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Original Research Article

Comparative Evaluation of Shunt Passive and Shunt Active Power Filters for Harmonic Mitigation in an Electrical Distribution Network

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ABSTRACT

This study evaluated and compared the performance of shunt passive filter (SPF) and shunt active filter (SAF) in mitigating harmonic distortion in an electrical distribution network of a typical bottling company, 7-Up Industry Plc in Ibadan, Nigeria. The distribution network layout was modelled and simulated with and without SPF and SAF in MATLAB/Simulink software environment. The voltage and current total harmonic distortions (V_{THD}) and (I_{THD}) were determined. The voltage and current waveforms of the network without filter were distorted indicating harmonics presence. The V_{THD} and I_{THD} under no filter condition were estimated as 6.084 and 19.790%, respectively. Application of SPF and SAF on the network minimised the V_{THD} from 6.084 to 0.7802 and 1.311%, giving an improvement of 5.304 and 4.773%, respectively in voltage harmonics minimization over the no filter condition. Similarly, I_{THD} was mitigated from 19.790 to 2.448 and 4.163% with the use of SPF and SAF on the network, producing an enhancement of 17.342 and 15.627%, respectively in current harmonics reduction compared to no filter case. This study established that shunt passive filter exhibited a superior performance over shunt active filter and hence, more appropriate for harmonics mitigation on 7-Up Industry Plc distribution network.

1. INTRODUCTION

Harmonic is a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency (Kiran *et al.,* 2011). Its causes voltage, current, and frequency to deviate from their statutory or tolerance limit, leading to a poor power quality of a power system network. Power quality is a set of electrical boundaries that allows equipment to function in its intended manner without significant loss of performance or life expectancy conditions that provides satisfactory operation (Sankaran, 2002). Specifically, power quality is defined as any problem manifested in voltage, current or frequency deviation which leads to damage or malfunctioning of the consumer equipment.

Power quality problems may be short duration voltage variation, long-duration voltage variations, transient disturbances, voltage notching, voltage flickers and harmonic distortions (Mikkili and Panda, 2016). With technological advancements and industrialization, power system with emphasis on distribution network predominantly comprises non-linear loads that draw harmonic current from alternating current source (Yogita and Shaikh, 2013). The proliferation of these loads has resulted in an increase in harmonic distortion that disrupts optimum operating state of the power distribution system (Baggini, 2008). Harmonic distortion is commonly generated by non-linear loads such as computers, adjustable speed drives, high voltage direct current transmission, electric traction, magnetic core equipment including transformers, electric motors, generators among others (Das, 2002). Due to the effects such as equipment maloperation, damage, overheating and high losses caused by harmonic distortion, there is the need to put in place measures to minimize the negative impacts of harmonics in power system networks.

According to the literature, a series of techniques have been deployed to mitigate harmonics in power networks occasioned by the proliferation of non-linear loads (Zooba, 2006; Kanade and Chaoudhari, 2016; Ghulbet, 2017; Yuehui *et al.,* 2019; Jafrodi *et al.*, 2020). These include the use of phase-shifting loads, power filters such as active, passive and hybrid filters and space vector modulation. Among these highlighted techniques, harmonic compensation using filters shows a very promising result (Wu *et al.*, 2012; Adejumobi, *et al.*, 2017; Das, 2018; Neelima *et al.,* 2020). Harmonic filters are applied to either eliminate or attenuate harmonic distortions caused by non-linear loads, so that harmonic current or voltage source will not unduly interfere with the power system (Sankaran, 2002).

Therefore, the goal of this study was to evaluate and compare the performance of SPF and SAF for harmonics mitigation in an electrical distribution network considering the power network layout of a typical bottling company, 7-Up Industry Plc, as a case study. Shunt filters are useful devices for mitigating the impacts of harmonic distortion in power system networks. They are commonly deployed for filtering applications in power networks due to their low cost resulting from the smaller size requirements and potential to provide a path of low impedance for grounding currents on one or more harmonic frequencies (Kumar *et al.*, 2021).

2. MATERIALS AND METHODS

2.1. Harmonic Measures for Power Quality Analysis

One of the basic and important measures used for quantifying the penetration level of harmonics in power system networks is total harmonic distortion (THD). Voltage and current harmonic distortions (V_{THD} and I_{THD}) respectively measure the total deviation or variation in voltage and current at harmonic frequencies to the value at fundamental frequency and are expressed mathematically by the Equations (1) - (4) (Adebisi *et al.*, 2017; Adebisi *et al.*, 2021).

$$V_{THD} = \sqrt{\frac{\sum_{h=2}^{\infty} {V_h}^2}{{V_1}^2}} \times 100\% \tag{1}$$

$$V_{HD} = \frac{V_h}{V_1} \times 100\% \tag{2}$$

$$I_{THD} = \sqrt{\frac{\sum_{h=2}^{\infty} {I_h}^2}{{I_1}^2}} \times 100\% \tag{3}$$

$$I_{HD} = \frac{I_h}{I_1} \times 100\% \tag{4}$$

Where V_h, I_h, V_1, I_1, V_{HD} and I_{HD} respectively represent rms value of harmonic component h of voltage, rms value of harmonic component h of current, harmonic component of voltage at system fundamental frequency, harmonic component of current at system fundamental frequency, individual voltage harmonic distortion level and individual current harmonic distortion level.

2.2. Design of Passive Harmonic Filter

2.2.1. Single tuned passive filter

A single tuned passive filter (STPF) consists of an inductor and a capacitor in series. The schematic diagram of the filter is shown Figure 1. The resistance R in Figure 1 is the intrinsic resistance of the series reactor sometimes used to prevent the filter overheating. All harmonic currents whose frequency coincides with that of the tuned filter will find a low impedance path through the filter (De la Rosa, 2006).

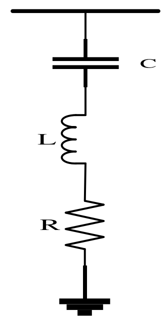

Figure 1: Schematic diagram of a STPF

The components' values of the filter are determined from Equations (5) and (6).

$$C = \frac{Q}{2\pi f V^2} \tag{5}$$

$$L = \frac{1}{(2\pi f)^2 C} \tag{6}$$

Where C, L, Q, V and f respectively denote capacitance, inductance, reactive power generated by the filter at fundamental frequency, voltage level at which filter is installed and fundamental frequency.

The impedance, Z, of a STPF is given by Equation (7).

$$Z = R + j(X_L - X_C) \tag{7}$$

Where X_L and X_C are the filter's inductive and capacitive reactances expressed by Equations (8) and (9) respectively.

$$X_L = j\omega L \tag{8}$$

$$X_C = \frac{1}{j\omega c} \tag{9}$$

with ω as the angular frequency.

Since inductive and capacitive reactances of a STPF are equal at resonant frequency, Equation (10) is obtained.

$$\omega_n = \sqrt{\frac{L}{C}} \tag{10}$$

Where ω_n is the tuned angular frequency and n is the index of tuning given by Equation (11).

$$n = {}^{f_n}/_{f} \tag{11}$$

with f_n as the filter's tuned frequency.

The resonant frequency, f_o, of a STPF is given by Equation (12) while the quality factor, Q, which determines the sharpness of the tuning reactance is expressed by Equation (13) (Das, 2018).

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{12}$$

$$Q = \frac{X_o}{R} = \frac{\sqrt{L/C}}{R} \tag{13}$$

Where X_o is the reactance of the inductor or capacitor at the tuned frequency

2.2.2. Double tuned filters

A double tuned filter (DTF) comprises a series connection of an inductor, L_1 and a capacitor, C_1 coupled in series with a parallel combination of an inductor, L_2 and a, capacitor, C_2 as presented in Figure 2. Figure 3 is a parallel STPF equivalent of Figure 2.

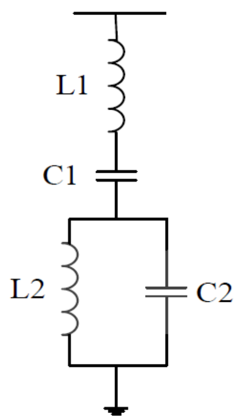

Figure 2: Double tuned filter

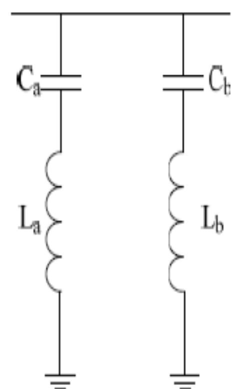

Figure 3: Parallel single tuned filter

The components' values in Figure 2 are determined from Equations (14) and (15) (Abood and Abdul-Wahhab 2021).

$$\omega_s = \frac{1}{\sqrt{L_1C_1}} \tag{14}$$

$$\omega_p = \frac{1}{\sqrt{L_2C_2}} \tag{15}$$

Where ω_s and ω_p are angular frequencies of the series and parallel resonant circuits respectively.

The angular frequencies ω_a and ω_b of the parallel filter circuits in Figure 3 are given by Equations (16) and (17) respectively.

$$\omega_a = \frac{1}{\sqrt{L_aC_a}} \tag{16}$$

$$\omega_b = \frac{1}{\sqrt{L_bC_b}} \tag{17}$$

Since the DTF and the parallel STPF are equivalent, Equation (18) is obtained.

$$\omega_a\omega_b = \omega_s\omega_p \tag{18}$$

The capacitance, C_1 and inductance, L_1 in Figure 2 are related to capacitances C_a and C_b and angular frequencies ω_a and ω_b in Figure 3 by Equations (19) and (20) respectively.

$$C_1 = C_a + C_b \tag{19}$$

$$L_1 = \frac{1}{C_a\omega_a^2 + C_b\omega_b^2} \tag{20}$$

The parameters L_2 and C_2 are calculated from Equations (21) and (22) respectively.

$$L_2 = \frac{\left(1-\frac{\omega_a^2}{\omega_s^2}\right)\left(1-\frac{\omega_a^2}{\omega_p^2}\right)}{C_1\omega_a^2} \tag{21}$$

$$C_2 = \frac{1}{L_2\omega_p^2} \tag{22}$$

2.3. Design of Shunt Active Filter Configuration

Figure 4 shows the shunt configuration of a single-phase active filter applied based on the injection of harmonic current equivalent to the distorted current waveform, therefore eliminating the original distorted current.

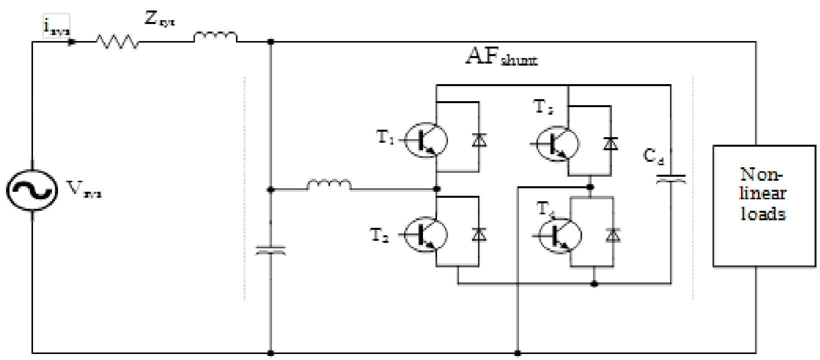

Figure 4: Shunt configuration of a single-phase active filter (Masoum and Fuchs, 2015)

To determine the compensation requirement imposed by the load, the power rating of the power converter used in shunt active power filter (SAPF) is determined from Equation (23) (Reddy *et al.,* 2020).

$$S_{SAPF} = \frac{\sqrt{(sin\emptyset_1)^2 + THD^2}}{\sqrt{1+THD^2}} S_{load} \tag{23}$$

Where $\emptyset_1$ is the minimum angle of the load power factor and THD is the maximum total harmonic distortion of the load currents.

If only harmonic compensation is required, the power rating of the SAPF is obtained from Equation (24).

$$S_{SAPF} = \frac{THD}{\sqrt{1+THD^2}} S_{load} \tag{24}$$

The design of the dc-link capacitor is achieved by computing the energy balance of the SAPF. Therefore, the active power injected into the SAPF system by the power converter is expressed as Equation (25).

$$P_{conv(t)} = P_s(t) - P_l(t) = \overline{P}_{conv} + \tilde{P}_{conv} \quad (25)$$

Where $\overline{P}_{conv}$ *and* $\tilde{P}_{conv}$ are the dc and ac components of $P_{conv(t)}$ respectively.

Considering that the converter power loss can be approximated by a constant term, the magnitude of P_{conv} is calculated from Equation (26).

$$\bar{p}_{conv} = \frac{1}{2}(V_s I_l - V_s I_{l(1)} cos\emptyset_1) \quad (26)$$

Where V_s, I_l, $I_{l(1)}$ and $cos\emptyset_1$ respectively are the r.m.s value of the grid voltage, the load current, the fundamental load current and the load power factor.

Therefore, the energy stored in the dc-link capacitor is obtained from Equation (27).

$$\frac{1}{2}c\Delta V_c^{\,2} = (\overline{P}_{conv} - P_{loss})\Delta t \quad (27)$$

The voltage ripple of the dc-link is expressed by Equation (27).

$$\Delta V_c = \sqrt{\left(\frac{V_s I_l - V_s I_{l(1)} Cos\emptyset_1 2ploss}{c}\right)\Delta t} \quad (28)$$

Equation (28) shows that the ripple of the dc-link voltage can be computed as a function of the energy stored in the capacitor. Based on this ripple, it is possible to design the capacitors of the dc-link. The filter's inductor is determined using similar principle.

2.4. Test Network

7-Up Industry Plc power distribution network was used as the test system in this study. 7-Up Industry Plc is a bottling company located at Oluyole Industrial Estate Ibadan, Oyo State, Nigeria. The company was fed from a dedicated 33 kV feeder which was stepped down to 11/0.415 kV through a 33 MVA rating power transformer. The company has a back-up consisting of four generators of 500 kVA rating each. The layout of the company's electrical distribution network is shown in Figure 5 while the power requirements of the major loads are presented in Table 1.

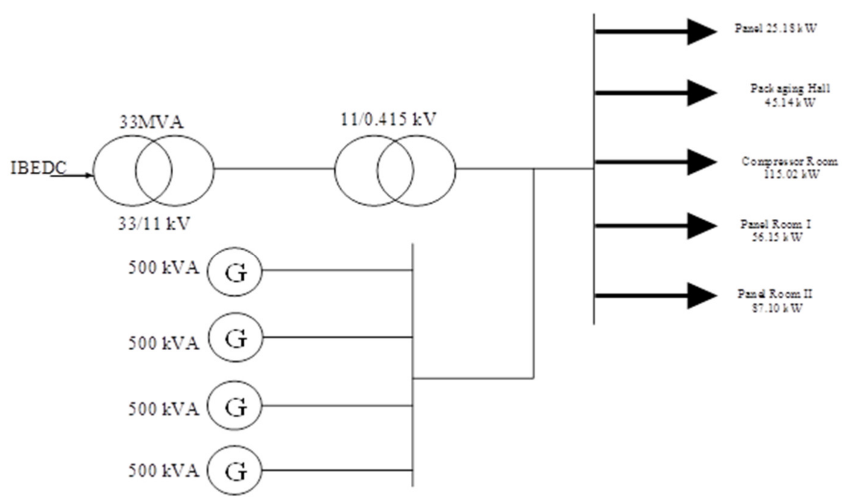

Figure 5: The power network layout of the 7-Up Industry Plc

Table 1: Power requirements of the 7-Up Industry Plc loads

Loads	Apparent power S(kVA)	Active power (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

2.5. Implementation Software

MATLAB/Simulink software was used as a simulation environment in the study. Simulink is a graphical programming environment for modeling and analyzing dynamical systems. It is interactive and provides an enabling environment to explore design concept to model non-linear system at any level of complexity. The Simulink model of the considered 7-Up Industry Plc power distribution network is shown in Figure 6.

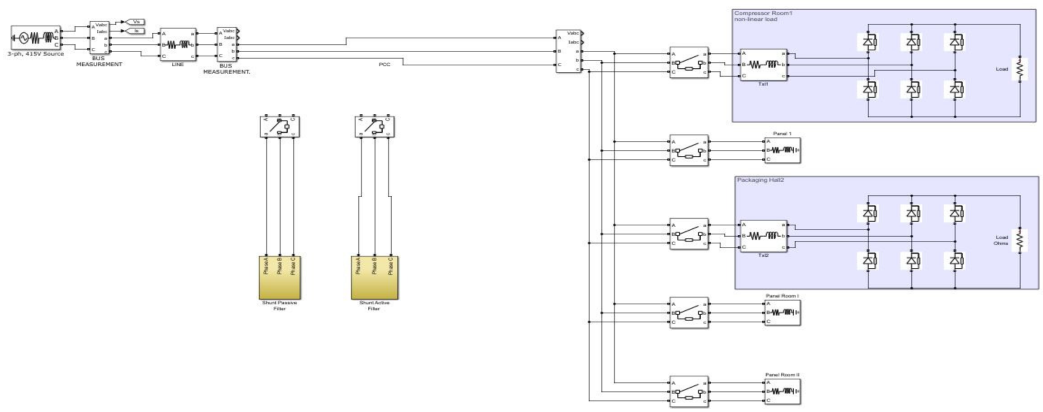

Figure 6: Simulink model of 7-Up Industry Plc power distribution network

3. RESULTS AND DISCUSSION

3.1. Simulation Results of the 7-Up Industry Plc Power Network without any Filter

The simulation results of the Simulink model of 7-Up Industry Plc power network layout in Figure 6 without any filter are presented in Figures 7 to 10. Figures 7 to 10 respectively show the voltage waveform, current waveform, voltage harmonic spectrum and current harmonic spectrum. Observing from Figures 7 and 8, the voltage and current waveforms of the 7-Up Industry Plc were distorted, showing the presence of harmonics. The V_{THD} and I_{THD} computed from Figures 9 and 10 were 6.084 and 19.790%, respectively.

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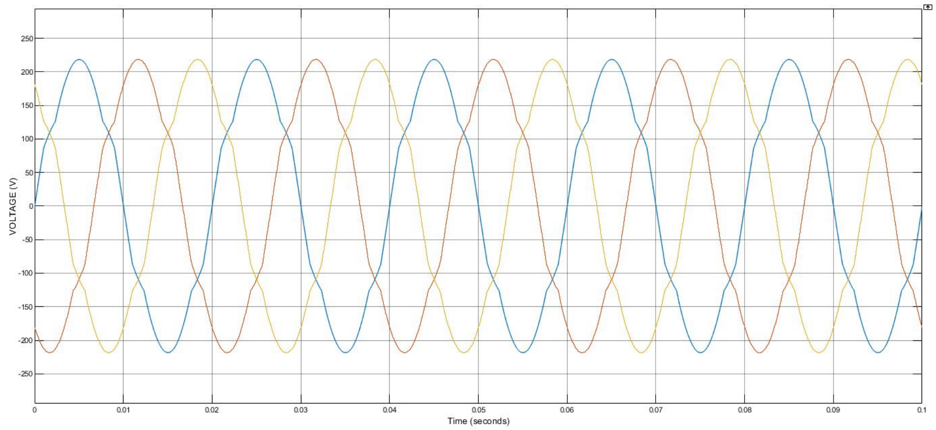

Figure 7: Voltage waveform of 7-Up Plc power distribution network without filter

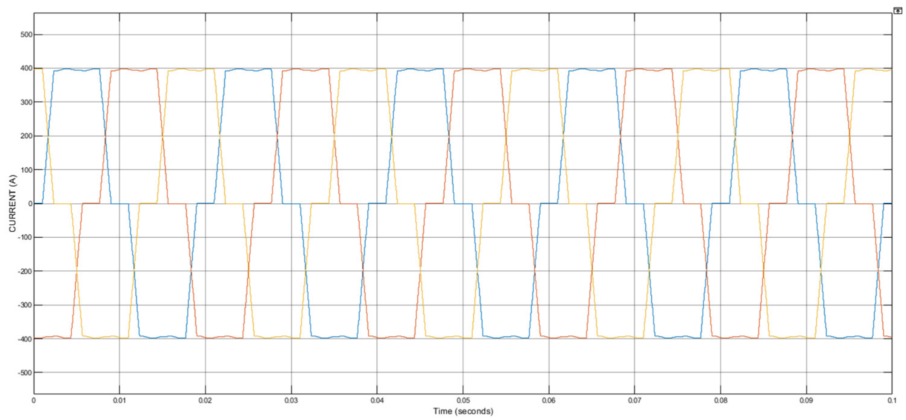

Figure 8: Current waveform of 7-Up Plc power distribution network without filter

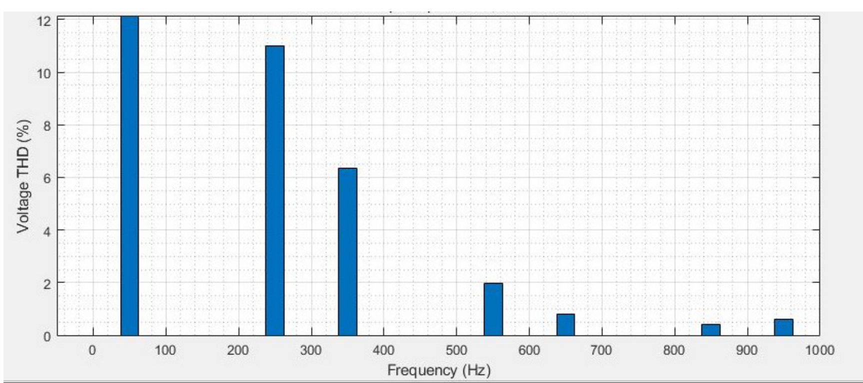

Figure 9: Voltage harmonic spectrum of 7-Up power distribution network without filter

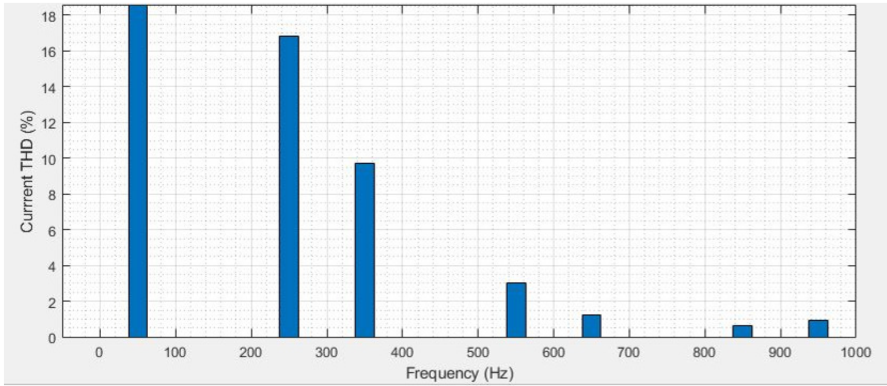

Figure 10: Current harmonic spectrum of 7-up power distribution network without filter

3.2. Simulation Results of 7-Up Industry Plc Power Network with SPF

The results obtained when the Simulink model of the 7-Up Industry Plc power distribution network in Figure 6 was simulated with SPF are presented in Figures 11 to 14. While Figures 11 and 12 respectively show the voltage and current waveforms, the voltage and current harmonic spectra are respectively presented in Figures 13 and 14. Figures 11 and 12 respectively revealed that there was a substantial reduction in the level of harmonic distortion present in the voltage and current waveforms of the considered network. The V_{THD} estimated from Figure 13 was 0.780%, giving a 5.304% reduction in voltage harmonic distortion compared with Figure 9, while the I_{THD} was evaluated as 2.448%, producing a reduction of 17.342% in current harmonic distortion when compared with Figure 10.

3.3. Simulation Results of 7-Up Industry Plc Power Network with SAF

The obtained results from the simulation of the Simulink model of the 7-Up Industry Plc power distribution network in Figure 6 with SAF are shown in Figures 15 to 18. Figures 15 and 16 show the respective voltage and current waveforms of the network during simulation whereas Figures 17 and 18 present the voltage and current harmonic spectra respectively.

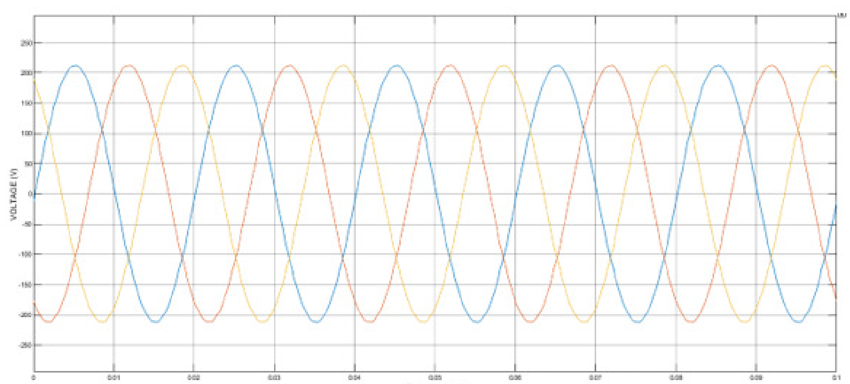

Figure 11: Voltage waveform of 7-Up Industry Plc power distribution network with SPF

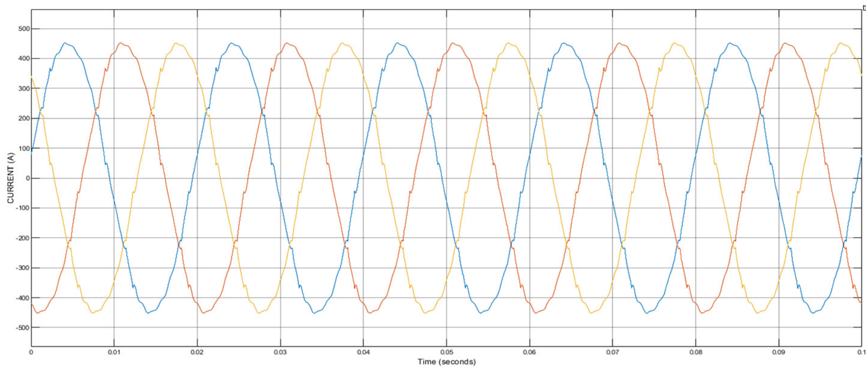

Figure 12: Current waveform of 7-Up Industry Plc power distribution network with SPF

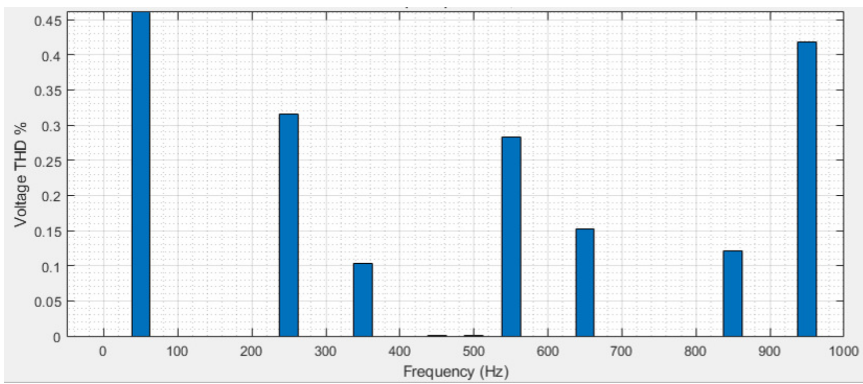

Figure 13**:** Voltage harmonic spectrum of 7-Up Industry Plc power distribution network with SPF

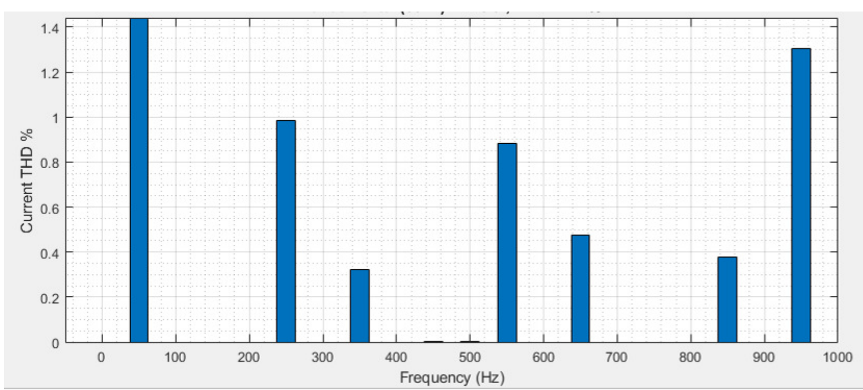

Figure 14: Current harmonic spectrum of 7-Up industry plc power distribution network with SPF

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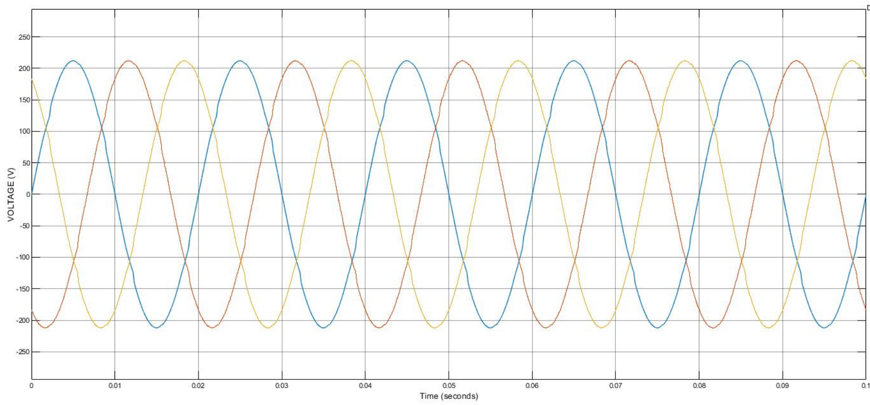

Figure 15: Voltage waveform of 7-Up industry plc power distribution network with SAF

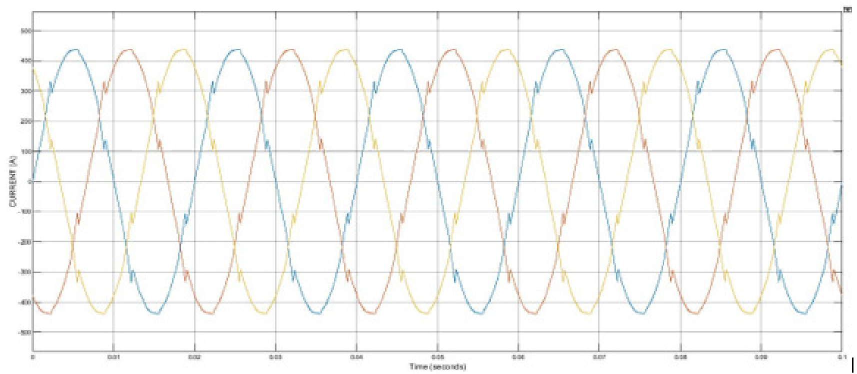

Figure 16: Current waveform of 7-Up industry plc power distribution network with SAF

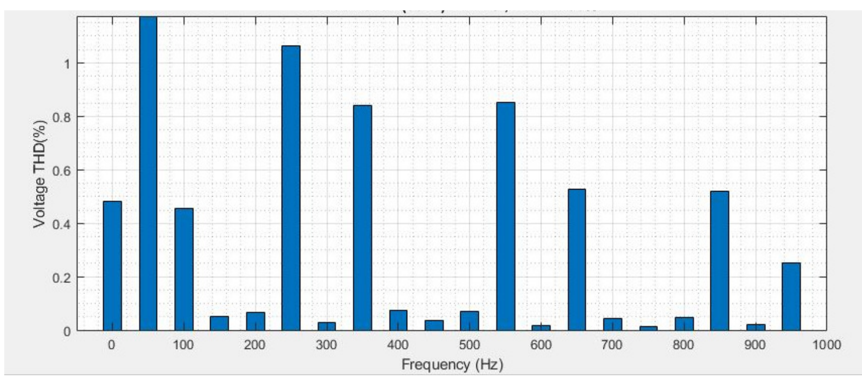

Figure 17**:** Voltage harmonic spectrum of 7-Up Industry plc power distribution network with SAF

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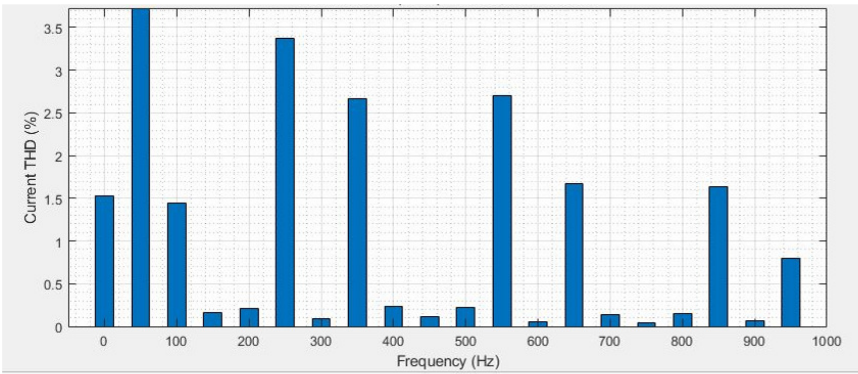

Figure 18**:** Current harmonic spectrum of 7-Up Industry plc power distribution network with SAF

Figures 15 and 16 revealed that there was an appreciable reduction in the amount of harmonic distortion present in the voltage and current waveforms of the 7-Up Industry Plc power network. The V_{THD} and I_{THD} as estimated from Figures 17 and 18 were 1.311 and 4.163 %, respectively. These values when compared with Figures 9 and 10 produced an improvement of 4.773 and 15.627 % in the voltage and current total harmonic distortion respectively.

The presence of harmonics in a power system network results in an unhealthy operation of the system. This study analysed the performance of two shunt filters namely SPF and SAF in mitigating harmonics in an electrical distribution network of the 7-Up Industry Plc, a typical bottling company for power quality improvement. Prior to the application of the filters, high penetration level of harmonics was observed on the network. The use of both SPF and SAF, however, mitigated the harmonic distortion in the network appreciably, however, to a varying degree. Figures 19 and 20 are bar charts showing the comparison of the V_{THD} and I_{THD} in the 7-Up Industry Plc electrical distribution network with and without SPF and SAF.

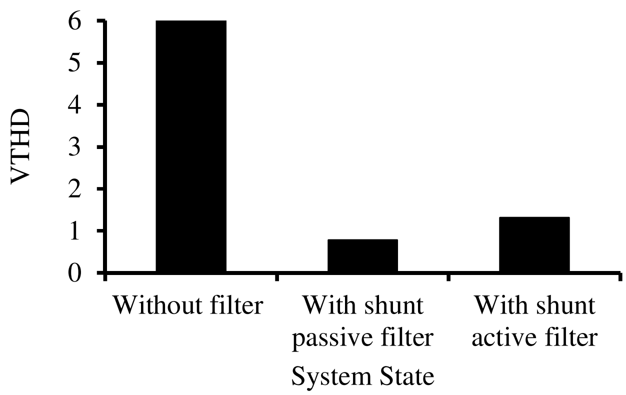

Figure 19: Comparison of voltage harmonic distortion mitigation of SPF and SAF

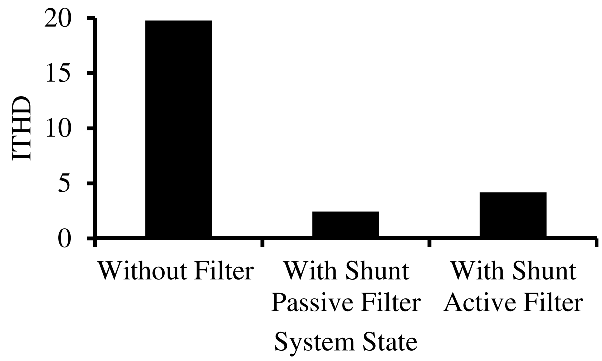

Figure 20: Comparison of current harmonic distortion mitigation of SPF and SAF

From Figures 19 and 20, the SPF was observed to exhibit a better performance in mitigating harmonic distortion in the network compared to the SAF. SPF mitigated the V_{THD} and I_{THD} from 6.084 and 19.790% to 0.780 and 2.448%, respectively. In contrast, SAF minimized V_{THD} and I_{THD} to 1.311 and 4.163%, respectively. These results are indications that SPF is a more appropriate harmonic mitigation approach for the considered 7-Up Industry Plc electrical distribution network than SAF since the voltage and current obtainable from the system after both filters were separately applied contain a lesser harmonic content with SPF compared to SAF. This may be attributed to the fact that SPFs are usually superior in efficiency when compared to SAFs (Peng et al., 1990). Hence, the more improved power quality observed in the distribution network with SPF over the SAF.

4. CONCLUSION

This study assessed the harmonic mitigation capability of shunt passive and shunt active filters on an electrical distribution network of a typical bottling company, 7-Up Industry Plc. High penetration level of harmonics was observed on the modelled 7-Up Industry Plc power distribution network without any filter being applied. The observed voltage and current harmonic distortions in the test system were appropriately mitigated with the use of shunt active and shunt passive filters. It was, however, established that shunt passive filter has a better harmonic distortion mitigation capability on the considered 7-Up Industry Plc power network layout than the shunt active filter. Hence, it is a more suitable approach for power quality enhancement of the considered network.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this study

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