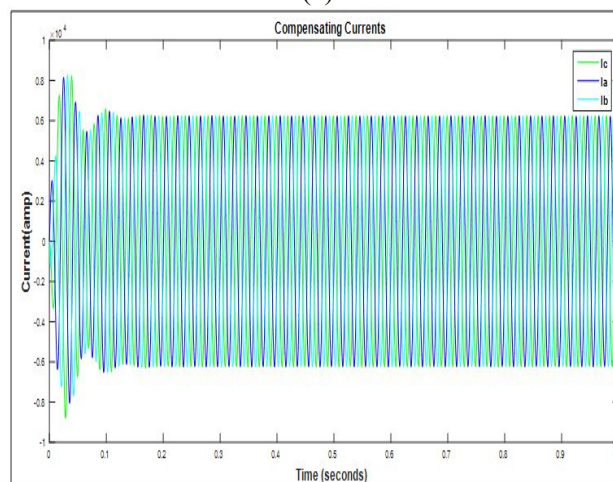
(b)

Fig. 13: Compensating Waveforms of ShAPF: (a) Shunt Voltage, (b) Shunt Current

The potential of the DC-link capacitor as connected across the converter is noticed to be constant over the entire course of action shown in the figure 14.

Load Parameter	Value
Load Resistance	10Ω
Grid Voltage (RMS)	230 V
DC Link Capacitance	200μF
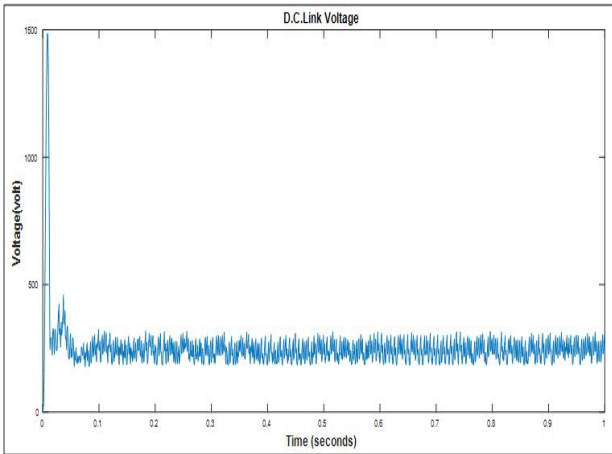
Fig. 14 D.C. Link Voltage

A theoretical analysis of ShAPF is accomplished for 3-φ 3-W system under passive loading condition using non linear load. The sinusoidal current control strategy drives the ShAPF ensuring the supply to draw constant sinusoidal current under steady state condition.

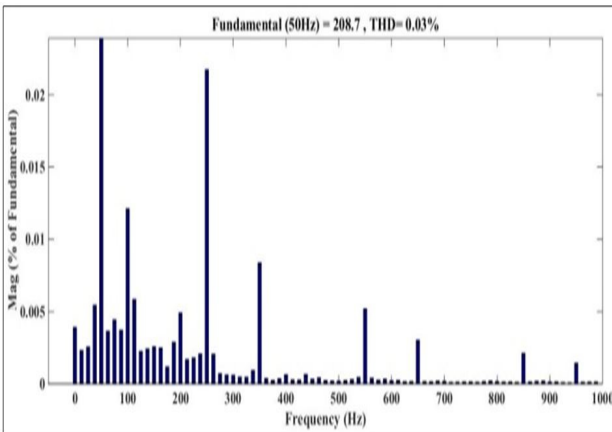The FFT analysis of the source current has been shown in the figure 15.

Fig. 15 FFT Analysis of Source Current

It is observed that besides fundamental, 5th, 7th, 9th harmonics exist, but these harmonics are quite suppressed. The 5th harmonic percentage is little higher than 0.02 percent while that of the 7th harmonic is less than 0.01 percent. The resultant THD of source current is 0.03 percent because of the ShAPF compensation process.

II. For a PV-grid System (Constant Irradiance condition):

Several simulation studies for the entire system have been performed considering the parameters as given in Table 2.

TABLE 2
SIMULATION PARAMETER

The figure 1.16 illustrates the Injected current by the ShAPF.
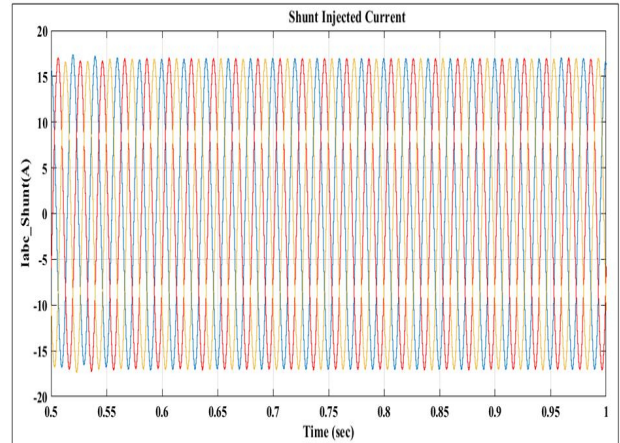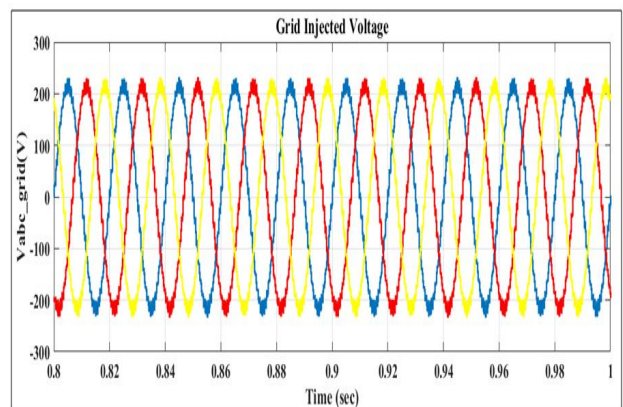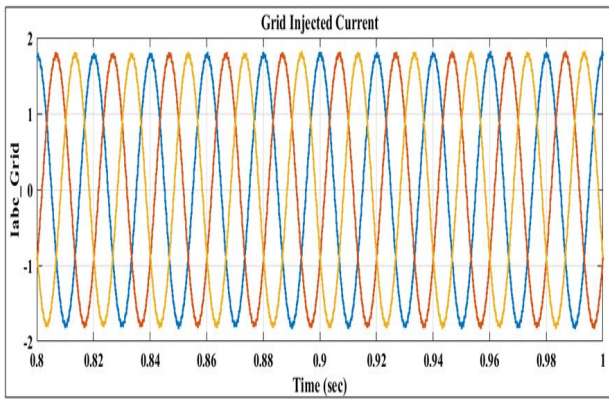

Fig. 16 Injected Current by Shunt Compensator of a PV-grid system

The waveforms so associated disclose about the compensation of the abnormalities by the ShAPF at the supply end. Moreover, the current THD of grid injected voltage side is found as 1.40% due to the compensation.

The figure 17 illustrates the grid injected voltage and current.

(a)

(b)
Fig. 17 PV-grid network: (a) Grid Injected Voltage
(b) Grid Injected Current

The FFT analysis result of the system has been illustrated in the figure 18.
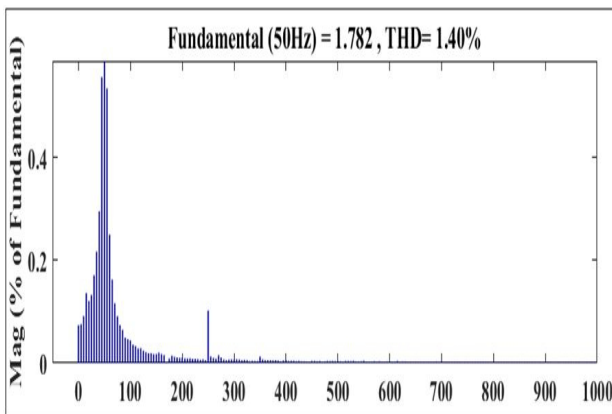

Fig. 18 Harmonic Analysis of Grid Injected Current Waveform

The grid injected voltage as well as current are almost sinusoids and does not have significant content of dominant harmonics. It is observed that more of the current is diverted through the filter. So it can be inferred that the shunt component must have high current carrying capacity.

The DC Link voltage does not fluctuate much. Its fluctuation is around 1.25V, which is within limit of 5 percent. The THD of grid injected current waveform is 1.4. There exists only one dominant harmonics, i.e. 5th harmonics, which has been suppressed significantly. Its value is of the order of 0.1 percent. Some of the inter harmonics of very low magnitude seen to exist. Although these inter harmonics are not of concern but these are still can be eliminated by passive filter.

The above results show that, the injected current waveform of the ShAPF is sinusoidal which indicates the achievement of the basis of sinusoidal

current control strategy. Apart from that it also provides an effective injection of power to the grid in interconnected mode which is very much desirable.

B. Series Active Filter

Sinusoidal current control strategy was applied to grid connected PV system to see for tolerance to voltage disturbances.

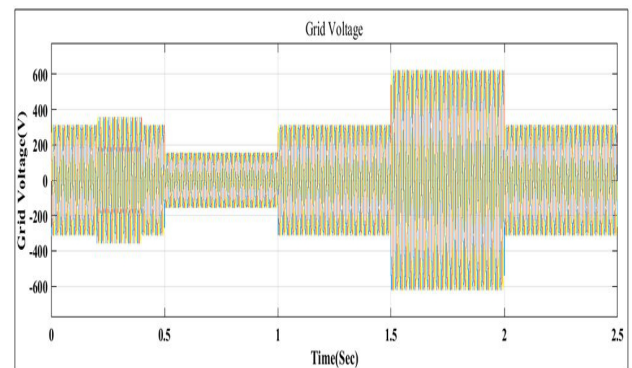The figure 19 shows the grid voltage at different instances.

Fig. 19 Grid injected voltage

In the figure 19 it can be observed that there is voltage sag between 0.5 sec to 1 sec and voltage swell in between 1.5 sec to 2.0 sec. But series active filter maintains the voltage level fixed at 311V RMS.

The load voltage is found to be fixed due to the voltage injected by the SAF as seen in the figure 20.
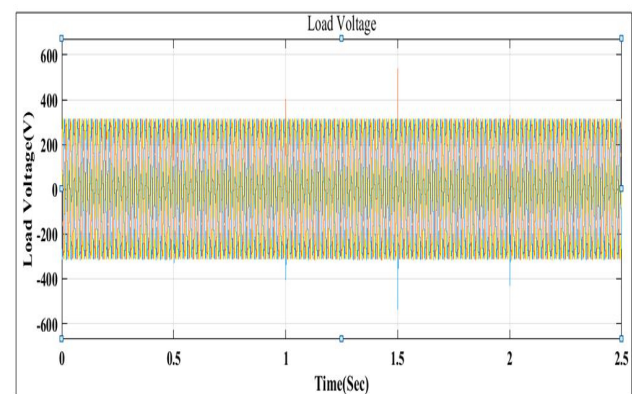

Fig. 20 Load voltage waveform

The injected voltage by the series inverter has been presented in the figure 21.
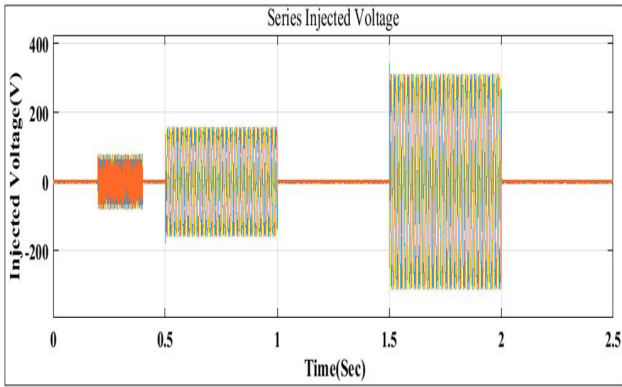
Fig. 21 Series inverter injected voltage

The injected voltage adds up to grid voltage during 0.5 sec-1.0 sec and nullifies during 1.5 sec-2.0 sec. This has been taken care by SAF by injection of voltage during the same period.

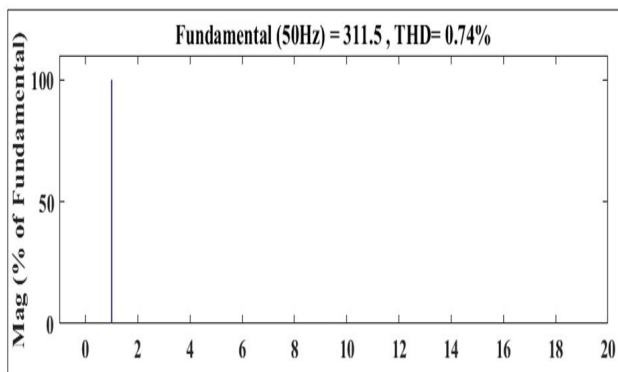The harmonic analysis of load voltage is obtained has been shown in the figure 22.

Fig. 22: Harmonic analysis of load voltage

The THD in load voltage is found to be 0.74%. The RMS value of load voltage is 311.5 V. Presence of higher order harmonics are suppressed by SAF which can be seen from the THD analysis.

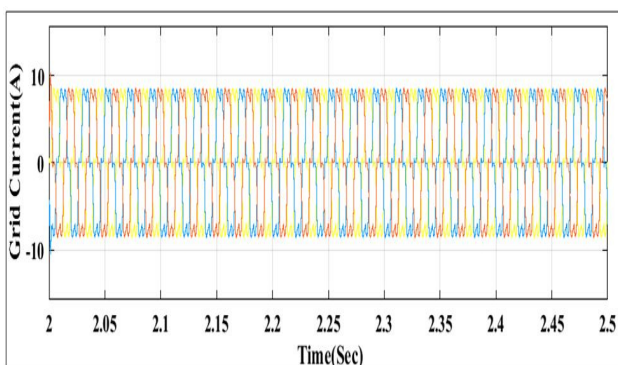The Grid current is shown in the figure 23.

Fig. 23 Grid Current Waveform

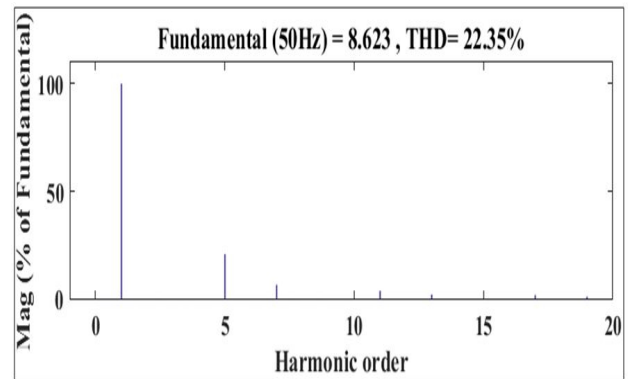The harmonic analysis of the grid current has been shown in the figure 24.

Fig. 24: THD of Grid current

The THD in grid current was found to be 22.35%. The RMS value of grid current was 8.623 A. Presence of 5th order harmonics has been suppressed by SAF significantly. Its magnitude in respect of fundamental is found to be below 20 %.

The shunt active filter based on sinusoidal current control strategy offers assurance against current harmonics as well as improves the power factor. The performance of both shunt and series active filters are studied. The grid injected current in case of shunt active filter under the PV-integrated condition is found to be 1.4 percent. The efficacy of the proposed methodology for shunt active filter can be validated by comparing the performance of some other techniques proposed by other authors, can be seen in Table 3.

TABLE 3
VALIDATION TABLE FOR ShAPF

Author	Proposed Methodology	Grid Current THD
Jain et al. [30]	Fuzzy Logic Controller	1.42%
Tang et al. [31]	Shunt Active filter with LCL Filter	3.49%
Proposed Sinusoidal Current Control Strategy	Sinusoidal Current Control Strategy applied to Three Phase Three Wire Strategy	1.40%

The SAF based on sinusoidal current control strategy offers assurance against voltage sag and swell. Besides this, it offers harmonic isolation to load voltage, as evident from the results. The THD in load voltage is found to be 0.74 percent which is

quite satisfactory. The performance of series active filter can be validated by comparing the performance of some other techniques proposed by other authors, which is can be seen in the Table 4.

TABLE 4
VALIDATION TABLE FOR SAF

Author	Proposed Methodology	Grid Voltage THD
Wang et al. [32]	Hybrid control approach based on reference generation	5.7%
Kim et al. [33]	Shunt Active filter with LCL Filter	1.37%
Proposed Sinusoidal Current Control Strategy	Sinusoidal Current Control Strategy applied to Three Phase Three Wire Strategy	0.74%

9 Conclusion

A concept oriented study of APF using Sinusoidal Current Control Strategy has been carried out for 3P3W system using passive and non-linear load, with fluctuating voltage condition. Even though the voltage and current in three phases are subjected to disturbance in transient state, the control strategy leads to drawing of constant current by the load during steady state condition. Moreover, from the in second fold of simulation study, the THD value in source current is found to be as low as 1.40 % and THD in load voltage is observed to be 0.74% which is quite satisfactory and found below the values observed, given in various literatures so far.

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