ABUAD Journal of Engineering Research and Development (AJERD)
Volume 1, Issue 1, 32-48

Assessing the Performance of Harmonic Filters for Power Quality Improvement on Industrial Load: 7-Up Industry Plc Power Network as a Case Study

Oluwaseun Ibrahim ADEBISI[1,*], Isaiah Adediji ADEJUMOBI[1], Rufus Akinnusimi JOKOJEJE[2], Olusegun Daniel ADEKOYA[3]

[1]*Department of Electrical and Electronics Engineering, Federal University of Agriculture, Abeokuta, Nigeria*
adebisioluwaseun@funaab.edu.ng/adejumobiia@funaab.edu.ng
[2]*Department of Electrical and Electronics Engineering, Moshood Abiola Polytechnic, Abeokuta, Nigeria*
akinnusimialaba@yahoo.com
[3]*Federal College of Forestry, Jericho, Ibadan, Nigeria*
segunadekoya74@yahoo.com

[*]*Corresponding Author:* adebisioluwaseun@funaab.edu.ng

Date of First Submission: 28/09/2017
Date Accepted: 15/11/2017

Abstract: *Poor power quality due to widespread use of non-linear loads such as semiconductor based devices etc. causes less productivity, reduced power efficiency and equipment malfunction and damage. Therefore, the need to address power quality problems with deserved attention. This work assessed the performance of harmonic filters for power quality improvement on industrial load using 7-Up Industry Plc power network as a case study. The theoretical analyses of filter design and harmonics were presented. The test system was modelled and simulated using MATLAB/Simulink software version R2015a. The results from simulations showed without compensation, voltage and current waveforms of the test network were distorted with total harmonic distortion (THD) for voltage and current estimated as 16.93% and 19.25% respectively. Harmonic compensation on the test system with shunt passive filter reduced* V_{THD} *and* I_{THD} *to 0.20% and 0.00% respectively. The series and shunt active filters separately used alone on the test network mitigated the* V_{THD} *and* I_{THD} *to 15.67% and 18.97% respectively for series filter and 5.50% and 11.43% respectively for shunt filter. Hybrid combination of series active filter and shunt passive filter mitigated the* V_{THD} *and* I_{THD} *to 0.20% and 0.11% respectively whereas* V_{THD} *and* I_{THD} *were respectively 0.07% and 0.43% using the hybrid combination of shunt active filter and shunt passive filter. Hence, for the test network considered in this work, shunt passive filter and hybrid combinations of series active filter and shunt passive filter and shunt active filter and shunt passive filter were the suitable mitigation solutions for harmonic distortions.*

Keywords: Harmonic, Harmonic filter, Non-linear load, Power quality, Total harmonic distortion

1. INTRODUCTION

Provision of secure, reliable, and high quality electricity is very essential in any power system especially to the end-users for effective and efficient operation of their loads. However, various diseased conditions such as faults at the utility end and the proliferation of high technological advanced equipment and devices such as microprocessors, microcomputers, information technology devices, telecommunication equipment, television sets, programmable logic controllers, switch-mode power supplies, silicon controlled rectifiers, energy efficient lighting, power factor correction condensers, transformers, arc welders, arc furnaces, adjustable speed drives among others have led to changes in the characteristics of electric loads [1, 2]. These loads can be the major sources and/or the major recipients of power quality problems [1]. Being non-linear, these loads can distort supply voltage waveform.

The quality of electric power supply measures the ability of power system to support smooth operational efficiency of its loads. Power is said to be of good quality if the supply is stable, the voltage magnitude and the frequency are within the recommended statutory limits and the waveform is a distortionless sinusoidal signal. However, due to varying electricity demands, presence of non-linear loads and faults in power system, the electricity supply usually deviates from its normal characteristics and consequently results into power quality issues such as voltage sag or dip, very short and long interruptions, voltage spike, voltage swells, harmonic distortion, voltage fluctuation, noise, voltage unbalance and altered power system performance [3, 4, 5].

Poor power quality undermines the activities of the consumers at every level of usage- domestic, commercial and industrial. It causes incorrect or damaged production processes, less productivity, lost and corrupt data, poor power efficiency or can even damage the equipment [3]. The economic loss resulting from equipment malfunction or destruction due to poor power quality may be very significant and should be avoided as much as possible. Hence, there is the need for control techniques or mitigative measures to minimise the problems of poor power quality in power systems.

Of the several power quality related issues, the focus of this work is on power system harmonics, which have been receiving great deal of research attention recently. Harmonic in power system is an electrical pollution which is an integral multiple of the 50 or 60 Hz fundamental frequency. It causes severe problems ranging from equipment overheating, premature equipment failure, false tripping of protective relays resulting in unnecessary down time in industrial production, rotary machine vibration, voltage quality degradation, low power factor, distortion of supply waveforms etc. [6, 7]. Therefore, harmonic mitigation in power system is very germane to industrial electrical systems in order to increase system reliability, enhance economical operation, avoid unwanted equipment failure and process downtimes.

Various techniques of mitigating power quality problems have been proposed in literature [8, 9, 10, 11] but only few solutions address the issues of reactive power compensation and harmonic mitigation [7]. In this category of solutions, filtering technique plays a leading role owing to its inherent simplicity, high efficient performance and cost effectiveness. Passive, active and hybrid power filters are the most commonly employed filtering techniques for harmonic mitigation. Each of these techniques has their peculiarity and on this account, several research attempts have been conducted [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Passive power filters have been employed for compensating current quality problems in power distribution network due to its low cost, simplicity and high efficiency but suffer from drawbacks of low dynamic performance, resonance problems and bulk size. Active power filters came into existence to offer improvement on passive power filter technologies in terms of modularity, flexibility and reactive power compensation. However, active power filters are also not cost-effective to implement. In order to overcome the limitations of high cost associated with the active power filters, hybrid power filters were developed. Hybrid power filters consist of active and traditional passive filters in series and/or parallel (shunt) configurations. These connections allow for improved compensation characteristics of the passive power filters and reduced voltage and/or current ratings of the active power filters leading to cost and performance effectiveness. Since there are varieties of improved filter technologies to address the problems of poor power quality in power systems, the choice of right filtering technique for a given application has become an important task that must be treated with adequate attention today.

Therefore, in this paper, the performance of passive, active and hybrid power filters in mitigating harmonics arising from the use of non-linear loads in industrial electrical system was assessed using the 7-Up Industry Plc power network in Ibadan, Oyo State, Nigeria as a case study. The harmonic filters considered were shunt passive filter, series and shunt active filters and hybrid combinations of series active filter and shunt passive filter and shunt active filter and shunt passive filter. Total Harmonic Distortion (THD) was utilised as a performance index to measure the effectiveness of these filters to mitigate harmonic distortion for power quality improvement on industrial electricity supply network.

2. MITIGATION TECHNIQUES FOR POWER QUALITY IMPROVEMENT IN POWER SYSTEMS

A number of mitigation techniques are available for addressing the problems of poor power quality in power systems. Some of these techniques include efficient design of equipment, use of interfacing devices such as automatic voltage regulator (AVR), uninterruptible power supply (UPS), dynamic voltage restorer (DVR) etc., harmonic filters, proper grounding of electrical system and the use of mitigating devices and equipment such as tap-changing transformer, static var compensator (SVC), transient voltage surge suppressor (TVSS), lightning arrester among others [8]. Of these highlighted techniques for power quality improvement, harmonic filters are of interest since the power quality problem addressed on the test network considered in this work is harmonic distortion. A brief review of harmonic filters is hereby presented.

2.1 Harmonic Filters

An electric filter is characteristically a network that allows desired system frequency to pass through and prevents any undesired signal from advancing. The primary components of an electric filter are resistors, capacitors and inductors. These components combine in different forms to provide a low impedance path for desired system fundamental frequency and a high impedance path for undesired system frequency. Harmonic filters produce compensating harmonic currents that cancel out harmonics produced by non-linear load in electrical systems, thereby improving the power quality. Different types of electric filters employed in power system for mitigation of harmonics include active harmonic filters, passive harmonic filters, line-reactors, electronic feedback filters and special transformers that use out of phase windings to accomplish harmonic reduction [11]. However, the attention here is on passive, active and hybrid power filters.

2.1.1 Passive filter

Passive filters have conventionally been used to mitigate series of power quality problems including harmonic current problems, voltage imbalance problems etc. [24]. They can be installed in any industrial power network for power quality improvement and deployed either as standalone or in combination with phase shifting transformers [25]. Some of the important functions being performed by passive filters are prevention of propagation of electromagnetic interference from switching sources to power lines and other components, prevention of high-frequency voltage from integrating with the output of power supply system, minimization of harmonic distortions among others. Passive filter consists of basic elements such as inductor, capacitor and resistor in various configurations for filtration purposes. They are generally categorised into series and shunt types [26]. Series passive filter uses high impedances to block harmonics and carries the full load current in the network. It is a recommended mitigation method for voltage source type harmonic producing loads [26, 27]. Shunt passive filter on the other hand is the most commonly implemented technique of harmonic current minimization in distribution network and operates on the principle of single tuned or bandpass filter technology [26, 27]. It is a preferred mitigation solution for current source type harmonic producing load [27] and usually connected in parallel with the load. It has low impedance at the tuned frequency and only carries a fraction of the whole system current, hence, providing reduced ac power losses compared to series types. Additionally, shunt passive filter has the capacity to compensate harmonic current as well as reactive power in power network [28].

2.1.2 Active filter

Active filters provide solutions for various power quality problems such as compensation of voltage harmonics, voltage imbalance etc. in power systems [29, 30]. They operate in such a way that they produce current of the same magnitude but exact phase opposition to the harmonic current produced by non-linear loads. By so doing, they damped the effects of harmonic current produced by the non-linear loads. Active power filters are mainly available in series and shunt forms, although other configurations are derivable. Shunt active power filter is the most important configuration widely employed for active filtering applications for current harmonic reduction and power factor improvement [28, 31]. It acts as controllable current source by injecting a compensating current of equal magnitude but anti-phase to the harmonic and reactive current produced nonlinear loads. Series active power filter is usually connected in series with the distribution line by an equivalent, matching or interfacing transformer [31]. It acts as a controllable voltage source by injecting harmonic voltage across the matching or interfacing transformer which adds to or reduces the source voltage to maintain the undistorted sinusoidal waveform across the non-linear loads.

2.1.3 Hybrid filters

Hybrid filters consist of active and passive power filters configured in various forms. They have the capacity to provide dynamic harmonics and reactive power compensation and so have gained much recognition from experts in the area of reactive power compensation and harmonic suppressing in recent times [29]. The main objective of hybrid filters is to reduce the rating requirement of the active component and enhance the performance of the passive component [7, 32], hence, providing cost-performance effectiveness over the two latter solutions for harmonic mitigation. The three general configurations of hybrid filters available are series active power filter and shunt passive power filter, shunt active power filter and shunt passive power filter and active power filter in series with shunt passive power filter. In series active power filter and shunt passive power filter configuration, the active filter acts as the harmonic isolator and forces all the harmonic currents to pass through the passive filter. In shunt active power filter and shunt passive power filter configuration, the passive filter acts as the main harmonic compensator while the remaining harmonic currents are compensated for using the active filter. In the configuration involving the active power filter being combined in series with the shunt passive power filter and the resulting connection shunted to the distribution system, the system's fundamental voltage drops across the capacitor of passive filter, thereby reducing the voltage rating of the active power filter.

3. METHODOLOGY

In this section of the work, theoretical backgrounds to power relations, filter design and power system harmonics are presented.

3.1 Power Relations

Consider a load S in VA operating on a lagging power factor $\cos\theta$ in an electrical network, the active power P in W and the reactive power Q in Var are related to S by equations (1) to (4):

$$S = P + jQ \tag{1}$$

$$S = \sqrt{P^2 + Q^2} \tag{2}$$

$$P = \mathrm{Re}[S] = S\cos\theta \tag{3}$$

$$Q = \mathrm{Im}[S] = S\sin\theta \tag{4}$$

If the load S is given in terms of voltage V and current I as expressed by equation (5), equations (3) and (4) become modified as equations (6) and (7).

$$S = VI \tag{5}$$

$$P = VI\cos\theta \tag{6}$$

$$Q = VI\sin\theta \tag{7}$$

With the above equations (1) to (7), apparent, active and reactive powers in an electrical network can easily be determined.

3.2 Filter Design

Filters are one of the commonly used techniques for mitigating the effects of harmonics in electrical networks. As earlier highlighted, different types of power filters exist, however, for the purpose of this work, passive, active and hybrid power filters were considered.

3.2.1 Design of passive filter

The interest here is on shunt passive power filter with special attention on tuned filter. Shunt passive power filter is the most commonly implemented method of harmonic current mitigation in distribution system networks. It has the ability to provide low impedance path for harmonic current at tuned frequency and also carries only a fraction of the whole system current, minimising system ac losses. The schematic diagram of the shunt passive power filter considered in this work and the basic structure of a tuned filter are respectively shown in Figures 1 and 2.

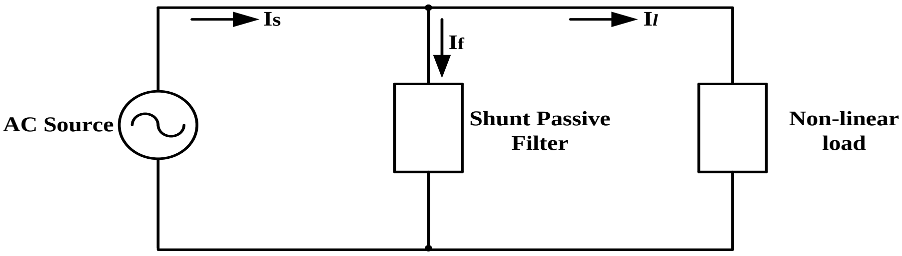


Figure 1: Schematic diagram of a shunt passive power filter

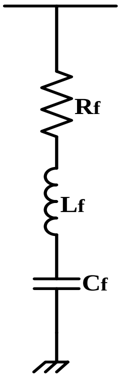


Figure 2: Tuned filter

In the design of tuned passive filters, the right choice of capacitor size is very vital from the perspective of power factor [24]. According to Tali *et al.* [33], the filter capacitor C_f is generally sized for a known reactive power compensation Q_c required to improve power factor. Therefore, the relation between C_f and Q_c is given by equation (8):

$$C_f = \frac{Q_c}{2\pi f V^2}\left(1 - \frac{1}{n^2}\right) \quad (8)$$

Where V is the supply voltage, f is the fundamental frequency and n is the harmonic order.

At the harmonic frequency $f_n = nf$, the filter reactor L_f provides a series resonance governed by equation (9):

$$X_L = X_C \quad (9)$$

Where X_L is the inductive reactance and X_C is the capacitive reactance.

X_L and X_C are respectively given by equations (10) and (11) as:

$$X_L = 2\pi f_n L_f \quad (10)$$

$$X_C = \frac{1}{2\pi f_n C_f} \quad (11)$$

Making L_f the subject in equation (10) and C_f the subject in equation (11), equations (12) and (13) are obtained as:

$$L_f = \frac{X_L}{2\pi f_n} \quad (12)$$

$$C_f = \frac{1}{2\pi f_n X_C} \quad (13)$$

The use of equations (12) and (13) in equation (9) yields equation (14) which gives the inductive value of the filter.

$$L_f = \frac{1}{4\pi^2 f_n^2 C_f} \quad (14)$$

The resistance R_f of a tuned filter depends on the quality factor Q of the filter which determines the sharpness of tuning [24, 33]. R_f is mathematically obtained from equation (15) [33], which is further modified in equations (16) and (17) with the use of equation (14) in (15).

$$R_f = \frac{2\pi f_n L_f}{Q} \quad (15)$$

$$R_f = \frac{\sqrt{\frac{L_f}{C_f}}}{Q} \quad (16)$$

$$R_f = \sqrt{\frac{L_f}{Q^2 C_f}} \quad (17)$$

Q has a value ranging between 20 and 100 [24, 33], with higher value of Q giving better minimization of harmonic distortion.

3.2.2 *Design of active filter*

The development of active power filter is to address the major deficiencies of passive power filter in mitigating harmonic distortion. The schematic diagrams of the active power filter considered in this work are shown in Figures 3 and 4.

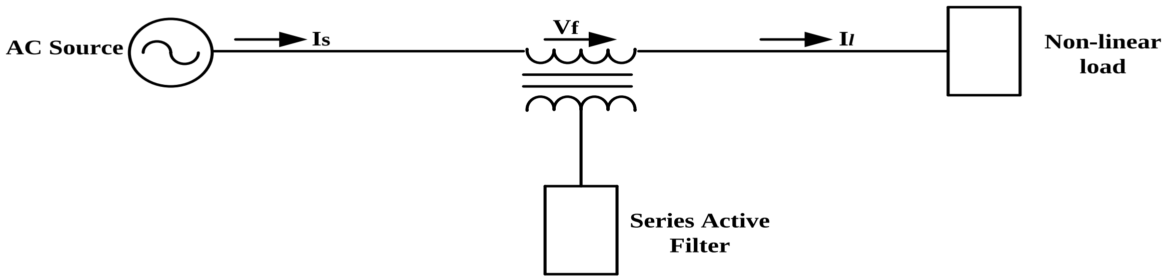


Figure 3: Schematic diagram of a series active power filter

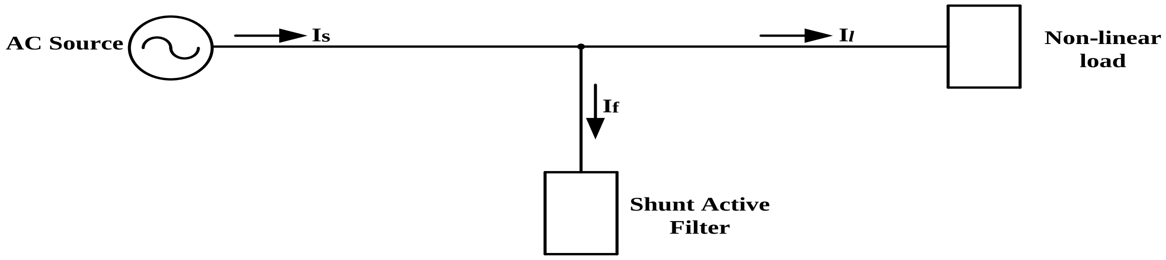


Figure 4: Schematic diagram of a shunt active power filter

One of the important considerations in active filter design is the control strategy with which the reference voltage is generated for the operation of the filter. According to Akagi [30], the control strategy has a great impact on the filter compensation objective, required kVA rating and filtering characteristics in transient as well as in steady state.

An active power filter employed for harmonic isolation prevents harmonic currents from flowing in and out of the distribution feeders and hence, the filter detects the supply current I_s. The filter is controlled in such a way to present zero impedance to the system's fundamental frequency and to act as a resistor with high resistance of G (Ω) for the harmonic frequencies. This implies that characteristically series active filter must satisfy equation (18) [30]:

$$V_{Af} = GI_{sh} \tag{18}$$

Where V_{Af} is the filter's injected harmonic voltage across the interfacing transformer, G is the filter feedback gain and I_{sh} is the harmonic current.

Similarly, the shunt active power filter required for harmonic compensation absorbs current harmonic generated from the feeders and therefore, it detects the bus voltage at the point of installation, V_s. The filter is controlled to present infinite impedance to the system's fundamental frequency and to acts as a resistor with low resistance of $^1/_K$ (Ω). The shunt active power filter satisfies equation (19) for harmonic compensation capability [30]:

$$I_{Af} = KV_{sh} \tag{19}$$

Where I_{Af} is the filter's harmonic compensating current, K is the filter feedback gain and V_{sh} is the harmonic voltage.

3.2.3 Design of hybrid filter

The hybrid filters designed for this work are such that the operational characteristics of the previously designed passive and active power filters were combined in two different configurations presented in Figures 5 and 6 respectively to mitigate harmonic distortion.

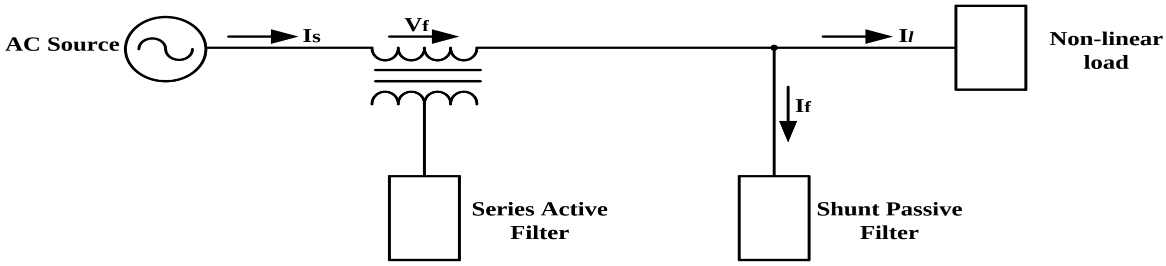


Figure 5: Schematic diagram of series active power filter and shunt passive power filter

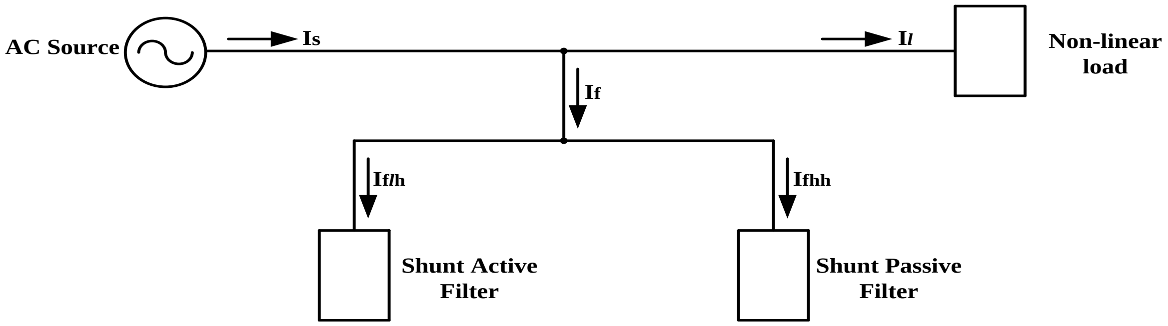


Figure 6: Schematic diagram of shunt active power filter and shunt passive power filter

3.3 *Harmonic Analysis in Power System*

In power system, voltage and current distortions are quantified respectively by voltage total harmonic distortion (V_{THD}) and current total harmonic distortion (I_{THD}). THD is a measure of the effective value of the harmonic components of a distorted waveform. It is evaluated for voltage and current by equations (20) to (23) [25]:

$$\%V_{THD} = \sqrt{\frac{\sum_{h=2}^{\infty} V_h^2}{V_1^2}} \times 100\% \quad (20)$$

$$\%V_{HD} = \frac{V_h}{V_1} \times 100\% \quad (21)$$

$$\%I_{THD} = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1^2}} \times 100\% \quad (22)$$

$$\%I_{HD} = \frac{I_h}{I_1} \times 100\% \quad (23)$$

Where V_h, I_h are rms value of harmonic component h of voltage and current respectively, V_1 , I_1 are harmonic component of voltage and current respectively at system fundamental frequency.

The distribution level caused by individual harmonic components (voltage and current magnitudes) is expressed as a percentage of the fundamental component magnitude and used as a measure of observing which harmonic component contributes more to the total harmonic distribution.

3.4 *Standard Voltage and Current Distortion Limits*

IEEE 519-1992 standard is an IEEE recommended practices and requirements for harmonic control in electrical power system. This standard specifies the acceptable voltage and current distortion distribution limits for general systems. The limits for voltage and current distortions as specified in IEEE 519-1992 standard are shown in Tables 1 and 2 respectively.

Table 1: Voltage distortion limits [34]

Bus Voltage at PCC	Individual Voltage Distribution (%)	Total Voltage Distortion THD (%)
69 kV and above	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

Table 2: Current distortion limits [34]

Maximum Harmonic Current Distribution in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	< 11	$11 \le h \le 17$	$17 \le h \le 23$	$23 \le h \le 35$	$35 \le h$	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Where I_{SC} is the maximum short circuit current at the point of common coupling (PCC), I_L is the maximum demand load current (fundamental frequency component) at PCC, h is the harmonic order and TDD is the total root-sum-square harmonic current distortion in percent of the maximum demand load current (15 or 30 min demand).

3.8 Modelling of the Test System

The 7-Up Industry Plc power network used as the test system in this work was modelled using MATLAB/Simulink software version 2015a for easy interaction and manipulation. 7-Up is a bottling company located at Oluyole Industrial Estate Ibadan, Nigeria. The company is fed from a dedicated line of 33 kV which is stepped down to 11/0.415 kV through a

33 MVA power transformer. The company is backed up by four generators, each of 500 kVA rating. The layout of 7-Up Industry Plc power network is shown in Figure 7 while the power requirements of major important loads are presented in Table 3. The Simulink models of 7-Up Industry Plc power network without and with filters are presented in Figures 8 to 13.

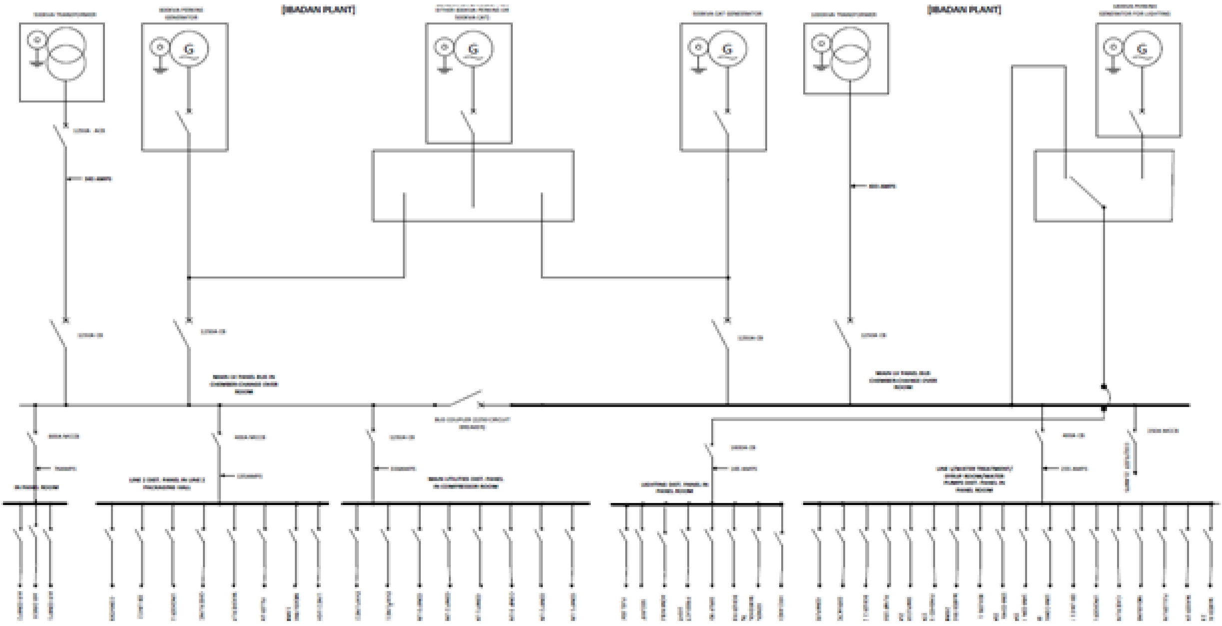


Figure 7: The layout of power network of 7-Up Industry Plc

Table 3: Power requirements of 7-Up Industry loads

Loads	Apparent Power S (kVA)	Active Power P (kW)	Reactive Power Q (kVar)
Panel	30.70	25.18	18.43
Packaging Hall	56.03	45.14	33.61
Compressor Room	140.27	115.02	84.16
Panel Room I	68.48	56.15	41.09
Panel Room II	106.24	87.10	63.74

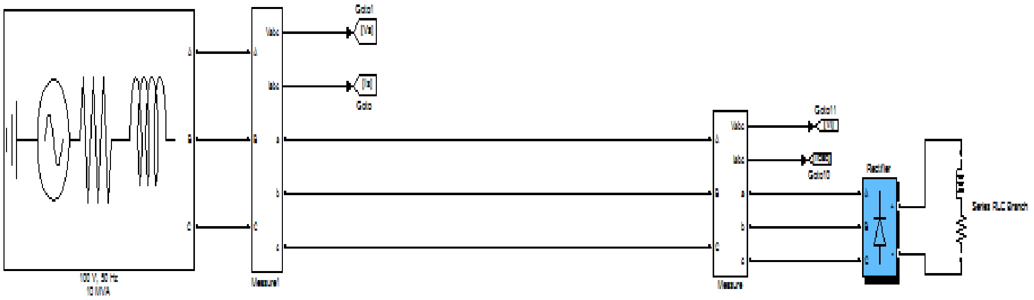


Figure 8: Simulink model of the 7-Up power network without filter

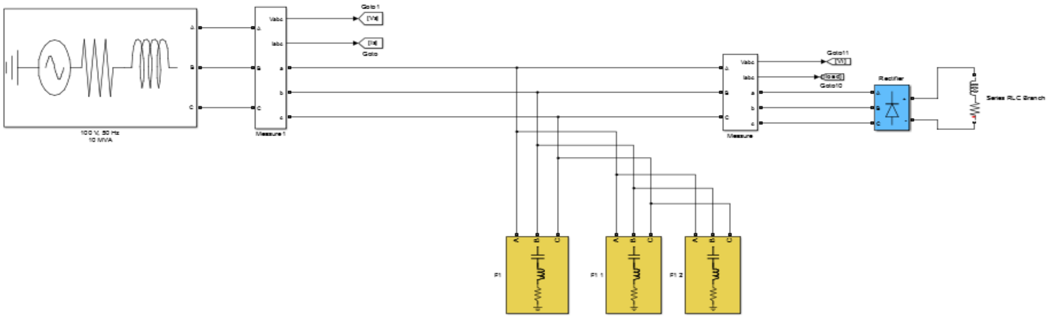


Figure 9: Simulink model of the 7-Up power network with shunt passive power filter

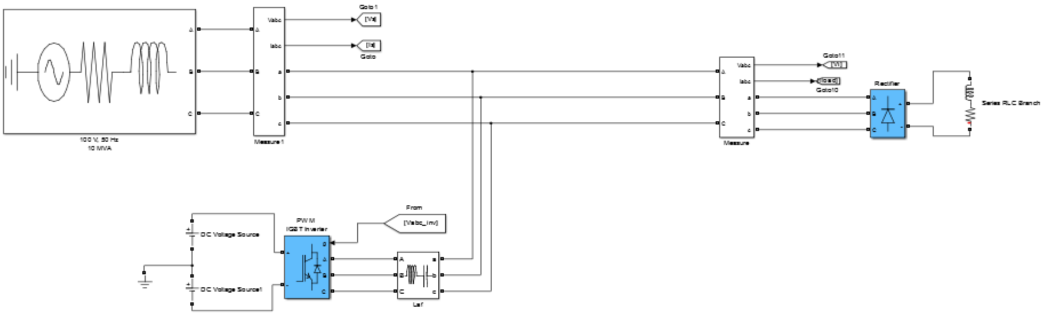


Figure 10: Simulink model of the 7-Up power network with series active power filter

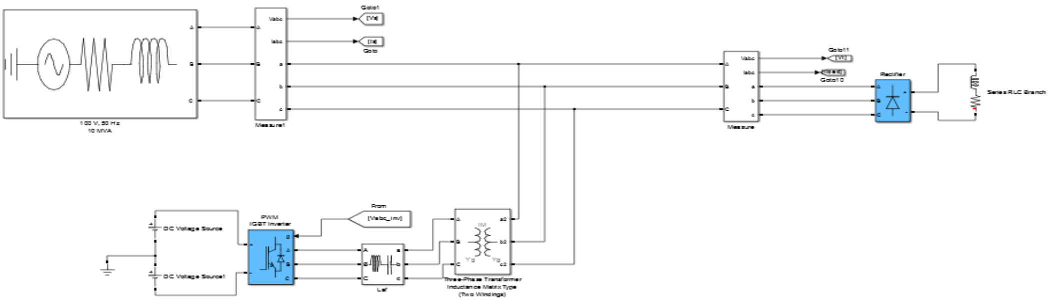


Figure 11: Simulink model of the 7-Up power network with shunt active power filter

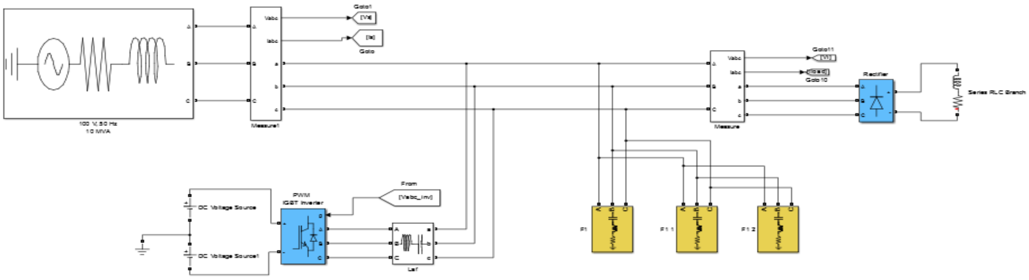


Figure 12: Simulink model of the 7-Up power network series active and passive shunt power filters

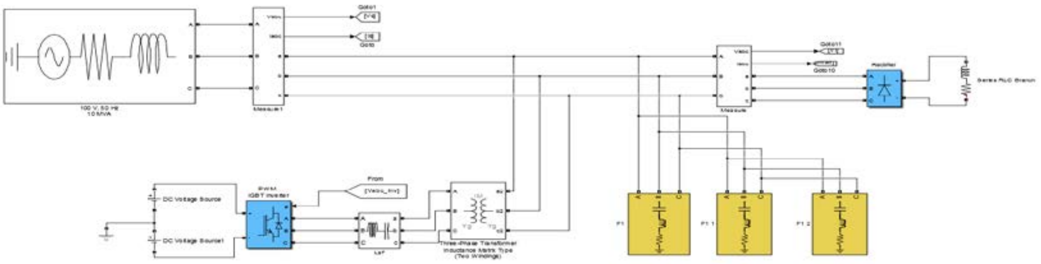
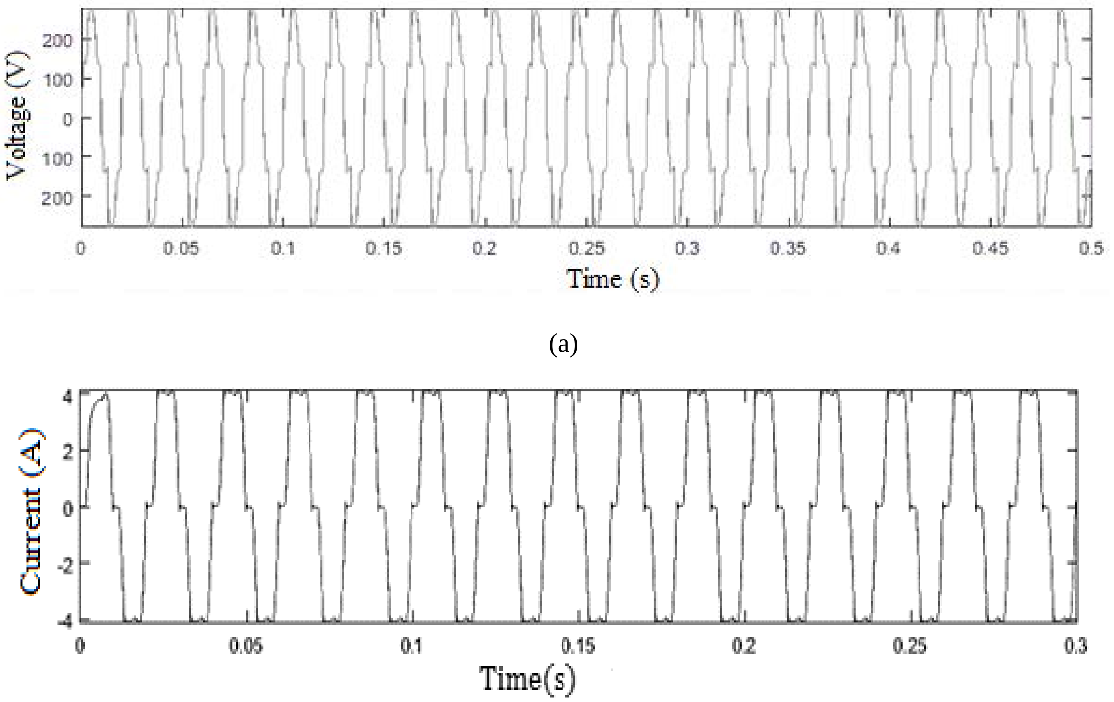


Figure 13: Simulink model of the 7-Up power network with shunt active and shunt passive power filters

4. SIMULATION RESULTS AND DISCUSSION

4.1 Simulation Result of 7-Up Industry Power Network without Filter

The results obtained from simulation of 7-Up Industry power network in MATLAB/Simulink environment without any filter applied are presented in Figures 14 to 16.



(a)

(b)

Figure 14: (a) Voltage waveform of 7-Up Industry power network without filter (b) Current waveform of 7-Up Industry power network without filter

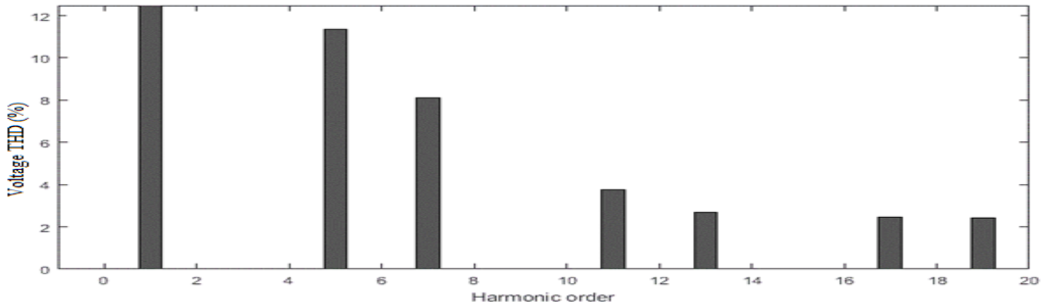
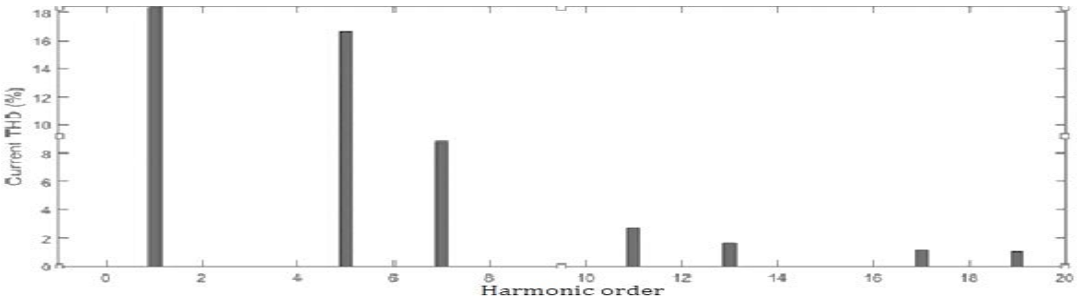


Figure 15: Voltage harmonic spectrum of 7-Up Industry power network without filter



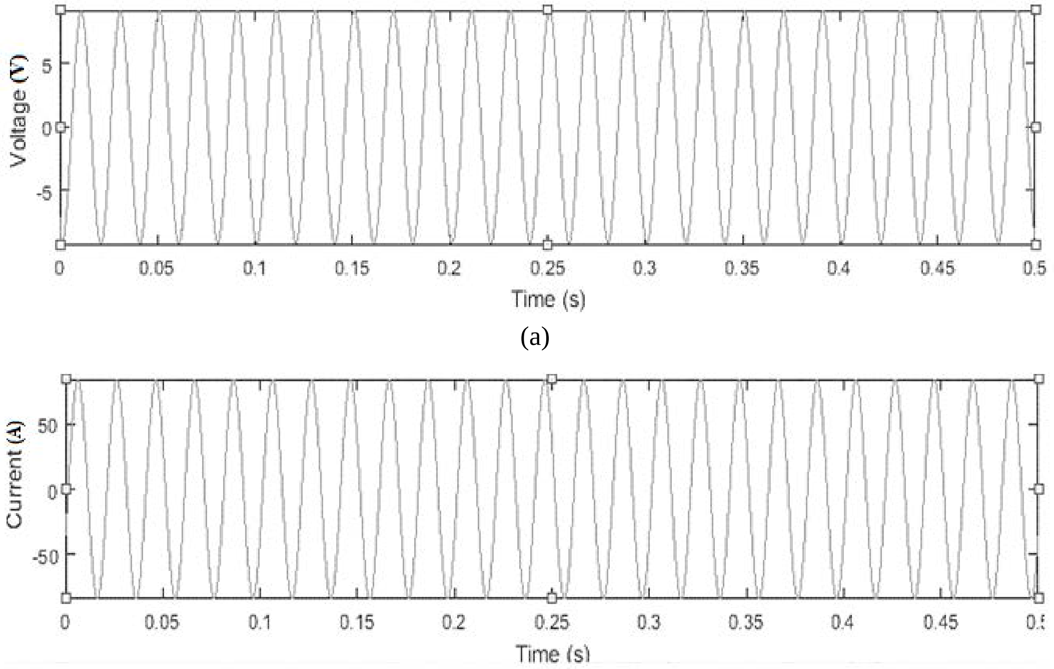
(b)

Figure 16: Current harmonic spectrum of 7-Up Industry power network without filter

The results in Figure 14 showed that the voltage and current waveforms of 7-Up Industry electricity supply system were distorted. This implies the presence of harmonics in 7-Up Industry power system network. Figures 15 and 16 are respectively voltage and current harmonic spectra of 7-Up Industry power network. From Figure 15, the highest individual voltage harmonic distortion was obtained from 5th order harmonic with an approximate value of 14.50%, followed respectively by 7th, 11th, 13th harmonic order etc. while taking into account that harmonic at fundamental frequency (harmonic of order 1) has no negative consequence on the electricity supply system. The voltage THD using equation (20) was evaluated as 16.93%. The highest individual current harmonic distortion as observed from Figure 16 was also obtained from 5th order harmonic with approximate value of 16.90%, followed respectively by 7th, 11th, 13th harmonic order etc. The current THD using equation (22) was evaluated as 19.25%.

4.2 *Simulation Result of 7-Up Industry Power Network with Shunt Passive Power Filter*

The results obtained when 7-Up Industry power network was simulated with shunt passive power filter are presented in Figures 17 to 19.



(a)

(b)

Figure 17: (a) Voltage waveform of 7-Up Industry power network with shunt passive power filter (b) Current waveform of 7-Up Industry power network with shunt passive power filter

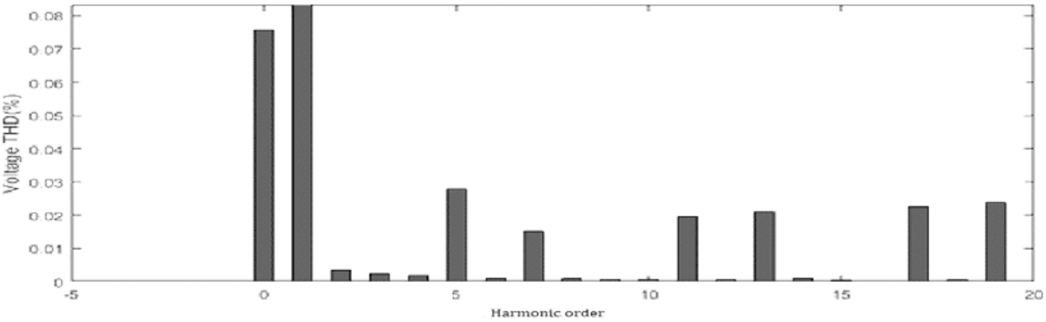


Figure 18: Voltage harmonic spectrum of 7-Up Industry power network with shunt passive power filter

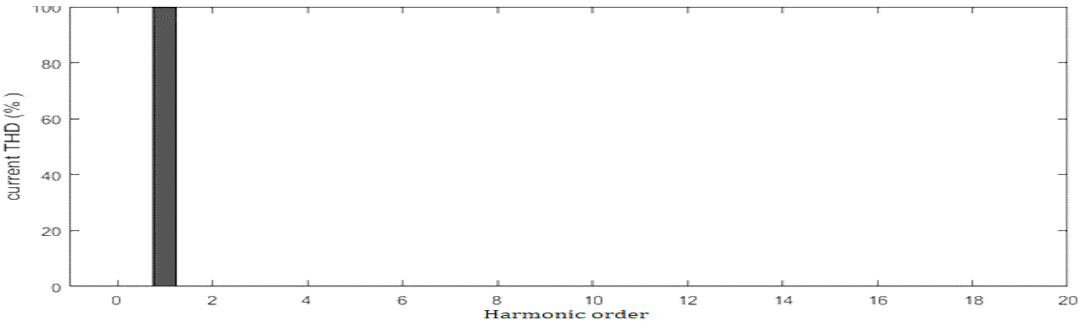
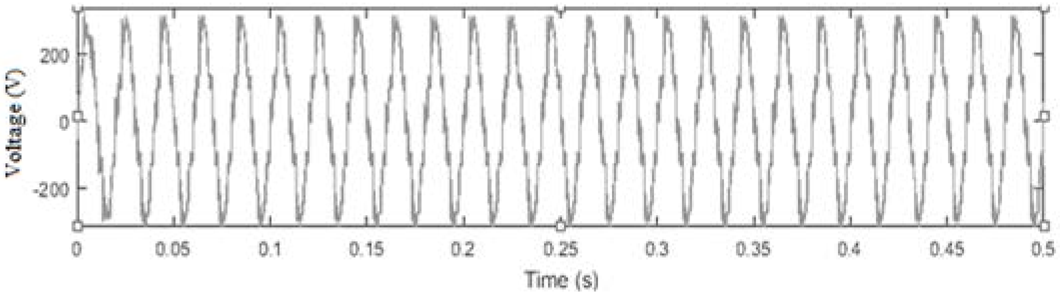


Figure 19: Current harmonic spectrum of 7-Up Industry power network with shunt passive power filter

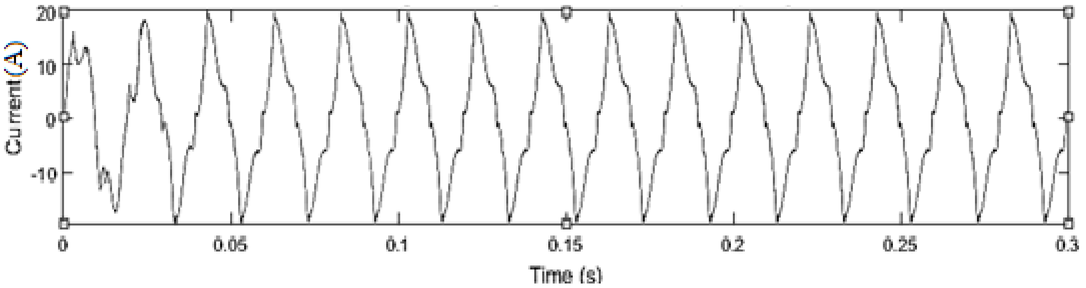
From Figure 17, the voltage and current waveforms appeared distortionless. Using equation (20), the THD for voltage from Figure 18 was 0.20%, showing that the employed filter was able to remove about 16.73% voltage distortion from the system when compared to that from Figure 15. As observed from Figure 19, the current THD was zero (0.00%). This indicates that the used filter was able to mitigate all the harmonics present in the current waveform, making it distortionless.

4.3 Simulation Result of 7-Up Industry Power Network with Series Active Power Filter

The simulation results of application of series active power filter on the 7-Up Industry power network are shown in Figures 20 to 22. Figure 20 showed that substantial amount of harmonic distortion still exists in the voltage and current waveforms despite the application of series active power filter. The voltage THD using equation (20) was estimated as 15.67%, giving 1.26% reduction in voltage distortion when compared with that from Figure 15. Equally, the THD for current was estimated as 18.97% using equation (22) and this produced 0.28% reduction in current distortion in 7-Up power network when compared with Figure 16.



(a)



(b)

Figure 20: (a) Voltage waveform of 7-Up Industry power network with series active power filter (b) Current waveform of 7-Up Industry power network with series active power filter

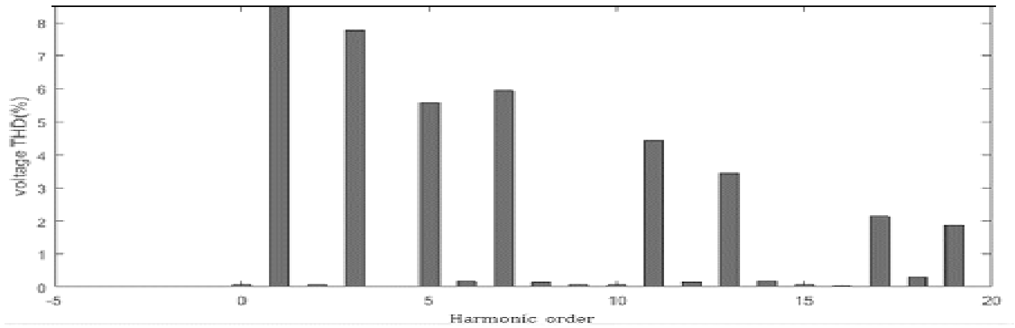


Figure 21: Voltage harmonic spectrum of 7-Up Industry power network with series active power filter

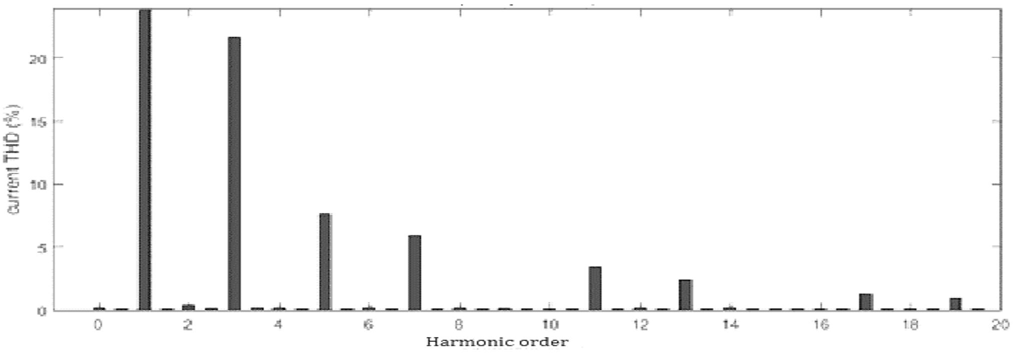
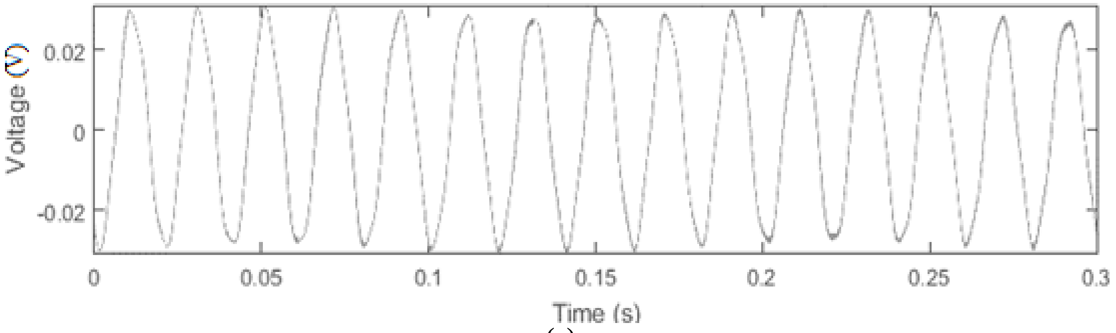


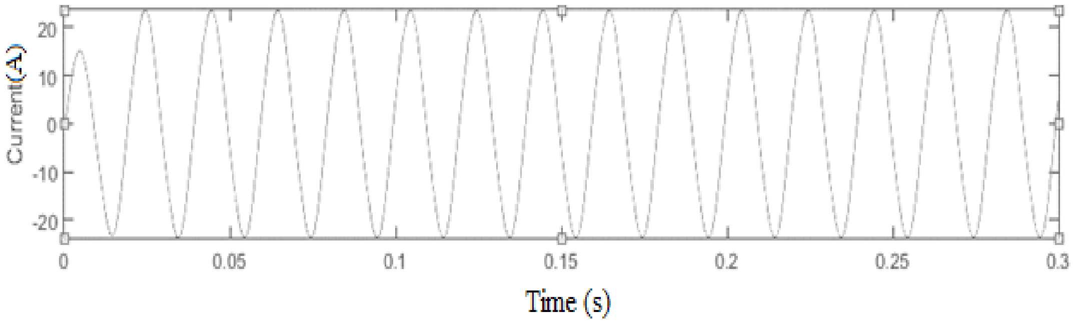
Figure 22: Current harmonic spectrum of 7-Up Industry power network with series active power filter

4.4 *Simulation Result of 7-Up Industry Power Network with Shunt Active Power Filter*

Figures 23 to 25 show the simulation results of application of shunt active power filter on the 7-Up Industry power network. As observed from Figure 23, the voltage distortion in the voltage waveform and current distortion in the current waveform had appreciably reduced. The estimated THD for voltage from Figure 24 using equation (20) was 5.50%, giving a percent reduction of 11.43% when compared with Figure 15. The current THD from Figure (25) using equation (22) was evaluated as 2.8%, which when compared with that from Figure 16 gave a percent reduction 16.45% in current distortion.



(a)



(b)

Figure 23: (a) Voltage waveform of 7-Up Industry power network with shunt active power filter (b) Current waveform of 7-Up Industry power network with shunt active power filter

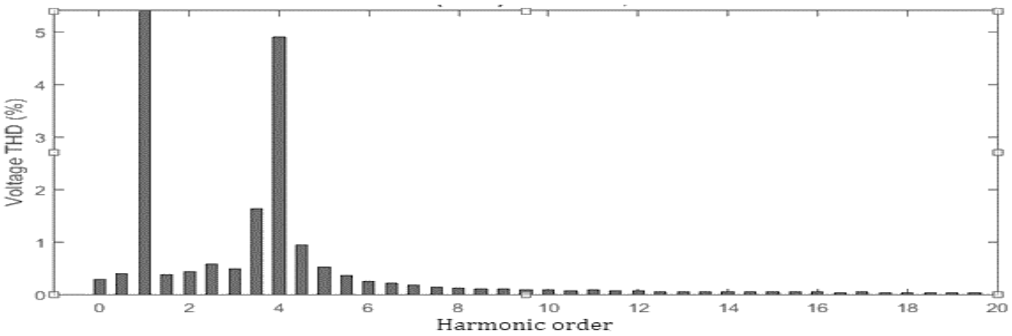


Figure 24: Voltage harmonic spectrum of 7-Up Industry power network with shunt active power filter

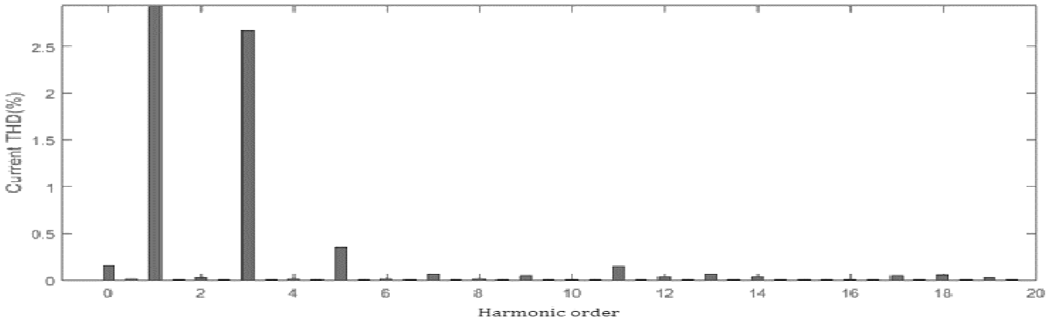
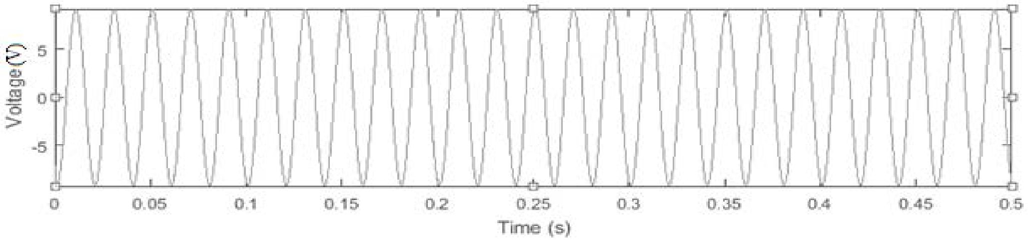


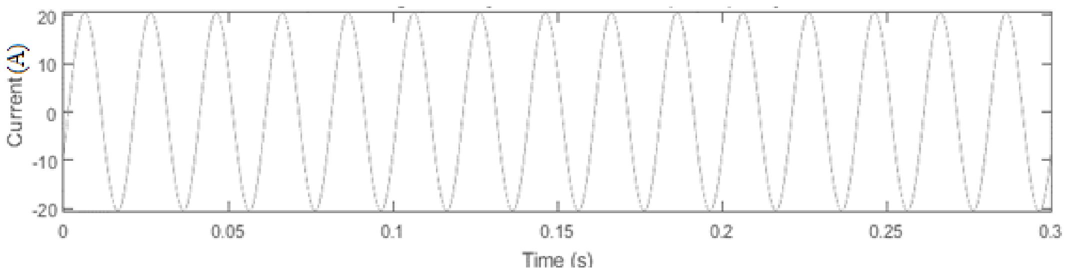
Figure 25: Current harmonic spectrum of 7-Up Industry power network with shunt active power filter

4.5 *Simulation Result of 7-Up Industry Power Network with Series Active Power Filter and Shunt Passive Power Filter*

The simulation results of 7-Up Industry power network with hybrid combination of series active power filter and shunt passive power filter are shown in Figures 26 to 28. Figure 26 showed that voltage and current waveforms were approximately distortionless. The voltage THD as calculated from Figure 27 using equation (20) was 0.20% which yielded 16.73% reduction in voltage distortion when compared with Figure 15. Similarly, an estimate of current THD from Figure 28 using equation (22) gave 0.11% and this produced a percent reduction of 19.14% in current distortion when compared with Figure 16.



(a)



(b)

Figure 26: (a) Voltage waveform of 7-Up Industry power network with series active power filter and shunt passive power filter (b) Current waveform of 7-Up Industry power network with series active power filter and shunt passive power filter

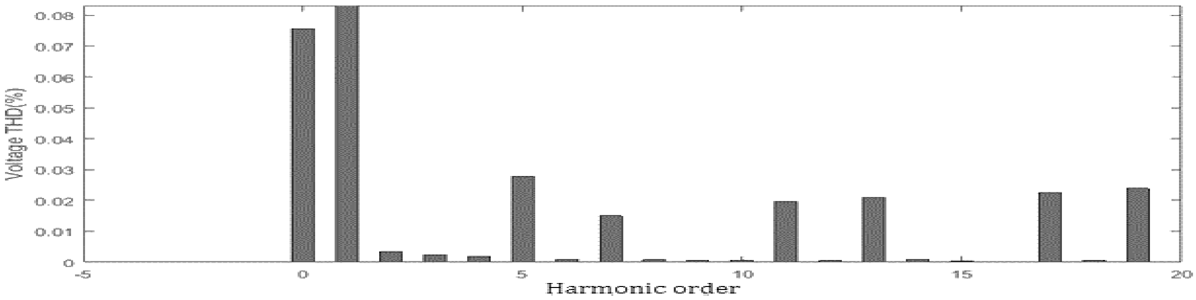


Figure 27: Voltage harmonic spectrum of 7-Up Industry power network with series active power filter and shunt passive power filter

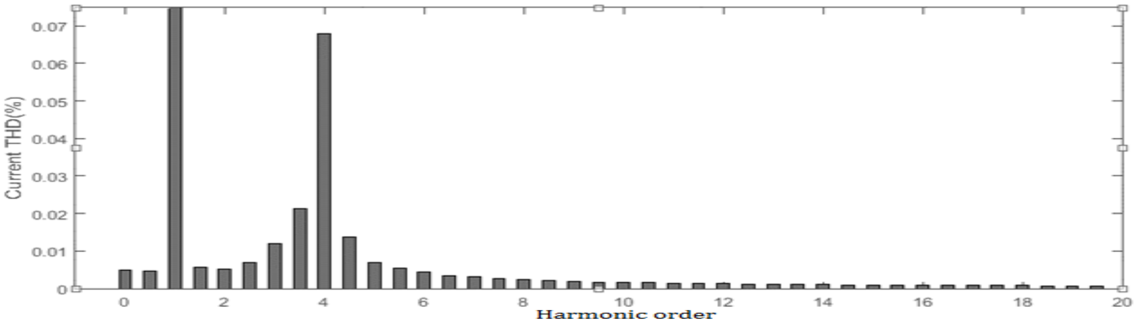
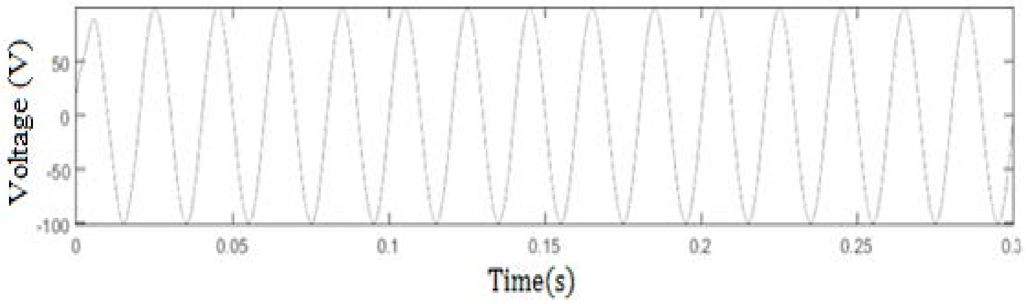


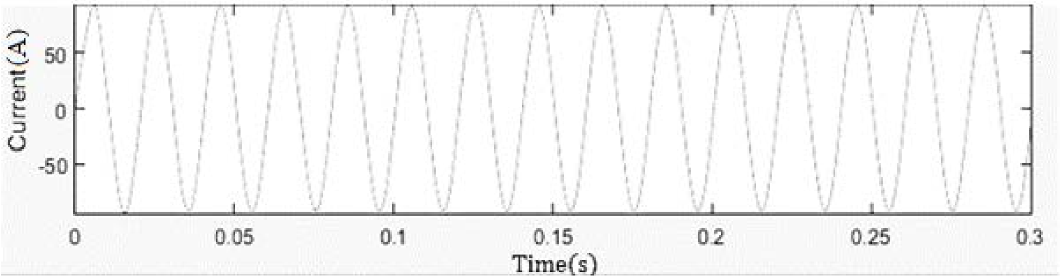
Figure 28: Current harmonic spectrum of 7-Up Industry power network with series active power filter and shunt passive power filter

4.6 *Simulation Result of 7-Up Industry Power Network with Shunt Active Power Filter and Shunt Passive Power Filter*

The obtained results when 7-Up Industry power network was simulated with hybrid combination of shunt active power filter and shunt passive power filter are presented in Figures 29 to 31. Figure 29 revealed that voltage and current waveforms were distortionless. The THD for voltage as calculated from Figure 30 using equation (20) was 0.07% which gave 16.86% reduction in voltage distortion when compared with Figure 15. Also, current THD estimated from Figure 31 using equation (22) resulted in 0.43%, giving a percent reduction of 18.82% in current distortion when compared with Figure 16.



(a)



(b)

Figure 29: (a) Voltage waveform of 7-Up Industry power network with shunt active power filter and shunt passive power filter (b) Current waveform of 7-Up Industry power network with shunt active power filter and shunt passive power filter

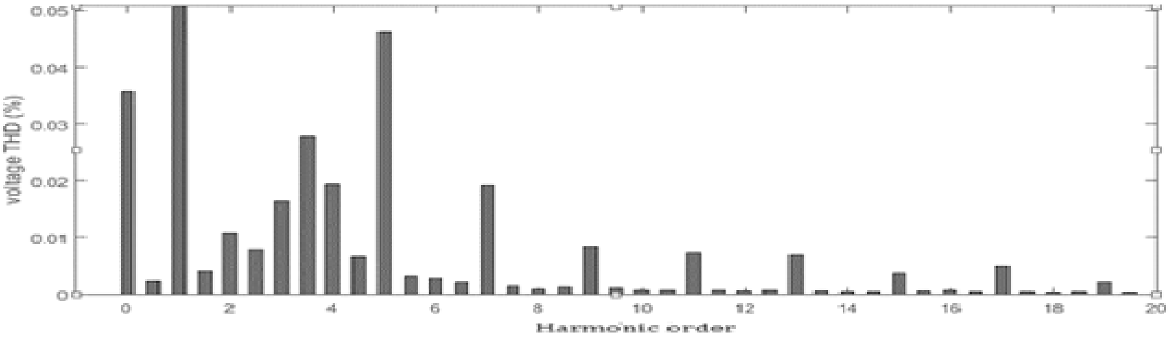


Figure 30: Voltage harmonic spectrum of 7-Up Industry power network with shunt active power filter and shunt passive power filter

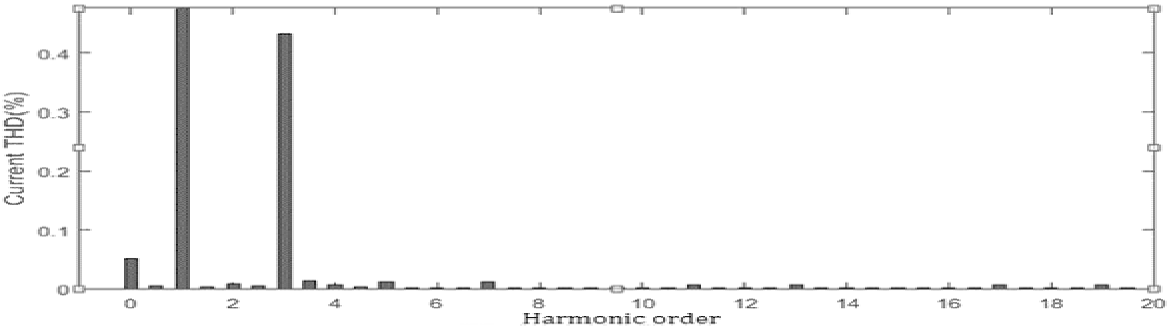


Figure 31: Current harmonic spectrum of 7-Up Industry power network with shunt active power filter and shunt passive power filter

4.7 Performance Analysis of Harmonic Power Filters Used on 7-Up Industry Power Network

The performance of the considered harmonic filters in this work on 7-Up Industry electricity supply network is summarised in Table 4.

From Table 4, it is evident that for the test network under consideration, the shunt passive power filter and hybrid combination of series active power filter and shunt passive power filter and shunt active power filter and shunt passive power filter were the efficient mitigation techniques for harmonic distortion on the network since the values of voltage and current total harmonic distortion were greatly reduced with the application of these filters. Although, series and shunt active filters also mitigated some harmonics on the test network, but the total harmonic distortion in terms of the voltage and current removed by these filters was not substantial as one would expect since they are improved technologies over the passive filter. Hence, when used alone separately as considered for the 7-Up Industry power network in this work, series and shunt active power filters were less efficient solution for harmonic distortion on the test network. However, as assessed by this work, series and shunt active power filters formed effective mitigation solutions for harmonic distortions when deployed in hybrid configurations with the shunt passive filter.

Table 4: Performance of Harmonic Power Filters Used on 7-Up Industry Power Network

Performance Index	THD Before Compensation (%)	THD After Compensation (%)				
		Shunt Passive Filter	Series Active Filter	Shunt Active Filter	Series Active Filter and Shunt Passive Filter	Shunt Active Filter and Shunt Passive Filter
V_{THD}	16.93	0.20	15.67	5.50	0.20	0.07
I_{THD}	19.25	0.00	18.97	11.43	0.11	0.43

5. CONCLUSION

The existence of harmonics in any electricity supply system can pose great threats to successful and efficient performance of such system, hence, causing a major power quality problem. The performance of shunt passive filter, series and shunt active filters and hybrid combination of series active filter and shunt passive filter and shunt active filter and shunt passive filter in mitigating harmonic distortions arising from the proliferation of non-linear loads in industrial electrical system was assessed in this work using the 7-Up Industry Plc power network in Nigeria as a case study. The results obtained revealed that without compensation, voltage and current waveforms of 7-Up Industry electricity supply system suffer from harmonics with the voltage and current THD respectively estimated as 16.93% and 19.25%. Harmonic compensation on the test system with shunt passive filter reduced THD for voltage and current to 0.20% and 0.00% respectively. The series and shunt active filters separately used alone on the test network mitigated the voltage and current THD to 15.67% and 18.97% respectively for the series filter and 5.50% and 11.43% respectively for the shunt filter. Hybrid combination of series active filter and shunt passive filter mitigated the THD for voltage and current to 0.20% and 0.11% respectively whereas the voltage and current THD were respectively 0.07% and 0.43% using the hybrid combination of shunt active filter and shunt passive filter. Hence, for the 7-Up Industry power network considered in this research work, shunt passive filter and hybrid combinations of series active filter and shunt passive filter and shunt active filter and shunt passive filter were the better mitigation solutions for harmonic distortions on the test network while the series and shunt active filters were less efficient for mitigating harmonic distortion on the network.

REFERENCES

[1] Ewald, F.F., and Mohammad, A. (2008). Power Quality in Power Systems and Electrical Machines. Elsevier Academic Press.

[2] Suriadi, S. M. (2006). Analysis of Harmonics Current Minimization on Power Distribution System Using Voltage Phase Shifting Concept. M.Sc. Dissertation, Universiti Sains Malaysia.

[3] Zbigniew, H., and Jovica, V.M. (2008) in: Strzelecki, R., and Benysek, G. Principle of Electrical Power Control. Springer. The University of Manchester, U.K. 13-54.

[4] João, A., Carlos, C., and Julio, M. (2000). Active Filters with Control Based on P-Q Theory. IEEE Industrial Electronics Society Newsletter. 47(3): 5-10.

[5] Isorkorpi, J., Keikko, T., and Korppinen, L. (1999). Power Frequency Electric and Magnetic Fields at 110/20 KV Substation. IEEE International Conference on Electric Power Engineering, Budapest, Hungary, August 29-September 2, 169.

[6] Adejumobi, I.A., Adebisi, O.I. and Amatu, J.E. (2017). Harmonics Mitigation on Industrial Load Using Series and Parallel Resonant Filters. Nigerian Journal of Technology, 36 (2): 611-620.

[7] Meera, S.N. and Deepa, S. (2015). A Review of Hybrid Filter Topologies for Power Quality Compensation. Inteernational Research Journal of Engineering and Technology, 2 (4): 613-621.

[8] Daniel, O.J. and Kabiru, A.H. (2016). Issues of Power Quality in Electrical Systems. International Journal of Energy and Power Engineering, 5 (4): 148-154.

[9] Pawar, D.S. and Vadirajacharya, K. (2016). Series Active Power Filter for Mitigation of PQ Problems. International Conference on Recent Innovations in Science, Technology, Management and Environment, Indian Federation of United Nations Associations, New Delhi, India, June19, 130-137.

[10] Yamini, A. (2014). A Review on Power Quality Problems and Its Solution at Distribution End Using Different Interfacing Devices and Distributed Generation. International Journal of Emerging Trends in Engineering and Development, 4 (5): 373-382.

[11] Anurag, A., Sangiv, K. and Sajid, A. (2012). A Research Review of Power Quality Problem in Electrical Power System. MIT International Journal of Electrical and Instrumentation Engineering, 2 (2): 88-93.

[12] Patil, A.A., Katkar, R.N., Ajit, P.A., Vijay, C.P., Patil, P.P. and Patil, S.V. (2017). Harmonic Mitigation Using Passive Filter. International Journal of Engineering Trends and Technology, 45 (2): 83-86.

[13] Prasad, S.C. and Khatod, D.K. (2015). A Review on Selection and Usage of Modern Active Power Filter. International Journal of Engineering Trends and Technology, 20 (2): 109-114.

[14] Kavita, D. and Pawan, C.T. (2014). Harmonic Reduction by Using Shunt Hybrid Power Filter. International Journal of Computational Hybrid Power Filter, 4 (5): 41-49.

[15] Anooja, C.L. and Leena, N. (2013). Passive Filter for Harmonic Mitigation of Power Diode Rectifier and SCR Rectifier Fed Loads. International Journal of Scientific and Engineering Research, 4 (6): 1615-1621.

[16] Kuldeep, K.S., Saquid, S. and Anand, V.P. (2013). Harmonics and Its Mitigation Techniques by Passive

Shunt Filter. International Journal of Soft Computing and Engineering, India, 3(2): 325-331.

[17] Erwin, N. (2012). Mitigation of Harmonics in a Three-Phase Four Wire Distribution System Using a System of Shunt Passive Filters. International Journal of Engineering and Technology, 2 (5): 761-774.

[18] Mishra, K.K. and Gupta, R. (2011). Load Compensation for Single Phase System Using Series Active Filter. International Journal of Engineering, Science and Technology, 3 (3): 83-93.

[19] Das, J.C. (2004). Passive Filters-Potentialities and Limitations. IEEE Transactions on Industry Applications, 40 (1): 232-241.

[20] Kumar, B.S. and Reddy, K.R. (2002). The Application of Particle Swamp Optimisation to Hybrid Active Power Filter Design for 3 Phase, 4 Wire System with Variable Load. International Journal of Engineering Inventions, 1 (4): 39-46.

[21] Fujita, H., Yamasuki, T. and Akagi, H. (2000). A Hybrid Active Filter for Damping of Harmonic Resonance in Industrial Power System. IEEE Transaction in Power Electronics, 15 (2): 215-222.

[22] Singh, B., Al-Haddad, K. and Chandra, A. (1999). A Review of Active Filters for Power Quality Improvement. IEEE Transaction on Industrial Electronics, 46 (5): 960-970.

[23] Fujita, H. and Akagi, H. (1991) “A Practical Approach to Harmonic Compensation in Power Systems: Series Connection of Passive and Active Filters. IEEE Transaction on Industry Application, 27 (6): 1020–1025.

[24] Memon, Z.A, Uquaili, M.A. and Una, M.A. (2015). Harmonics Mitigation of Industrial Power System Using Passive Filters. Mehran University Research Journal of Engineering and Technology, 31 (2): 355-360.

[25] Mandeep, S. and Sheila, M. (2015). Implementation of Passive Filters for Harmonic Reduction. International Journal of Advanced Science and Technology, 78: 1-2.

[26] Bafila, P. (2015). Power Quality Improvement Using Passive Shunt Filter. International Journal of Enhanced Research in Science, Technology and Engineering, 4 (6): 371-378.

[27] Sahana, C.B. (2015). Study on Mitigation of Harmonics by Using Passive Filter and Active Filter. International Journal of Innovative Research in Computer and Communication Engineering, 3 (5): 254-274.

[28] Agrawal, N. and Vardia, M. (2016). Harmonic Mitigation Techniques Using Shunt Active Power Filters. Journal of Environmental Science, Computer Science and Engineering and Technology, 5 (2): 187-193.

[29] Parmar, D.G. and Kumar, M.S. (2015). Comprehensive Review of a Study of Hybrid Filter. International Journal for Technological Research in Engineering, 2 (6): 516-520.

[30] Akagi, H. (1996). New Trends in Active Filters for Power Conditioning. IEEE Transaction on Industry Applications, 32 (6): 1312-1322.

[31] Gupta, S. and Gupta, P. (2013). Harmonics Mitigation Using Active Power Filter. International Journal of Advanced Computer Research, 3 (2): 116-120.

[32] Patel, M.D., Vaghamshi, A.L. and Kuavat, A.M. (2014). A Review of Harmonic Mitigation in Power System Using Hybrid Filter. Journal of Emerging Technologies and Innovative Research, 1 (6): 547-553.

[33] Tali, M., Obbadi, A., Elfajri, A. and Errami, Y. (2014). Passive Filter for Harmonic Mitigation in Standalone PV System for Nol Linear Load. Retrieved October 10, 2016 from https://www.researchgate.net

[34] IEEE Standard 519 (1992). IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.