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DESIGN PARAMETERS OF SHUNT ACTIVE FILTER FOR HARMONICS CURRENT MITIGATION

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ABSTRACT: This paper explains the design parameters of three phase shunt active filter based on PQ theory for mitigation of harmonics current. Design parameters include design of DC link voltage and design of filter inductance. Design parameters have very important role in performance of shunt active filter. If design is appropriate filter can respond to dynamic load condition along with steady state conditions. SAF can mitigate almost all current harmonics efficiently by effectively designing the parameters.

KEYWORDS

SAF, p-q theory, non-linear load, Hysteresis current control

Introduction

In last two decades, Pulse width Modulation(PWM) based power electronic devices have gained popularity for various industrial applications such as adjustable speed drives, renewable energy applications, UPS's, etc. Their vast use is because of many advantages such as controlled DC bus voltage, bi-directional power flow, etc. PWM based devices have certain disadvantages too as they introduce current and voltage harmonics in the power system, resulting in instability, voltage distortion, etc. Shunt active filters have proven to be excellent solution for current harmonics mitigation due to the use of non linear loads in power system.

Examples of harmonics producing load are computers, adjustable speed drives, semiconducting devices, etc. (Singh, Haddad, & Chandra, 1999). mitigation of harmonics can be done with the help of passive filters or active filters. Hybrid of active and passive filters also solves problems of harmonics. While shunt active filters are useful for solving problems related to current harmonics, series active filters are useful for solving problems related to voltage harmonics.

Power electronics is closely related with sources of power quality problems, for example, residential equipment such as PCs and TVs, office equipment like printers and industrial equipment such as PLCs.

P-Q Theory

"The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as instantaneous power theory or p-q theory was presented first by (Akagi, Watanabe, & Aredes, 2007). It is valid for transient as well as steady state conditions and it is based on the instantaneous values with or without neutral wire for three phase power system. Firstly, the three phase voltages and current are transformed to α-β-0 coordinates with the help of Clarke's Transformation then the instantaneous values of active and reactive power are calculated.

Inverse Clarke's Transformation is used to find the values of compensating currents from the values of active and reactive powers. Three phase source voltages and load currents are transformed in α-β coordinates using Clarke's theory which are then utilized to calculate instantaneous values of powers. We only require oscillating component of active power for compensation calculations. As the active power consists of oscillating component and average component, low pass filter is used to separate oscillating component.

This theory proves to give very good response for designing power controllers of harmonics compensation. The application of this theory starts from αβ0 transformation which is also known as Clarke transformation. The three-phase voltage and the line currents are transformed into αβ axes by following equations:

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{2.1}$$

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} \tag{2.2}$$

From equations (2.1) and (2.2) the instantaneous real power and instantaneous imaginary power on αβ axes can be expressed as:

$$\begin{bmatrix} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \tag{2.3}$$

As shown in equation (2.3), these two powers consist of average value as well as oscillating values which are to be separated. As shown $\bar{p}$ and $\tilde{p}$ are the average and the oscillating parts of p, whereas $\bar{q}$ and $\tilde{q}$ are the average and the oscillating parts of q. Both the oscillating real $\tilde{p}$ and imaginary $\tilde{q}$ powers represent the presence of harmonics in load current. By knowing the undesirable values of current in real time, they can be eliminated. Our aim is to make source current sinusoidal by eliminating harmonics in load current using shunt active filter.

The equations for compensating current reference in αβ axes can be written as equation (2.4).

$$\begin{bmatrix} i_\alpha` \\ i_\beta \end{bmatrix} = \frac{1}{V\alpha^2 + V\beta^2} \begin{bmatrix} V\alpha & V\beta \\ V\beta & -V\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{2.4}$$

Finally, by Inverse Clarke transformation the compensating current reference are expressed as equation (2.5).

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2.5}$$

Shunt Active Filter

To deal with problems related to current and voltage harmonics, active filters are used. Also, they are capable of dealing with problems related to poor power factor and reactive power compensation. Active filters are classified as shunt, series, and hybrid active filters. Shunt active filters for compensation of current harmonics, series active filters are used for compensation of voltage harmonics, and hybrid active filters for compensation of both current and voltage harmonics (Akagi,1996). In this paper, we will focus on shunt active filter to deal with problems related to current harmonics. A self-controlled dc bus shunt active filter has a topology similar to static compensator which is used in transmission system for reactive power compensation.

Figure 1 shows basic diagram of shunt active filter. As shown, a shunt active filter operates as a current source device injecting the harmonic component generated by the load current but 180° phase shifted. The nonlinear load may be considered as an ac motor driven by a voltage source PWM inverter. The shunt active filter with or without transformer is connected in parallel with the load producing harmonics.

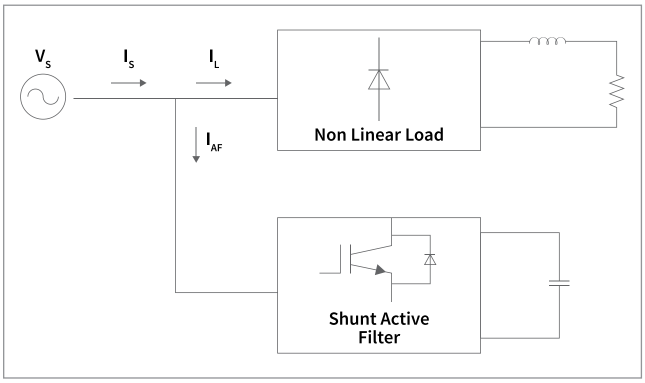


FIGURE 1. Basic shunt active filter

Figure 2 shows the block diagram of shunt active filter showing a voltage fed converter with a PWM current controller and shunt active filter controller. The controller detects the instantaneous load current I_L. Now the controller extracts the harmonic component from load current with the help of low pass filter. The ac inductor L which is placed on the ac side of diode rectifier plays a very important role of limiting the filter current. Shunt active filters can also provide reactive power compensation along with harmonics compensation (Sankaran, 2002).

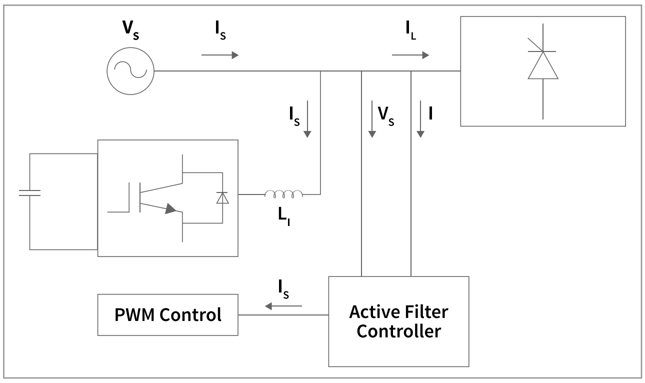


FIGURE 2. Shunt active filter for harmonics compensation

Selection of DC Voltage Reference

To actively control filter current I_c, the dc bus nominal voltage V_{dc} must be greater than or equal to line to line peak voltage i.e. the filter can only compensate when $V_{dc} > V_s$. If we assume that the PWM converter is operating in linear modulation mode then,

$$m_a = \frac{2\sqrt{2}V_{f1}}{V_{dc}} \quad \text{for } m_a = 1 \quad V_{dc} = 2\sqrt{2}V_{f1} \qquad (4.1)$$

In the above equation V_{f1} is the fundamental component at AC side of PWM converter. If the non-linear load is already known then the reference dc bus voltage chosen is the function of load power and the maximum harmonic order which is to be compensated (Colak, Bayindir, Kaplan& Tas,2010).

$$V_{dc} = 2\sqrt{2}V_{(fh)max} \qquad (4.2)$$

where, $V_{(fh)max}$ is the voltage value including harmonics of order to be compensated. In the paper (Krim, 2011). The authors proposed that if the switching frequency is very high then in (4.1) V_{f1}

approximately becomes equal to V_s source voltage, then

$$V_{dc} = 2\sqrt{2}V_s \qquad (4.3)$$

Selection of Filter Inductance L

The value of filter inductance should be kept small enough so that the injected current di/dt is greater than the reference compensating current to track its reference. The value of filter inductance can be mainly found out by reactive power requirement of the system and harmonic cancellations. There are four different approaches proposed by (Krim, 2011). as follows:

1.	$Q_{Lf1} = 3V_s I_{f1} = 3V_s \frac{V_{f1}}{\omega_{Lf}} \left(1- \frac{V_s}{V_{f1}}\right), I_{f1} = \frac{V_{f1}\omega_{mf}}{\omega_{mf\,Lf}}$ where m_f is the modulation ratio of PWM converter.
2.	$L_f = \frac{V_s}{2\sqrt{6}\, f_s\, \Delta I_{f,\,p\text{-}p,\,max}}$ where $\Delta I_{f,\,p\text{-}p,\,max}$ is 15% of the filter current.
3.	$L_{f,min} = \frac{V_{DC}}{8\, f_s\, \Delta I_{f,\,p\text{-}p,\,max}}$ and $L_{f,max} = \frac{V_{DC} - 2\sqrt{2}V_s}{2\,\Sigma_{h=0}^{\infty}\,\omega_h I_h \sqrt{2}}$ where h is the harmonic order.
4.	$L_f = \frac{V_{DC}}{6\, f_s\, \Delta I_{f,\,p\text{-}p,\,max}}$ where $\Delta I_{f,\,p\text{-}p,\,max}$ is maximum ripple current.

TABLE 1. Different methods to find filter inductance L

Based on the above methods we can calculate the filter inductance. Performance of the system can be observed taking different values of filter inductance and the value of filter inductance at which the current harmonics are minimum. Also, we observe that for the low values of filter inductor THD in current are lower due to the presence of high frequency in the signal

Selection of DC Side Capacitor C_{DC}

There are two main purposes of DC side capacitor server:
(i) in steady state it maintains DC voltage and
(ii) during transient period it serves as an energy storage element to supply real power differences.
The choice of DC capacitor is very important and therefore, the DC capacitor must be maintained with the help of a reference value.

When load condition changes, the real power balance between main and the load will be disturbed, which is to be compensated by DC capacitor.

During transients, DC side capacitor helps to maintain variations and ripples in V_{DC}. Change in C_{DC} does not much affect the error in V_{DC} but by change in C_{DC}, the settling time and final value of V_{DC} is affected. So, on the basis of settling time, response time and variation in V_{DC} the final value of C_{DC} is selected. As described by (Krim, 2011). following are the four different methods which can be used for designing C_{DC}.

1.	$C_{DC} = \frac{2\,E_{max}}{V_{DC}^{\,2} - V_{DC,\,min}^{\,2}}$ E_{max} is the maximum supplied energy by the capacitor in the worst case.
2.	$C_{DC} = \frac{\pi\, I_{f1,\,rated}}{\sqrt{3}\,\omega V_{DC,\,p\text{-}p,\,max}}$ where $V_{DC,\,p\text{-}p,\,max}$ is the peak to peak voltage ripple.
3.	$C_{DC} = \frac{s}{2\,\omega V_{DC} \cdot \Delta V_{DC}}$
4.	$C_{DC} = \frac{V_s \sqrt{I_5^2 + I_7^2 - 2\,I_5 I_7 \cos(5\alpha - 7\alpha)}}{2\,\omega V_{DC}^{\,2}\varepsilon}$ or, $C_{DC} = \frac{I_H}{\varepsilon\,\omega_h V_{DC}}$ where I_H is current of the lowest order harmonic.

TABLE 2. Different methods to find DC side capacitance

Simulation Results

Figure 3 shows the MATLAB Simulink model for diode rectifier load as a nonlinear load. Simulation results are obtained and the results are shown in figures 4 and 5. As shown is in figure 4, before compensation the source and the load current contains harmonics due to presence of nonlinear load. Figure 5 shows the results after compensation from shunt active filter. THD of source current reduces from 25.68% to 1.33% after the compensation. It can be seen that the source current becomes sinusoidal after compensation from shunt active filter. Figure 5 also shows that the DC link voltage is maintained at a constant value of 700V which is the reason that filter works appropriately.

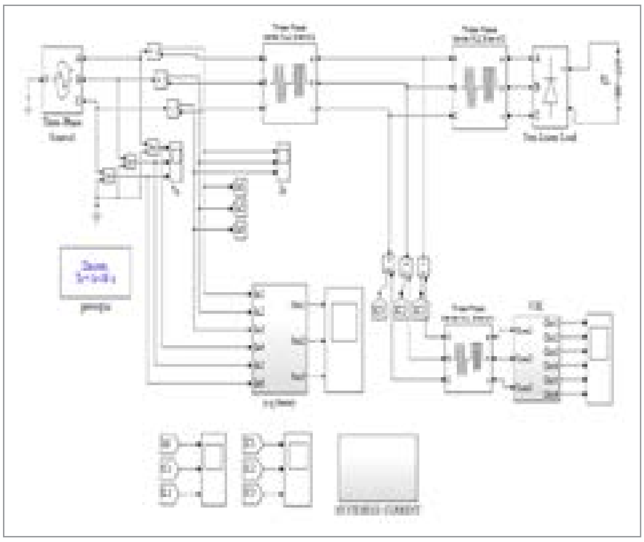
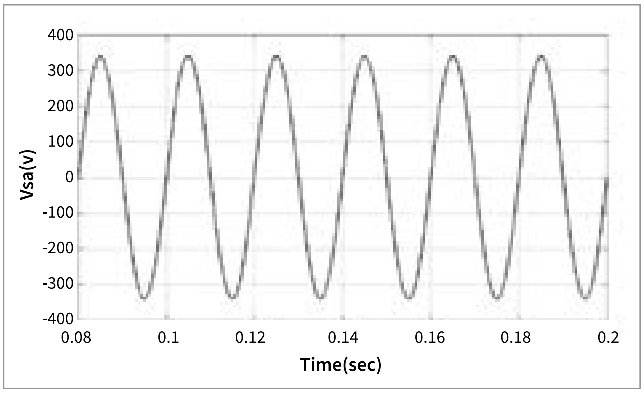


FIGURE 3. Simulink model for diode rectifier load

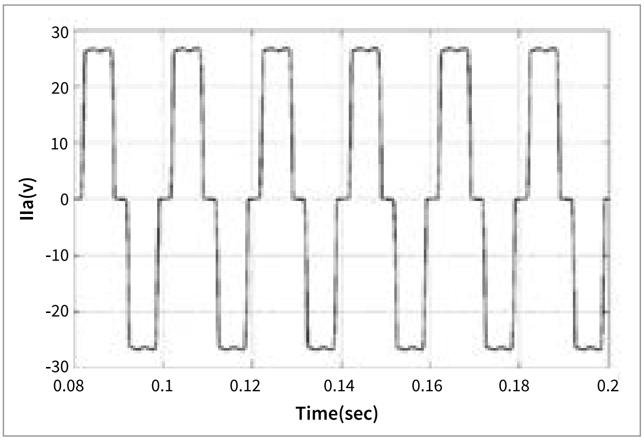
Simulation is done using MATLAB simulation tool. When nonlinear load is connected load due to the presence of harmonics in load the current gets distorted. Reference currents for active filter are generated using p-q theory and then hysteresis current control is used to generate switching signals. Table 3 shows various simulation parameters applied to SAF.

Sr. No.	**System Parameter**	**Values**
1	AC Supply	415 V, f = 50 Hz, R_s = 0.4Ω, L_s = 0.1 mH
2	Load Side	R_L = 0.1Ω, L_L = 0.1 mH
3	Filter Side	R_L = 0.4Ω, L_L = 0.3 mH, C_{DC} = 1000 μF
4	PI Controller	Kp = 0.2, Ki = 10
5	DC Side Capacitor Voltage	700 V
6	Diode Bridge Rectifier	R = 20Ω, L = 100 mH
7	DC Side Capacitor	1000μF

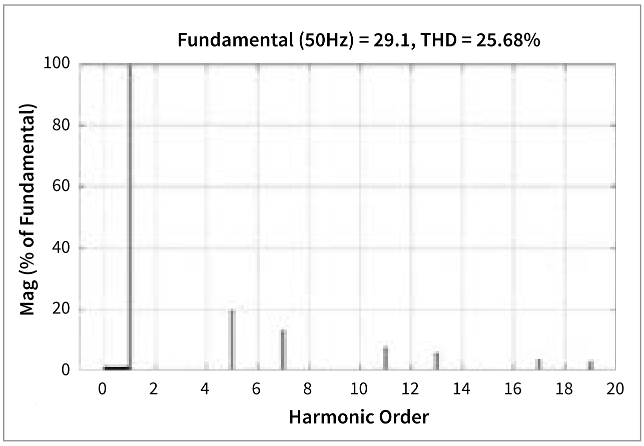
TABLE 3. Various parameters applied to SAF (Diode load)



(a)

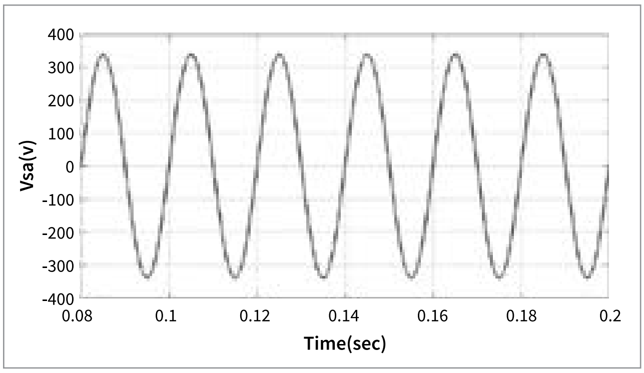


(b)



(c)

FIGURE 4. Simulation results of (a) source voltage (b) source/load current (c) THD before compensation for diode rectifier load



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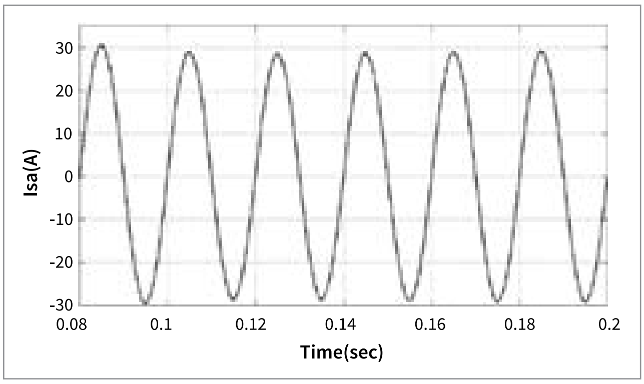

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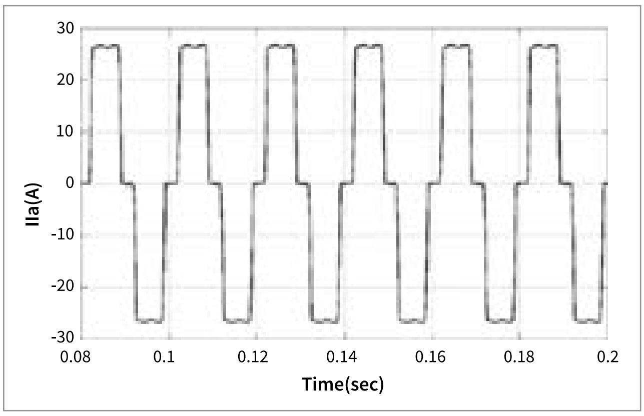

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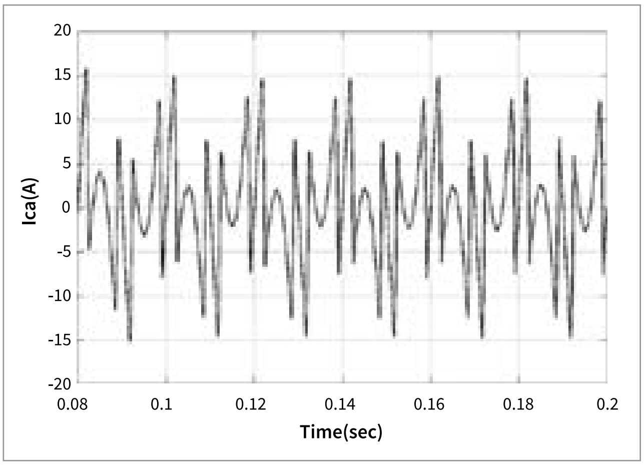
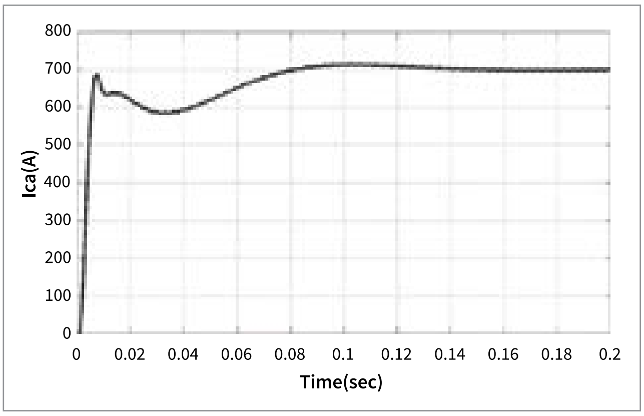
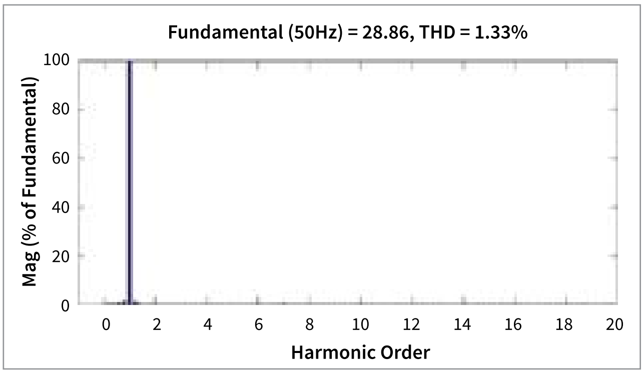


(d)



(e)



(f)

FIGURE 5. Simulation results of (a) source voltage (b) source current (c) load current (d) filter current (e) DC link voltage (f) THD after compensation for diode rectifier load

A shunt active power filter has been investigated for power quality improvement. The optimum values of Kp and Ki are found to be 0.2 and 10. From the above results of waveforms we can say that harmonics distortion is reduced after connecting shunt active filter. The system parameter selected for simulation are designed which are mentioned in table 3. After compensation, the source voltage and the source current are in phase with each other which means that the harmonics are eliminated from the source current and the power quality if system is thus improved.

Conclusion and Scope for Future Work

Table 4 shows the comparison of simulation result obtained before and after compensation form shunt active filter. Before compensation the harmonics component in source current was 25.68% which was reduced to 1.33% after compensation. PI control based shunt active filter is implemented for harmonic compensation of nonlinear load current. After the results are obtained it is found that shunt active filter is able to mitigate the current harmonics by eliminating the harmonic component in current.

From the study of reference papers, it was found that, better compensation and consequently better power-quality can be obtained by combining active filter with passive filters, that is, using the hybrid approach.

In hybrid filter, shunt or series, active filter is used along with passive filter to obtain better compensation.

Condition in simulation	THD in source current before active filtering	THD in source current after active filtering
Steady state condition (Diode-Rectifier load)	25.68%	1.33%

TABLE 4. Result obtained from simulation of SAF

Nomenclature

PQ – Power Quality

PWM – Pulse Width Modulation

SAF – Shunt Active Filter

THD – Total Harmonic Distortion

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