Power Improvement by Mitigating the Harmonic Distortions

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Abstract

The study of harmonics in power systems (PS) is very crucial and mitigation of harmonic distortions is one of the main issues these days. Harmonics are distortions in the waveform of a power system with a frequency that is an integral multiple of the frequency variable of the fundamental power line. In this research, our main concern is to design a complete PS model, analyze the effect of nonlinear loads, and mitigate the distortions in PS due to nonlinear loads. We are using three types of filters i.e. series passive, shunt passive, and shunt active filter. The main difference between an active and a passive filter is that we can alter the gain of the active filter even before implementing the model while the gain of the passive filter is fixed and cannot be changed after the model is implemented. Different techniques of active and passive filters are discussed. Furthermore, the SIMULINK model for active and passive filters is presented for validation of our methodology.

Keywords—Harmonics, Total harmonic distortion, Active filters, passive filters

1 Introduction

Mitigation of harmonic distortions is one of the main targets in today's electrical engineering. The distortions in PS called harmonic distortions have an important role in the power system, such as power deteriorations of power quality (PQ). The harmonic distortions affect the PQ very badly. In electrical power systems, mainly in distribution systems, the harmonic distortions are growing day by day with the addition of more nonlinear loads. The widespread use of nonlinear loads including high-rated diodes, thyristor rectifiers, arc furnaces, etc. at the domestic/industrial level draw a distorted current from three-phase sinusoidal voltages, and the even and odd harmonic contents of the actual frequency are added in the power system. Large consideration of these nonlinear loads has full potential to raise the harmonics of currents or voltage to an unacceptable level that can affect the system current adversely.

Many research studies have been conducted on different techniques for harmonic mitigation and the effects of adjustable speed drive (ASD) load which contributes to adding harmonic contents in PS at different points of common coupling (PCC) [1]. Designing different types of filters has been a major concern to mitigate the harmonics. The research and analysis were conducted on harmonic mitigation produced by a 6-pulse rectifier. Study and design of the desired passive series filter, passive shunt filter, and shunt active power filter (SAPF) according to the load at different points connected to the mains were conducted [2].

Passive filters are designed according to the order of harmonics present in the system. Series passive filter carries full load current because it is connected in series with the main line while the shunt passive filter carries only part of the full load current because it is connected in parallel with the main line. In this project, both series and shunt passive filters will be designed. Three types of active filters are being used with modern technology.

- Series active power filter
- Shunt active power filter
- Hybrid active power filter

SAPF is used to mitigate the current harmonics while HAPF is used for both [3]. For our designed PS, a SAPF-based PI controller based on the p-q model [4] will be designed and compared with a passive filter.

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SAPF based on the p-q model will be designed and implemented for harmonic and reactive power compensation of nonlinear load. We study and compare the efficiency, complexity, and performance of the shunt active filter with series passive filter, and shunt passive filter, and conclude which one filter is better to use when it comes to nonlinear loads. Using Fast Fourier Transform (FFT) analysis in MATLAB/Simulink, the THD can be measured and hence the harmonics in line current are measured through total harmonic distortion (THD) measurement.

2 HARMONIC DISTORTIONS

Harmonics are the distortion in the waveform of power systems which are multiples of fundamental frequency, and these harmonics are power quality problems. It has been created by nonlinear loads such as variable frequency driver (VFD), large computer systems, supervisory control data acquisition (SCADA) systems, AC/DC converters, UPS, etc. Nonlinear loads have been commonly used in domestic or industrial applications in recent years. Because of these nonlinear loads, various forms of problems occur in our system, such as voltage sag, swell, harmonics, power factor, etc. In the power system, many unpredicted events are caused by power electronic equipment and modern industrial automation developments. These loads draw lagging currents from the system and cause distortions in the system. As the current is distorted, it also affects the voltage and is distorted [5].

2.1 Sources of nonlinear loads

Nonlinear loads cause distortions in voltage and current waveforms which adversely affect electrical equipment. There are many sources of distortions. These sources are categorized into three types [6].

- Power Electronic equipment
- Saturable Devices
- Arcing Devices

2.2 Types of harmonics

There are three kinds of harmonics that are discussed in this paper [7];

- Negative-sequence harmonics
- Positive sequence harmonics
- Zero-sequence harmonics

The positive sequence is defined as the frequency which moves in the same sequence as the fundamental frequency. In an AC machine, it pushes the rotor of moving equipment in the proper direction. The presence of positive sequence harmonics causes overheating conductors, power lines, and transformers. The negative harmonics occur in the opposite direction to the fundamental frequency. In the rotor part of moving equipment torque produced by distorted power will oppose the rotor movement. It creates additional problems with the motor, as the magnetic field is weakened by opposite phasor rotation. A triple multiple of the fundamental frequency is called zero sequence harmonics. It neither opposes nor contributes to the torque [8]. In a balanced three-phase voltage and current are arithmetically added together in the neutral wire. The current in neutral wire is three times the amplitude of the phase current in fundamental frequency [9].

TABLE 1: Example of a sequence of harmonics [10]

Positive	**Negative**	**Zero**
1	2	3
4	5	6
7	8	9
10	11	12
13	14	15

TABLE 2: IEEE 519-2014 Current Distortion Limits (maximum harmonics current distortion I_L & individual harmonics order)

ISC /IL	3≤h 11	11≤h17	17≤h23	23≤h35	35≤h 50	TDD
<20	4	2	1.5	0.6	0.3	5
20 <50	7	3.5	2.5	1	0.5	8
50 <100	10	4.5	4	1.5	0.7	12
100 <1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

2.3 IEEE Limits

The harmonic distortion limits according to IEEE are given by IEEE 519-2014 both for the current and the voltage signals. The relevant voltage and current distortion limits are given in Table 2. The harmonic limits are given using ISC/IL and total demand distortion (TDD). The voltage distortion limits are given in Table 3.

2.4 Harmonics' effect

The harmonics in a system may cause the following effects [11];

- Harmonics causes many major challenges including:

TABLE 3: IEEE 519-2014 Voltage Distortion Limits

Bus Voltage V at PCC	Individual Harmonics (%)	Total Harmonics Distortion THD (%)
V≤1.0KV	5	8
1<V≤69KV	3	5
69<V≤161KV	1.5	2.5
161<KVV	1	1.5

- Harmonic currents, such as transformers and generators, are used in the power grid to trigger equipment heating and create a significant loss of copper.
- Taking into consideration the existence of harmonic currents, conductors must be dimensioned.
- The service life of the equipment is drastically shortened when the THD of supply voltage exceeds a particular maximum.
- In generators, voltage instability and voltage fluctuations are caused by several zero crossings of divergent current waveforms.
- Faulty operation of breaker and transfer operation can be triggered, which is unwanted.

3 METHODOLOGY

The model is designed in MATLAB/Simulink. It comprises of generator that generates the output voltage of 13.2KV. This output is stepped up to 132KV and transmitted over long distances. Step-down transformers are used to step down the voltage to the desired level say 11 kV. After this, this voltage is directly transmitted to some 11 kV industrial loads, and at the distribution end, this voltage is further stepped down up to 400 V to be used by domestic loads. A transmission line of 200km is used for the study of the effect of the line. The feeding voltage to the transmission line is 132Kv.

Two models of 10Km line of 11KV that supply power to industrial loads and three models of 5Km for domestic loads are also included. Industrial delta-connected inductors are a model for industrial loads study. Another load connected at the industrial loads side is nonlinear load. With this, a series-connected passive filter is used. While on the domestic side, three loads are connected. Two of them are nonlinear and one is a simple RLC load. The best way to mitigate harmonic distortion is to use the filter. Two types of filters active (shunt) and passive filters (shunt and series) are used. Both have their own pros and cons. Passive flirters are simple to construct but they are manually operated, while active filters have a controller for operation monitoring, and they are costly.

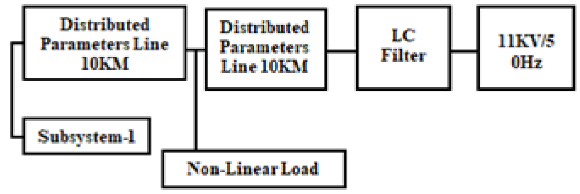

Fig. 1: Series passive filter with 11kV and load

TABLE 4: Parameter values for series passive filters

L_{f1}	50.9e-6 H
L_{f2}	36.4e-6 H
C_{f1}	25e-3 F
C_{f2}	25e-3 F

3.1 Series passive filter

There are two different loads connected to an 11kV grid. These are a three-phase delta-connected pure inductive load and a three-phase nonlinear load connected with 11kV mains at two different points. The system model for the series passive filter is given in Fig. 1.

The values of parameters selected for three-phase series passive filters are given in Table 4.

3.2 Shunt passive filter

Here SPF is connected in parallel to the 11KV main grid of the power system with the help of PCC. This power filter provides a low-impedance path to the harmonic currents from the main lines to the ground. The system model for the shunt passive filter is given in Fig. 2.

The values of parameters selected for three-phase shunt passive filters are given in Table 5.

3.3 Shunt active filter

The principle of shunt active filter is to produce the harmonic currents. This is equal in magnitude but opposite in phase (180°phase shift) to those harmonic

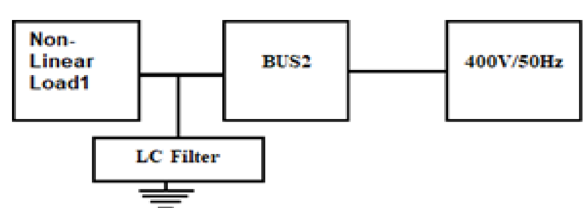

Fig. 2: Shunt passive filter with 400V and load

TABLE 5: Parameter values for shunt passive filters

L_{f1}	6.740e-6 H
L_{f2}	3.439e-6 H
C_{f1}	188.9e-4 F
C_{f2}	188.9e-4 F

currents that already exist in the system. This active filter is based on PI and p-q theory which is used to regulate the anti-harmonic currents that will be inserted into the grid lines where the non-linear load is connected. The injected anti-harmonic current is 180°phase shifted concerning the fundamental current. These injected anti-harmonic currents will cancel the effect of harmonic currents introduced by nonlinear loads and will leave only the fundamental currents in the system. The instantaneous source current (i.e. three phase) and voltages are transformed into stationary reference α-β-0 coordinates from a-b-c coordinates by using Clark's transformation which are given as:

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

This gives the voltages in a stationary reference frame for a phase system i.e. a wire system. But we are using the SAPF for a wire (i.e. three phase) system so, the zero sequence component can be neglected.
Currents in $\alpha - \beta - 0$ co-ordinates are:

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

The three-phase currents I_a, I_b, and I_c or voltages V_a, V_b, and V_c are displaced by 120°. But the $\alpha - \beta$ coordinates are 90° to each other. The instantaneous power p-q can be calculated from $\alpha - \beta - 0$ coordinate system by using current and voltage as;

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \tag{3}$$

The compensating current or reference current can be calculated from p_osc, q, V_α, V_β as;

$$\begin{bmatrix} I_{c1} \\ I_{c2} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p_{osc} \\ -q \end{bmatrix} \tag{4}$$

The negative q is used to eliminate the reactive power of the source current. The instantaneous power p and q contain both the fundamental components and harmonic components. The harmonic components are p and q while the fundamental components are P and Q. p_{osc} in the above equations are obtained from the difference between P and the sum of harmonic components (obtained using a low pass filter) and p_{loss} (obtained from the output of PI controller). The calculated compensating currents in equations are in the $\alpha - \beta$ referenced frame. Using inverse Clark's transformation we can convert $\alpha - \beta$ reference currents into a three-phase system I_a^*, I_b^*, and I_c^*.

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{5}$$

The reference currents I_a^*, I_b^*, and I_c^* are calculated to compensate for harmonic, neutral, and reactive currents in the loads in the three-phase system.
The configuration of SAPF consists of the following parts:

1) Hysteresis current Controller
2) Voltage source inverter with a capacitor on the DC side
3) PI controller
4) Compensating I, P, and Q block
5) Switching ripple filter

3.3.1 *Hysteresis current Controller*

Hysteresis current control is a signal generation technique for pulse width modulation (PWM) and is commonly used for active filter applications [12]. The hysteresis current controller is developed to generate the switching pulses to govern the voltage source inverter switches by comparing the reference current I_{ref} to the measured current I_{meas} by using the comparators. Two possibilities are there. if $I_{ref} > I_{meas}$ then $S = 0$

This shows that inverter output is negative to reduce line current and
if $I_{ref} <$ then $S = 1$

3.3.2 *Voltage source inverter with a capacitor on the DC side*

3-phase voltage source inverters based on IGBT/diode are coupled in parallel with the load. The required harmonics or compensating current and reactive power are provided by this VSI simultaneously. VSI in the current organized mode and the interface filter, provides the current waveform that is used to suppress the harmonics present in PS. Inverter uses a DC voltage capacitor as an input which can be switched to produce the current at a high frequency. This removes the harmonic current distortion from the main source [14].

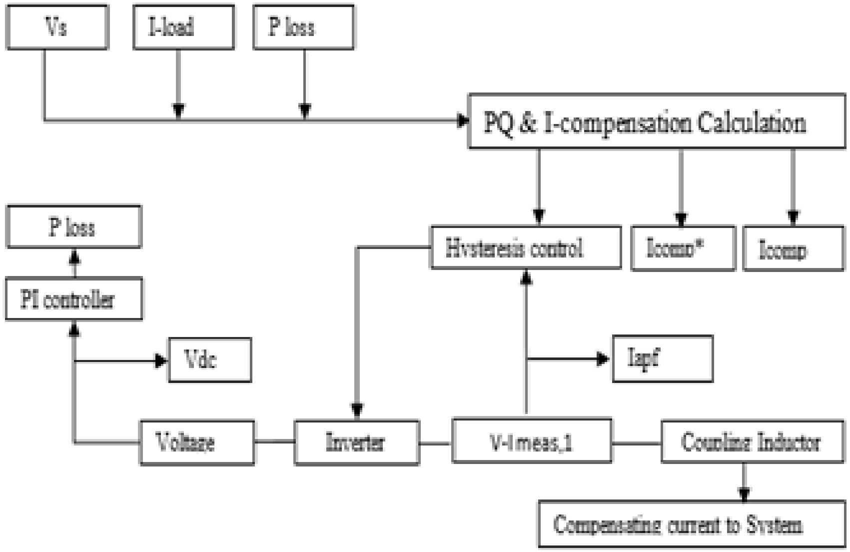

Fig. 3: Overall block diagram of SAPF

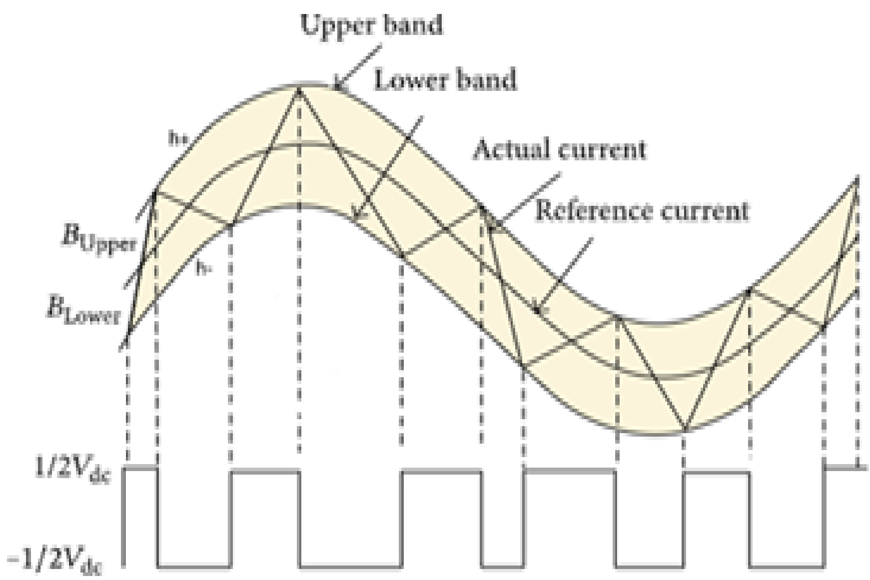

Fig. 4: Switching pattern of hysteresis current controller [13]

The switches of IGBT/diode set 0 or 1 depending upon the gate pulse signals that are provided by the hysteresis current controller.

3.3.3 PI controller

A PI controller regulates the DC capacitor voltage being used as a DC voltage controller [14]. A reference constant voltage V_{ref} and the actual DC voltage V_{dc} are compared and an error signal is generated. The steady-state error is eliminated by tracking the reference voltage which results in zero steady-state error. The reference current is estimated by regulating the DC capacitor voltage. The PI parameters can be calculated using different techniques such as Ziegler Nichol's method, using transfer function, etc.

3.3.4 Switching ripple filter

The function of the inductor is a ripple switch that is associated in series with each phase on the AC voltage side of the inverter [15]. It limits the ripple current and is linked among the output points of the voltage source inverter and main lines. The value of the inductance depends on the current ripple $I_{cr}(p-p)$ and can be considered by using the equation:

$$L = \frac{\sqrt{3}D_{dc}}{12af_s * I_{cr(p-p}} \tag{6}$$

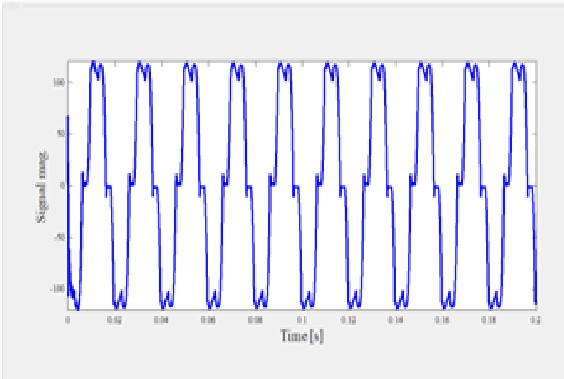

Fig. 5: Current waveform before the series passive filter

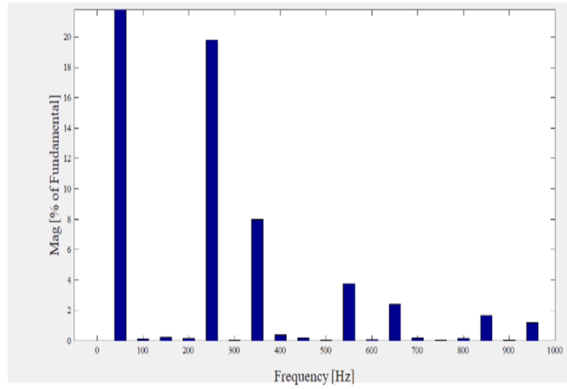

Fig. 6: Fundamental (50Hz) = 123.1, THD= 21.98%

Where f_s is switching frequency, $I_{cr(p-p)}$ is peak to peak of ripple current, a is an overloading factor, and V_{dc} is dc voltage.

4 RESULT AND ANALYSIS

For mitigation of harmonics created by non-linear load, we used two types of filters i.e. active and passive filters at three different load ends. A series passive filter connected with delta connected industrial inductive and nonlinear load, a shunt passive filter with non-linear load 1, which is domestic load, and a shunt active filter connected parallel to domestic non-linear load 2. Using the Fast Fourier Transform time domain signal is transformed into the frequency domain. This algorithm is used for the calculation of the discrete Fourier Transform (DFT) and inverse of it. An inverse Fourier transformation transforms the components of the frequency domain back to the original time domain.

4.1 Series passive filter

FFT analysis of one selected cycle of current wave before connecting the filter is shown in Fig. 5. The fundamental frequency of the system is 50 Hz, and total harmonic distortions are 21.98% as shown in Fig. 6. Same selected cycle when analyzed after connecting the filter is shown in Fig. 7 where we can see that total harmonic distortions of the selected cycle are reduced up to 0.13%, as can be seen in Fig. 8.

4.2 Shunt passive filter

The shunt passive filter is connected in parallel to the network. It provides the lower impedance path to the current and diverts the harmonics current to this path. In this way, distortion will not propagate to distribution lines and the system will be safe and secure. This will provide reactive power compensation.

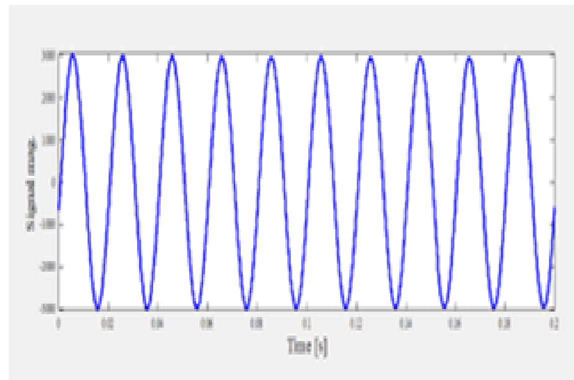

Fig. 7: Current waveform after series passive filter

Fig. 9-12 shows the FFT analysis of the result. There is a clear difference between results, before and after the filter. Before the filter is applied to the Simulink model, THD is 26.34%. After the filter is inserted in the system THD decreases to 1.01%.

4.3 Active power filter

An active power filter system contains a three-phase circuit breaker, a three-phase source, a nonlinear load,

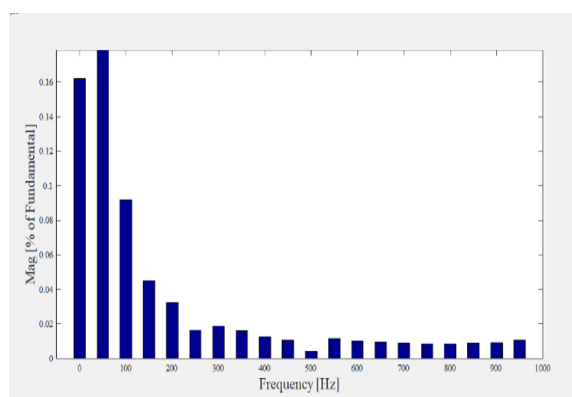

Fig. 8: Fundamental (50Hz) = 4.254e+04, THD=0.13%

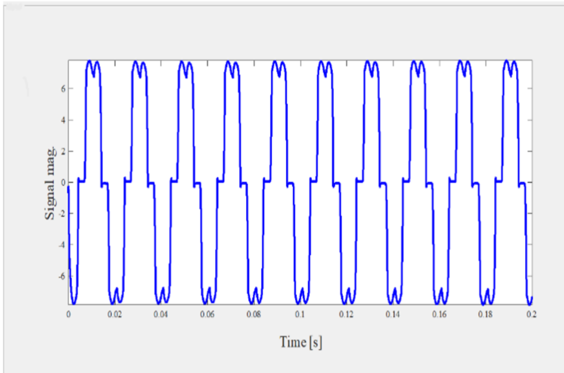

Fig. 9: Current waveform before shunt filter

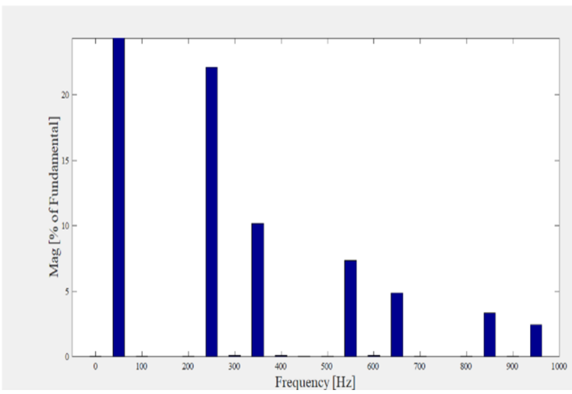

Fig. 10: Fundamental (50Hz) = 8.097, THD= 26.34%

PQ & I-compensations, and a PI controller. FFT analysis of the active shunt filter, in Fig. 13-16, shows the difference between total harmonic distortion (THD) before and after the filter is used. The THD after the filter is applied is more than the passive filter but this has its own merits as compared to passive. The total harmonic distortion is from 29.61% to 4.61%. This is according to the permissible limit of IEEE standards.

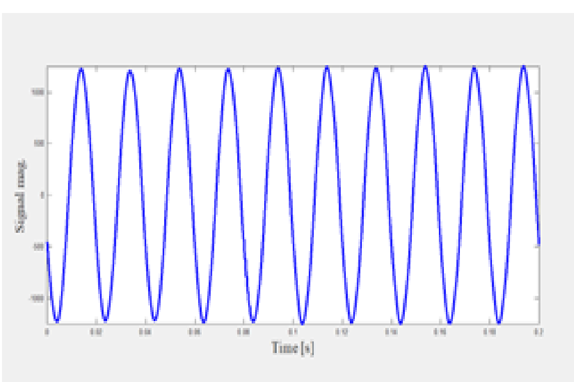

Fig. 11: Current waveform after shunt passive filter

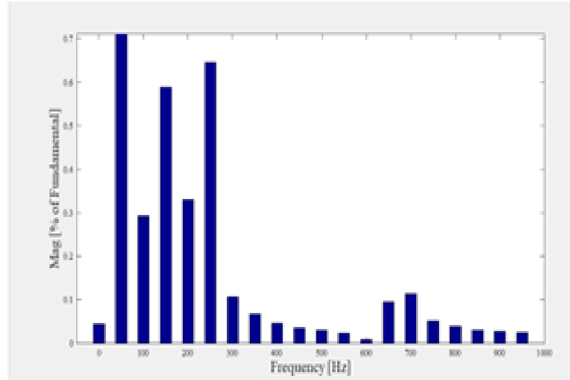

Fig. 12: Fundamental (50Hz) = 1210, THD= 1.01%

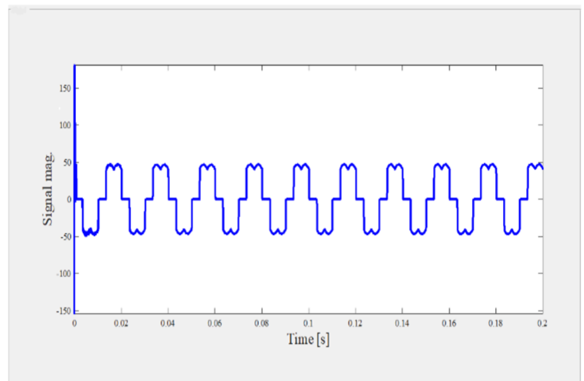

Fig. 13: Current waveform before active shunt filter

5 CONCLUSION

In this paper, a study is presented to analyze the effect of nonlinear loads on power systems by using two types of filters i.e. active (shunt) and passive (both series and shunt) filters. These filters are used at three different load ends. Through simulations it was concluded that all the filters reduce the total harmonic detorsion however active power filter gives the best results. The active filter reduces the THD to about

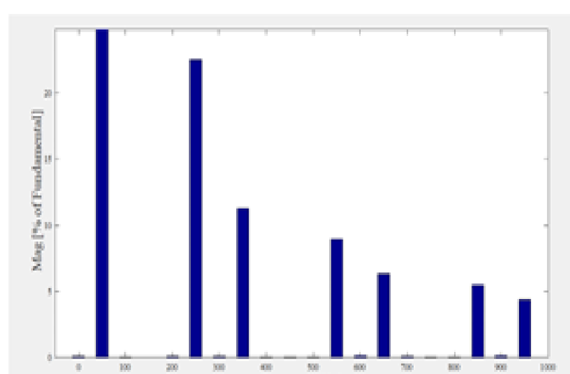

Fig. 14: Fundamental (50Hz) = 49.12 , THD= 29.61%

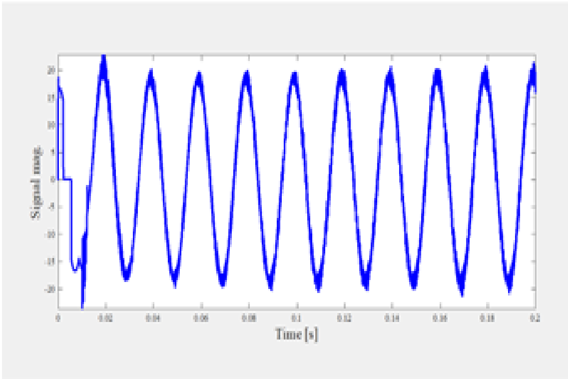

Fig. 15: Current waveform after active shunt filter

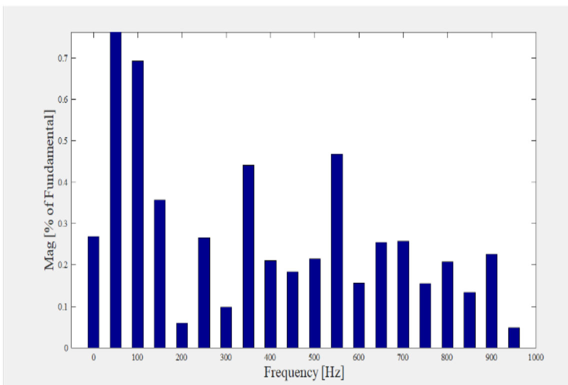

Fig. 16: Fundamental (50Hz) = 18.22, THD= 4.16%

25%. This is due to the reason that active filters can track incoming harmonics using a phase lock loop and generate harmonic energy to the limit of proportion to correct and relieve the source of this burden. In the future, we will focus on the impact of research on real-world applications in terms of cost durability, and installation.

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