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# Mitigation of Harmonics in a Three-Phase, Four-Wire Distribution System using a System of Shunt Passive Filters

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## ABSTRACT

Three-phase four-wire distribution systems are very common and widely used in commercial and industrial installations and therefore power systems harmonics is an area that merits a great deal of attention. Advancement in semiconductor devices has fuelled an increase in the use of non-linear loads which are the main causes of harmonic distortion in three-phase, four-wire distribution systems. Mitigation of harmonics in three-phase, four-wire electrical power distribution systems that supply balanced and unbalanced non-linear loads was therefore conducted. Giving consideration to the 5$^{th}$ and 7$^{th}$ order harmonics, the mitigation system was modeled and simulated using Matlab/Simulink. Three experiments were conducted for each order of harmonics. Simulation results showed that a better filtering ability is obtained when the characteristic impedance of the shunt passive filter is small and also for a larger resonance frequency also gave better filtering ability. Implementation of the developed model in a three-phase, four-wire power distribution systems promises an absolute minimum of the harmonics content and thus improved harmonics-focused power quality. This paper proposes an approach to compensate for harmonics in a three-phase four-wire power distribution system. The mitigation principle is described, and some interesting filtering characteristics are discussed.

**Keywords***: Power distribution system, harmonics, shunt passive filter, total harmonic distortion (THD).*

## 1. INTRODUCTION

Power quality (PQ) problems in power utility distribution systems are not new. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade, and there are indications that this trend will continue. However, power electronics based equipments which include adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers, electronic ballasts are responsible for the rise in power quality related problems. These nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system (Salam *et al*, 2006). Power quality is an important problem that a power system has to deal with to provide its consumers with reliable and economical power supply. Three-phase, four-wire distribution systems are very common and widely used in commercial and industrial installations and therefore power systems harmonics is an area that merits a great deal of attention. Today's electric power systems are connected to many non-linear loads. These include static power converters, arc discharge devices, electronic control equipment by way of semiconductor devices, saturated magnetic devices and rotating machines. The characteristics of these non-linear loads inevitably change the sinusoidal nature of the a.c. power current, resulting in the flow of harmonic current in the a.c. power system.

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. In modern test equipment today harmonics can be measured up to the 63$^{rd}$ harmonic source. When harmonic frequencies are prevalent, electrical power panels and transformers become mechanically resonant to the magnetic fields generated by higher frequency harmonics. Harmonic frequencies from the 3$^{rd}$ to the 25$^{th}$ are the most common range of frequencies measured in electrical distribution systems (Ramos, 2007). According to Ashok (2002), the effects of harmonics on distribution systems could be summarised thus: cable heating and degradation of dielectric strength; increase in copper losses and stray flux losses in transformers; additional heating, losses and increased dielectric stress in capacitor banks; improper relay operation; noise and malfunctioning of control systems. Total Harmonic Distortion (THD) can be used to describe voltage or current distortion and thus harmonics. It is calculated using Equation (1).

$$\text{THD (\%)} = \sqrt{(ID_1^2 + ID_2^2 + \cdots ID_n^2)} \qquad (1)$$

where IDn is magnitude of the n$^{th}$ harmonic as a percentage of the fundamental.

A non-linear load absorbs a non-sinusoidal current and thus harmonic currents, even when it is supplied by a purely sinusoidal voltage. Examples of non-linear loads are electronic lighting ballasts, adjustable speed drives, electric welding equipment, solid state rectifiers, uninterruptible power supply (UPS) system, and computer systems (Ahmad, 2007).

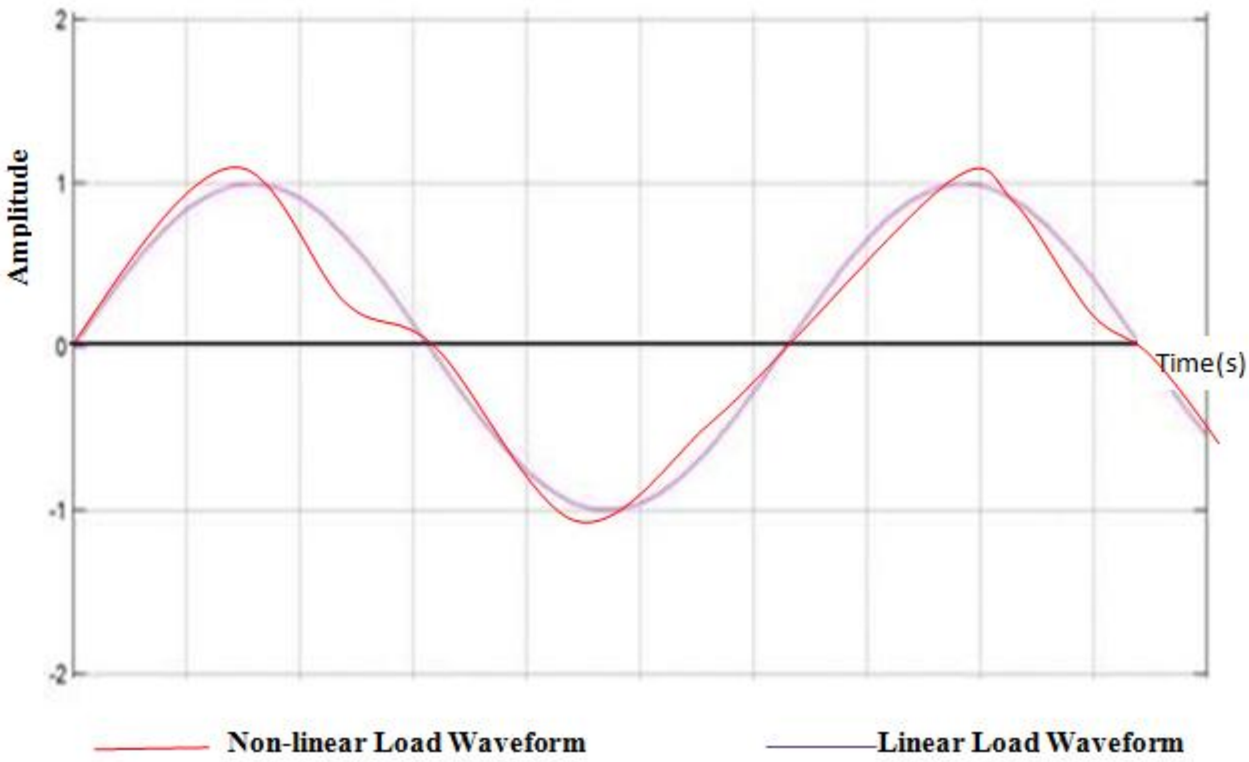


**Fig. 1: Linear and Non-Linear Load Waveform**

**Table 1: Order and Corresponding Frequencies of Harmonics**

| **Harmonics** | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | 10th |
|---|---|---|---|---|---|---|---|---|---|---|
| **Frequency (Hz)** | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |

Figure 1 shows the waveforms of linear and non-linear loads. Harmonics are grouped into positive (+), negative (-) and zero (0) sequence components. Positive sequence harmonics (harmonics numbers 1, 4, 7, 10, 13, etc.) produce magnetic fields and currents rotating in the same direction as the fundamental frequency harmonic. Negative sequence harmonics (harmonic numbers 2, 5, 8, 11, 14, etc.) develop magnetic fields and currents that rotate in a direction opposite to the positive frequency set. Zero sequence harmonics (harmonic numbers 3, 9, 15, 21, etc.) do not develop usable torque, but produce additional losses in the machine. Table 1 shows the order and corresponding frequencies of harmonics for the system frequency of Ghana.

The oldest as well as most effective and economical harmonic mitigation strategy is the addition of inductance. Other harmonics reduction methods include mains impedance reduction and also the use of components such as phase shifting transformers, isolation transformers, dc chokes, linear reactor, 12-Pulse distribution, harmonic trap filters, broadband filters, 18-Pulse converter, active filters (Kallianpur, 2008).

Use of shunt passive filters in the reduction of harmonics offers the advantages of more simplicity, high reliability, high efficiency and low cost. Disadvantageously, the frequency is fixed hence it is very difficult to adjust and secondly, series and parallel resonances are produced.

Efforts aimed at harmonics mitigation have been reported in the recent literature. These include the transformer based methods: use wye-zig-zag transformers to reduce triplen harmonic currents in the neutral conductors of a three-phase 415/240V distribution system (Omar *et al*, 2010); investigation of the effects of harmonic distortion of load current and voltages on distribution transformers using a K-FACTOR transformer (Jayasinghe *et al*, 2003); analysis of harmonic distortion effects and their mitigation in distribution systems introducing effective techniques by the application of phase shifting transformers (Attia *et al*, 2010). Ahmad (2007) employed four selected passive mitigation devices namely wye-zigzag transformer, neutral $3^{rd}$ harmonic blocking series filter, 3-phase $3^{rd}$ harmonic blocking series filter and a 3-phase $3^{rd}$ harmonic trap shunt filter to mitigate triplen harmonic distortion in 3-phase, 4-wire electrical distribution system. Another mitigation technique employs artificial intelligence and algorithms: Pairoj and Somyot (2010) employed cost function, Particle Swarm Optimisation (PSO) using Artificial Neural Network (ANN) to approximate the switching angles from sets of optimal angles evolved by PSO in the design of a Pulse Width Modulation (PWM) AC voltage controller minimising total Current Harmonic Distortion (THDi); Ghiasi *et al* (2002) economically determined the location and size of passive filters in distribution networks using genetic algorithm; Du *et al* (2004) worked on an optimal Total Harmonic Distortion (THD) control algorithm with implementation using Altera FLEX 10K Field Programmable Gate Array (FPGA) at 8 µ*s* control resolution, for cascaded H-bridges multilevel converter control with unequal DC sources. Low order harmonics such as the $5^{th}$, $7^{th}$,$11^{th}$ and $13^{th}$ are eliminated using elimination theory whilst magnitudes and phases of residual higher harmonics are computed and subtracted from the original output voltage waveform to eliminate the higher harmonics. The Newton climbing method was successfully used to eliminate higher order harmonics whilst low order harmonics are dealt with using either resultant theory applied to transcendental equations (Du *et al*, 2005; 2006) or use reduced switching-frequency active-harmonic-elimination method (Du *et al*, 2008). Active power filter (APF) harmonics-elimination technologies were reported by Key and Lai (2001) and Salam *et al* (2006). A combined series active filter and shunt passive filters quite different from the conventional shunt and series active power filters to give better filtering characteristics and lower initial and running costs (Mahalekshmi , 2010; Pinto *et al*, 2007; Vijayakumar and Eswarlal, 2009).

Employed in harmonics suppression are mathematical modeling or a simulation model (Degroote *et al*, 2007; Piel and Carnovale, 2004). Huang (1997) employed a constant duty cycle with sixth-order harmonic injection to suppress the dominant fifth-order harmonics in the input currents. Caumes *et al* (2005) investigated carrier-envelope phase effects in high-order harmonic generation using a single-shot method. Ortmeyer *et al* (2000) proposed a 5-step planning methodology for distribution system harmonic filtering intended for use on radial distribution systems with no large harmonic sources. Mindykowski *et al* (2007) focused attention on the problems of power quality in systems with varying frequency equipped with passive harmonic filters where the main differences between the ship system and land network were considered. Ray and Hapeshis (2005) gave an overview of harmonic considerations for designing industrial and commercial electric power distribution systems.

Morán *et al* (2007) looked at different power quality problems in distribution systems and their solutions with power electronics based equipment. Shunt, hybrid and series active power filters were described showing their compensation characteristics and principles of operation. Different power circuit topologies and control schemes for each type of active power filter were analysed. Simulations and experimentals proved the compensation characteristics of each topology with the respective control scheme. Ryckaert *et al* (2004) discussed the harmonic mitigation potential of a resistive shunt harmonic impedance (SHI) installed between the middle and the end of the feeder. Non-linear loads were concentrated in single nodes whereas the linear loads were disconnected to obtain the worst case for voltage distortion. Mansoor *et al* (2007) proposed an *LCL*-filter-based hybrid active power filter topology for harmonic mitigation of a 10/0.4kV residential distribution system. It achieved better switching ripples attenuation and significant improvement in the phase margin of the power stage at higher frequency. Adaptive linear neural network (ADALINE) is applied for individual harmonic component extraction and the estimated signals are used for selective harmonic elimination (SHE) purposes. Laboratory experiments and field tests confirmed the feasibility and effectiveness of the proposed system. Guesswork was taken out of harmonic filtering by giving the theory of operation of various passive harmonic mitigation techniques and demonstrating their typical real life performance (Anon, 2005).

The objectives of this paper are to mitigate $5^{th}$ and $7^{th}$ order harmonics in a three-phase four- wire power distribution system, reduce power system losses due to harmonics and propose a mitigation principle that will produce much better filtering characteristics for a power system.

## 2. MATERIALS AND METHODS

A simulation approach is adopted in this study. For non-linear loads, the shunt passive filter and the mitigation system were determined using the concept of mitigation of the predominate harmonic order in the system. An experimental set up was created based on mitigation of the $5^{th}$ and $7^{th}$ order harmonics. A simulation circuit diagram is developed by varying the filter parameters in accordance with the experimental set up.

### 2.1 Materials

A six diode rectifier bridge is considered as the non-linear load (Figure 2). The shunt passive filters (Figure 3) consist of inductors and capacitors connected in parallel with the line. It will by-pass the harmonic currents and allow only the fundamental current to pass to the load. The most common type of shunt passive filter is the single-tuned "notch" filter considered here for the mitigation system. This is the most economical type and is frequently sufficient for the application.

The notch filter is series-tuned to present low impedance to a particular harmonic current and is connected in shunt with the power system usually near the loads that produce harmonics (Figure 4). Thus, harmonic currents $I_h$ are diverted from their normal flow path on the line through the filter (Figure 4).

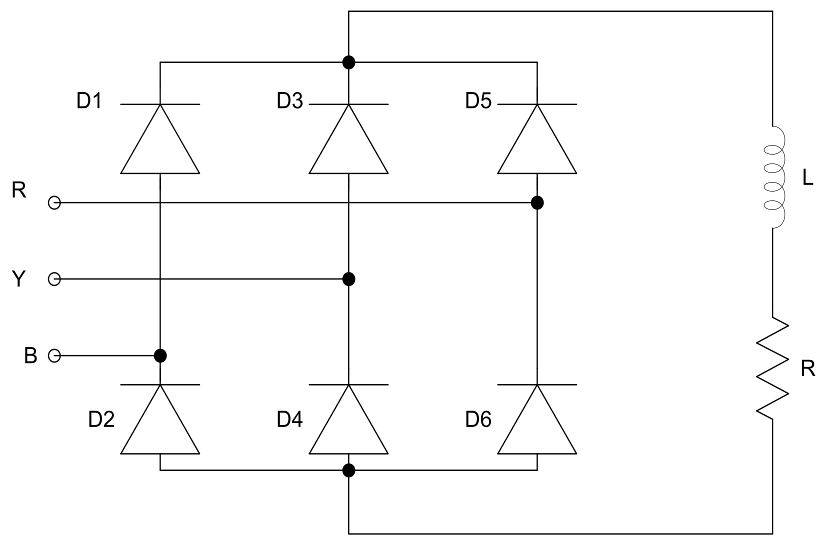


**Fig. 2: Non-linear Load**

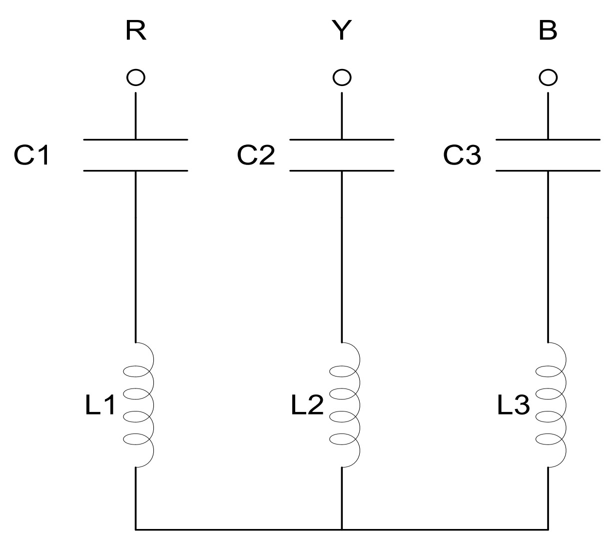


**Fig. 3: Shunt Passive Filter**

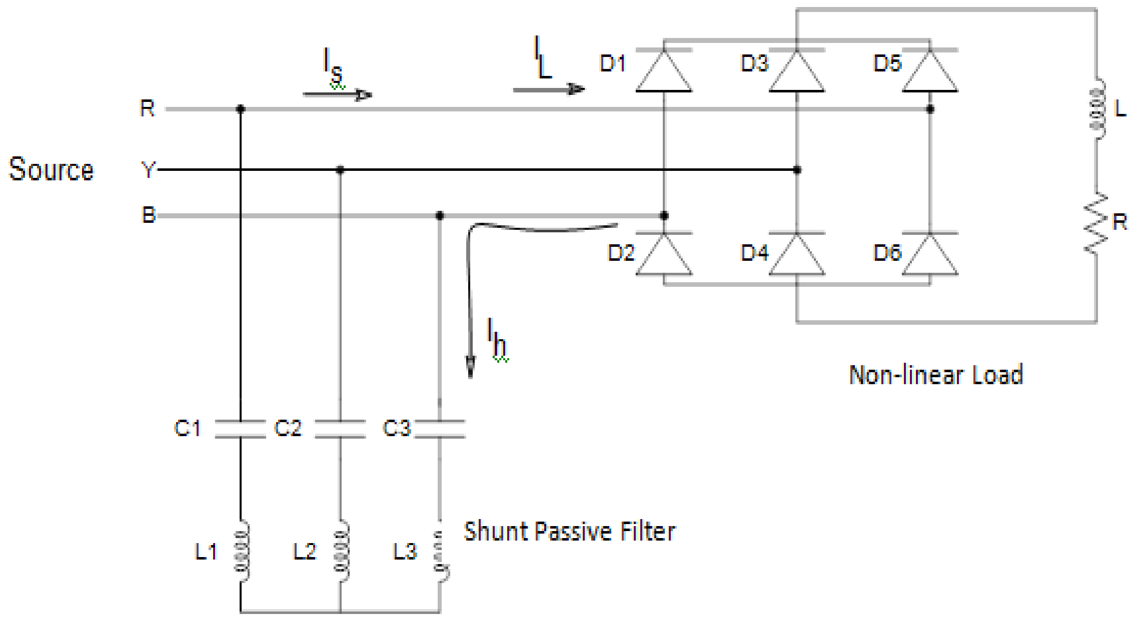


**Fig. 4: The Mitigation System**

where $I_s$ is source current, $I_h$ is harmonic current, $I_L$ is load current, C is filter capacitance. L is filter inductance. The 5th and 7th harmonic frequencies are selected as the resonant frequency. The resonant frequency of the passive filter in the system is given by Equation (2). The characteristic impedance of the passive filter, *Z* is given by Equation (3).

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (2)$$

$$z = \sqrt{\frac{L}{C}} \qquad (3)$$

The impedance, Z determines filter performance at harmonic frequencies except for the resonant frequency. The characteristic impedance should be as low as possible to obtain better filtering performance. This implies that the capacitance value of *C* should be as large as possible and the inductance value of *L* should be as small as possible.

## 2.2 Experimental Set-up

The experimental set-up was conducted on the Matlab interface using the Simulink tool to generate simulation results. The universal, the three-phase source and series RLC load blocks are generated in the interface and used in the set-up. These blocks are inter-connected to generate the mitigation system. The set-up was implemented for the 5th and 7th order harmonics. Filter parameters tuned to the 5th and 7th harmonics were varied in accordance with Equations (2) and (3) which determine the characteristic impedance and the resonance frequency of the passive filters.

### 2.2.1 5th Harmonics Tuned Filter

The parameter of the passive filter tuned to the 5th harmonic was chosen knowing that the resonance frequency for the filter should be around 250 Hz. Also, we took into consideration that the characteristic impedance should be as low as possible to present a better filtering characteristic. Three experiments were conducted using the filter tuned to the 5th harmonic frequency. The first experiment was conducted with a resonance frequency of 252 Hz. The parameters of the second experiment were chosen by decreasing the inductance and increasing the capacitance of the first experiment. This gave a resonance frequency of 256 Hz. The third experiment was conducted by increasing the inductance and decreasing the capacitance of the first experiment by the same margin. 247 Hz was obtained as the resonance frequency. Parameters for all the 5th harmonic filter experiments are presented in Table 2.

### 2.2.2 7th Harmonic Tuned Filter

Similarly, three experiments were conducted for the passive filter parameters tuned to the 7th harmonics taking cognisance of a filter resonance frequency around 350 Hz. Also, low characteristic impedance is required for a better filtering characteristic. 356 Hz is the resonance frequency for the first experiment. Similarly parameters of the second experiment are chosen by decreasing the inductance and increasing the capacitance of the first experiment. This is supposed to give a resonance frequency of 364 Hz. Parameters for the last experiment are chosen by increasing the inductance and decreasing the capacitance of the first experiment by the same margin as in the second experiment. The resonance frequency was 348 Hz. Parameters for all the 7th harmonics filter experiments are presented in Table 3. The passive filter tuned to the 7th harmonic frequency is expected to offer less impedance to the 11th and 13th harmonic components, compared to that tuned to the 5th harmonic frequency (Mindykwoski *et al*, 2007).

**Table 2: System Parameters for 5th Harmonic Filter**

| System Parameters | First Experiment | Second Experiment | Third Experiment |
|---|---|---|---|
| Source frequency | 50 Hz | 50 Hz | 50 Hz |
| Source voltage (phase to phase) | 415 V | 415 V | 415 V |
| Source impedance | 0.5 Ω and 1 mH | 0.5 Ω and 1 mH | 0.5 Ω and 1 mH |
| Passive filter impedance | 100 μF and 4 mH | 101.5 μF and 3.8 mH | 98.5 μF and 4.2 mH |
| Passive filter resonance frequency | 252 Hz | 256 Hz | 247 Hz |
| Passive filter characteristic impedance | 6.32 Ω | 6.12 Ω | 6.53 Ω |
| Load impedance | 10.6 Ω and 58.2 mH | 10.6 Ω and 58.2 mH | 10.6 Ω and 58.2 mH |

**Table 3: System Parameters for 7th Harmonic Filter**

| System Parameters | First Experiment | Second Experiment | Third Experiment |
|---|---|---|---|
| Source frequency | 50 Hz | 50 Hz | 50 Hz |
| Source voltage (phase to phase) | 415 V | 415 V | 415 V |
| Source impedance | 0.5 Ω and 1 mH | 0.5 Ω and 1 mH | 0.5 Ω and 1 mH |
| Passive filter impedance | 100 μF and 2 mH | 100.5 μF and 1.9 mH | 99.5 μF and 2.1 mH |
| Passive filter resonance frequency | 356 Hz | 364 Hz | 348 Hz |
| Passive filter characteristic impedance | 4.47 Ω | 4.35 Ω | 4.59 Ω |
| Load impedance | 10.6 Ω and 58.2 mH | 10.6 Ω and 58.2 mH | 10.6 Ω and 58.2 mH |

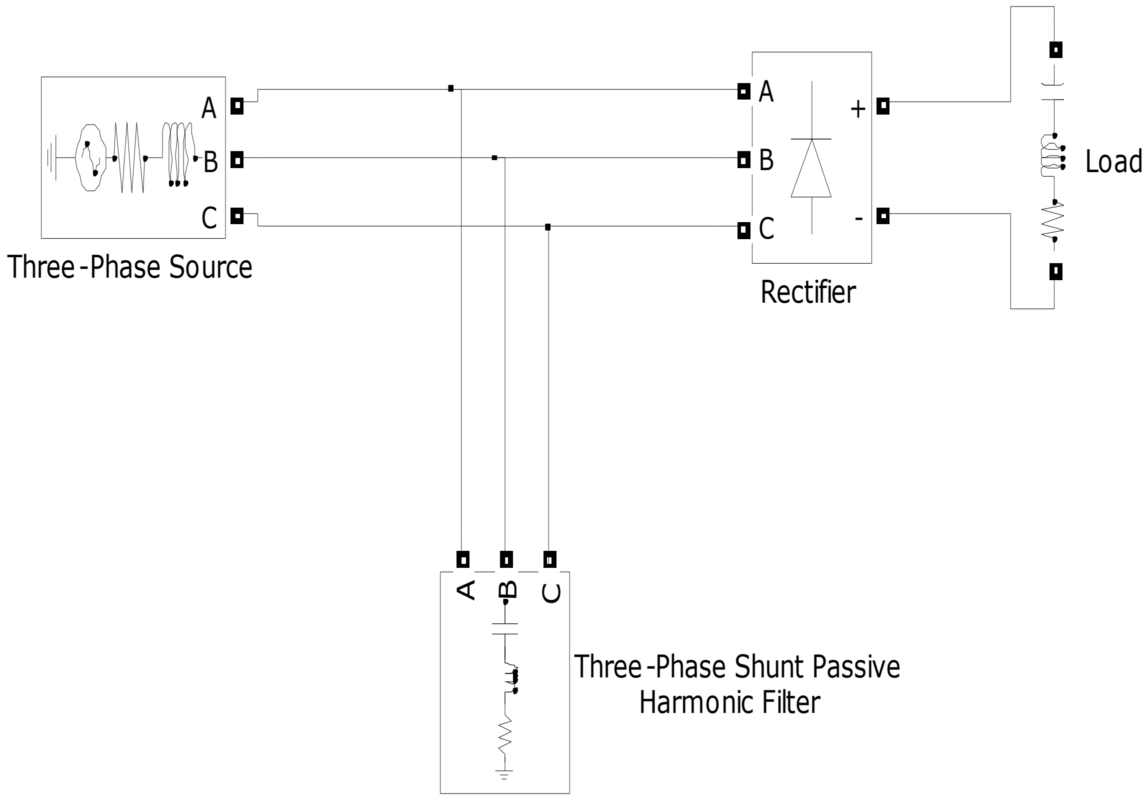


**Fig. 5: Simulation Diagram**

### 2.3 Simulation

Simulation model of the mitigation system was developed to verify the ability of the shunt passive filter in a generated non-linear circuit. The simulation diagram of the proposed shunt passive filter is shown in Figure 5. The diagram consists of the AC source, non-linear load and the three-phase shunt passive harmonic filter.

## 3. RESULTS AND DISCUSSION

Simulation using Matlab/Simulink version R2008 was conducted on the proposed mitigation system before and after the passive filter compensation was conducted and results of the simulation are discussed. The results consist of three

experiments each of the $5^{th}$ and $7^{th}$ tuned harmonic filters. The main parameters here are the capacitance and inductance of the tuned passive filters. Graphs were plotted from the simulation results. The discussion is centered on the variation of the capacitance and inductance, and their effects on the filtering ability of the tuned passive filter.

### 3.1 Simulation Results

The simulation results were obtained by varying the parameters of both tuned filters for increasing and decreasing inductance and capacitance values. Also, some of the parameters such as source voltage, frequency and impedance were kept constant. The interface of the Matlab/Simulink is shown in Figure 6. The upper path of the window shows the voltage waveform of the signal and the lower portion shows the THD of the system. The simulation is done on the Simulink window and results are obtained from the FFT window. The simulation time was ten minutes.

Results of simulation for the $5^{th}$ harmonic tuned filter at frequencies of 252 Hz, 256 Hz and 247 Hz are as shown in Figures 7, 8, and 9 respectively. Figures 10, 11 and 12 correspond to results for the $7^{th}$ harmonic filter at 356 Hz, 364 Hz and 348 Hz respectively.

 

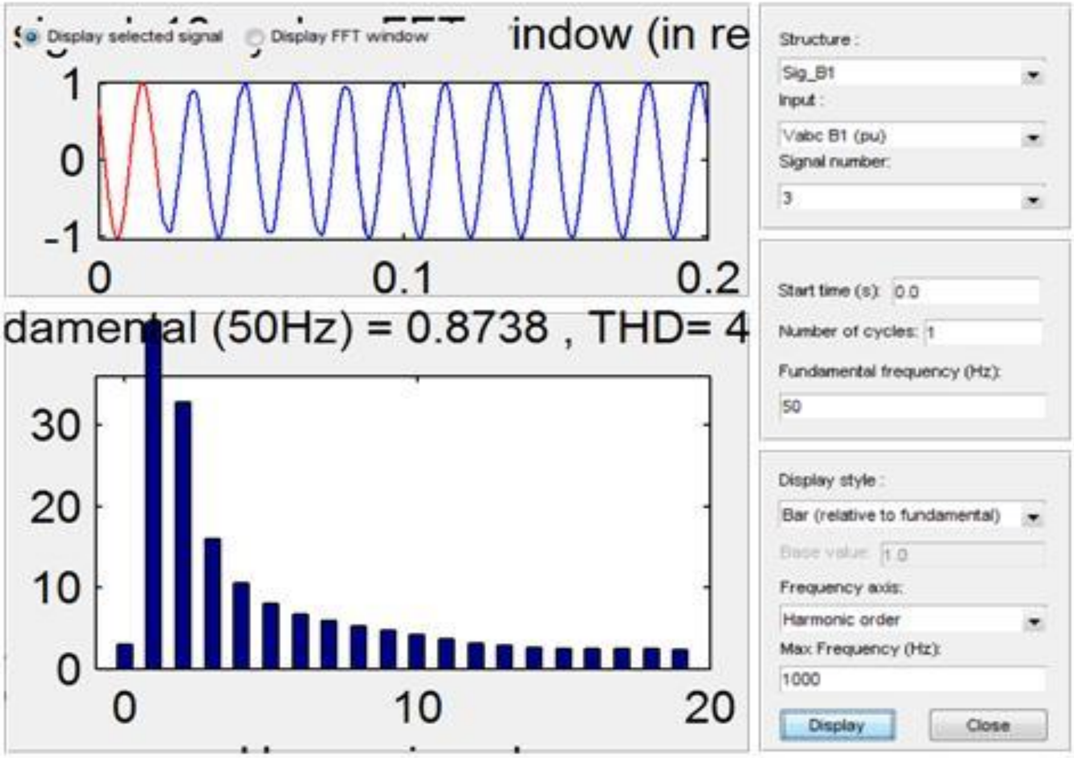


**Fig. 6: Matlab Interface**

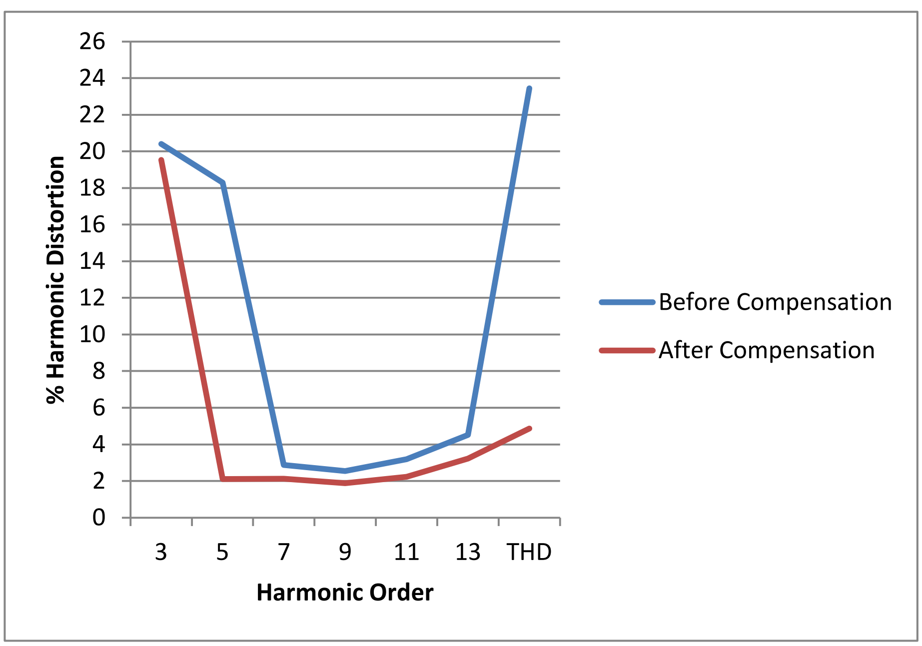


**Fig. 7: Harmonic Distortion for the First Experiment of 5th Harmonic Tuned Filter at 252 Hz**


**Fig. 8: Harmonic Distortion for the Second Experiment of 5th Harmonic Tuned Filter at 256 Hz**

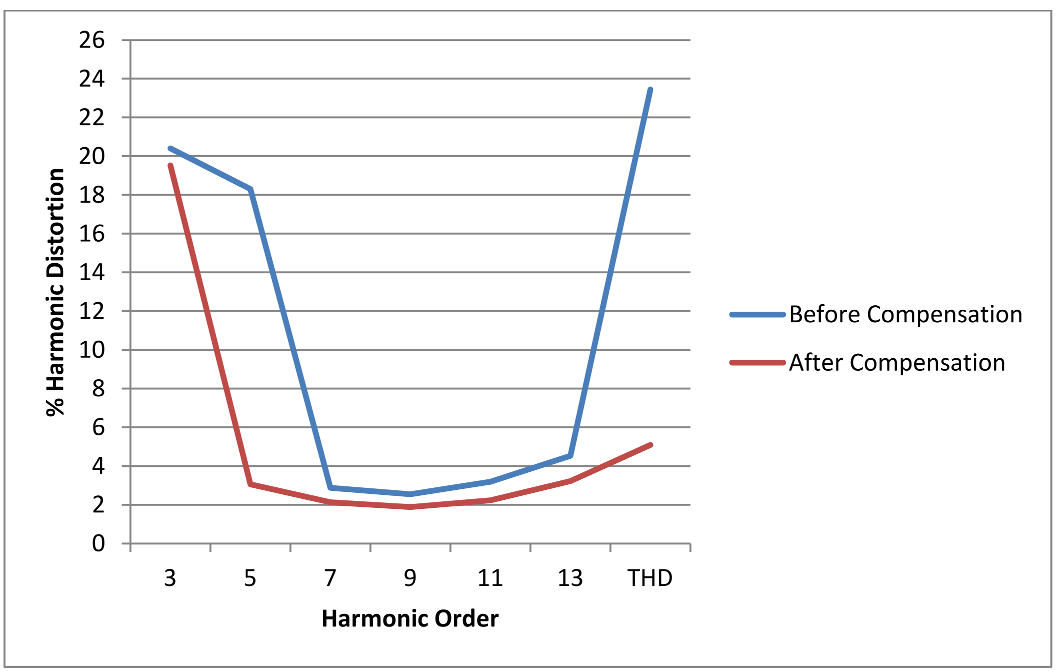


**Fig. 9: Harmonic Distortion for the Third Experiment of 5th Harmonic Tuned Filter at 247 Hz**


**Fig. 10: Harmonic Distortion for the First Experiment of 7th Harmonic Tuned Filter at 356 Hz**


**Fig. 11: Harmonic Distortion for the Second Experiment of 7th Harmonic Tuned Filter at 364 Hz**


**Fig. 12: Harmonic Distortion for Second Experiment of 7th Harmonic Tuned Filter at 348 Hz**

## 3.2 Discussion of Results

### 3.2.1 Change in THD due to Change in Filter Parameters for 5th Harmonic Tuned Filter

For the 5th harmonic tuned filter the resonance frequency was supposed to be about 250 Hz. The first, second and third experiments considered 252 Hz, 256 Hz and 246 Hz respectively. From the simulation results, the first experiment gave a change in the 5th harmonic distortion from 18.30 to 2.11 percent representing a change of 88 % in THD. For the second experiment, the change was 18.3 to 1.43 percent giving 92 % change in THD. The third experiment gave a change from 18.3 to 3.06 percent representing a change of 83 % in THD. In the second experiment of the 5th harmonics, the inductance reduced from 4 mH to 3.8 mH and the capacitance increased from 100 µF to 101.5 µF. Also, the inductance increased from 4 mH to 4.2 mH and the capacitance decreased to 98.5 µF for the third experiment. Clearly, it can be stated that a variation in the filter parameters affects the performance of the filter. The performance of the shunt passive filter is dependent on the characteristic impedance. The characteristic impedance for the first, second and third experiments were 6.32 Ω, 6.12 Ω and 6.53 Ω respectively. It can be stated from the results that the lower the characteristic impedance of the shunt passive filter, the better is the filtering ability of the filter. Also, the resonance frequency has an effect on the filtering ability of the shunt passive filter. A resonance frequency below the 5th harmonics frequency gave poor filtering as compared to a resonance frequency above it. From our results, the second experiment gave the best filtering with a resonance frequency of 256 Hz, followed by the first with a resonance frequency of 252 Hz. From the graph, it can be seen that the 5th harmonic tuned filter has little effect on the other harmonic orders. Even when the filtering ability was improved in the second experiment, it caused no change in the distortion of the other orders of harmonics. Also, it can be noted that the THD was reduced when the filtering for the 5th harmonic order was improved.

### 3.2.2 Change in THD due to Change in Filter Parameters for 7th Harmonic Tuned Filter

For the 7th harmonic tuned filter the resonance frequency was supposed to be about 350 Hz. The first, second and third experiments considered 356 Hz, 364 Hz and 348 Hz respectively. From the simulation results, it can be stated that the 7th harmonic distortion is very small as compared to that of the 5th harmonics. The first experiment gave a change in the 7th harmonic distortion from 2.87 to 0.22 percent which represented a change of 92.33 % in the THD. For the second experiment the change was from 2.87 to 0.14 percent representing a change of 95.12 % in the THD. And for the third experiment, the change was 2.87 to 0.45 percent giving a change of 84.32 % in THD. Also in the third experiment, the inductance increased from 2 mH to 2.1 mH and the capacitance decreased from 100 µF to 99.5 µF. The inductance decreased from 2 mH to 1.9 mH and the capacitance increased from 100 μF to 100.5 μF in the second experiment of the $7^{th}$ harmonics. Once again variation in the filter parameters affected the performance of the shunt passive filter. The performance of the shunt passive filter is dependent on the characteristic impedance. 4.47 Ω, 4.35 Ω and 4.59 Ω were the characteristic impedances for the first, second and third experiments respectively. The experiment with the lowest characteristic impedance gave the best reduction in harmonic distortion. This affirms the fact that the characteristic frequency has direct effect on the performance of the shunt passive filter. The results prove that the resonance frequency is directly proportional to filtering ability of the shunt passive filter. A higher resonance frequency gives a better filtering ability. From the graph, it can be seen that the $7^{th}$ harmonic tuned filter has little effect on the other harmonic orders. Even when the filtering ability was improved in the third experiment it caused just a little change in the distortion of the other orders of harmonics. Also, it can be noted that the THD was reduced when the filtering for the $7^{th}$ harmonics order was improved.

### 3.2.3 Comparison of the $5^{th}$ and $7^{th}$ Harmonic Order Shunt Passive Tuned Filters

From the results, the THD of the filters vary from the $5^{th}$ to the $7^{th}$ harmonic tuned filters. The $5^{th}$ harmonic tuned filter gave a lower THD than that of the $7^{th}$ harmonic tuned filter. This is due to the fact that the $5^{th}$ harmonics is predominant in the system than the $7^{th}$. Also, the $7^{th}$ harmonics plays little role in the overall THD of the system since its effect is very small. To propose a system for mitigation of harmonics using shunt passive filters, it is advised that the predominant order of harmonics is dealt with in passive filter design. The $7^{th}$ harmonic tuned filter has an advantage of low cost and reduced bulkiness than that tuned to the $5^{th}$ harmonic frequency as long as both filters have the same filter inductor, L. This is because at the same inductor value the capacitance value of the $5^{th}$ harmonic tuned filter will have to be larger to attain a value close to 250 Hz.

## 4. CONCLUSION

The mitigation of $5^{th}$ and $7^{th}$ order harmonics in 3-phase, 4-wire power distribution system using shunt passive filters has been presented. Harmonics level has great effect on the performance of the system components and equipment. The passive filter provides a simpler and a cost effective approach to reducing harmonic distortion in three-phase, four-wire power distribution systems. Filtering ability of shunt passive filters can be improved by tuning the passive filter to a specific resonance frequency, usually of the predominant harmonic order in the three-phase, four-wire electrical power distribution system. Secondly, the filtering ability is improved by keeping the inductance at a high value while the capacitance is kept low for a tuned passive filter. This reduces the characteristic impedance size of filter and also the cost. During the next decade, an increase in nonlinear loads up to 70 % is expected. It is therefore important to consider their impact when contemplating changes to the power distribution system. It is appropriate that utility companies should educate their customers about the dangers of using more non-linear loads in the home and work places. Also, power consumers need be educated on the use of filters to reduce harmonic effects, since they are meant to be installed close to the load.

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