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POWER QUALITY ENHANCEMENT IN AN ELECTRICAL DISTRIBUTION NETWORK USING SHUNT PASSIVE FILTER

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Abstract
Harmonics are one of the key power quality issues on the front burner in the power system. Advancements in solid-state technology in recent times have resulted in the proliferation of non-linear loads which are the main sources of harmonics. Harmonics penetration in power system networks is detrimental to effective system operation and can result in frequent failures and damage to electrical equipment. This, therefore, creates the need for harmonic mitigation in power system networks for power quality enhancement. This work examined the impact of a shunt passive filter (SPF) in minimizing harmonic distortion on an electrical distribution network considering the power network layout of 7-Up Industry Plc as a case study. The indices for quantifying the level of harmonic distortion and shunt passive filter design for harmonic mitigation in power networks were respectively analysed and presented. The considered 7-Up Industry Plc power network was modelled and simulated with and without SPF in MATLAB/Simulink software environment R2020a. The voltage and current total harmonic distortion, V_{THD} and I_{THD}, from the two system states, were evaluated. The observed voltage and current waveforms from the simulation of the test network without any filter applied were distorted, signifying the harmonics' presence. The estimated V_{THD} and I_{THD} values with no filter used were 6.084 and 19.79 % respectively. SPF application on the test network mitigated the V_{THD} and I_{THD} to 0.7802 and 2.448 %, giving an improvement of 5.304 and 17.342 % respectively in the minimization of voltage and current total harmonic distortion compared to the no filter case. This study established that a shunt passive filter is suitable for power quality enhancement in an electrical distribution network.

Keywords: *Electrical distribution network, harmonics, non-linear load, power quality, shunt passive filter, total harmonic distortion*

Introduction

Electricity distribution system is an important and final phase of power system through which electrical energy is delivered to the end users. The increasing technological innovations in the solid-state field have led to a sizeable growth in the usage of non-linear loads in power distribution networks in recent times. Non-linear loads are ones for which sinusoidal input voltage produces distorted output (Bajwa *et al.,* 2022). Such loads draw harmonic current from the alternating current sources (Aljarrah *et al.*, 2023).

Harmonics in electricity distribution system constitute a major threat to the power quality of the electricity supplied to the end-users. Power quality is an index normally used to express the current and voltage quality to maintain a sinusoidal waveform at rated voltage and frequency. (Masoum and Fuchs, 2011). Power quality related issues in electrical distribution systems are of different kinds and include issues such as voltage dips, spikes and interruption, transient overvoltages, slow voltage variations, harmonic distortion among others (Masoum and Fuchs, 2011; Kiran *et al.*, 2011). However, the high adverse effects posed by harmonic distortion at every level of electrical energy usage make its mitigation one of the top priorities in power system.

The presence of harmonics can cause the basic system parameters such as voltage, current and frequency to deviate from their statutory or tolerance limit, leading to an unhealthy or poor operation which can eventually decrease the quality of electric power supplied to a great extent (Kaur and Thakur, 2016). Harmonic distortions can result in overheating, maloperation and breakdown of electrical equipment (Kiran *et al.*, 2011; Baggani, 2008). There is, therefore, the need for harmonic mitigation in power distribution system for power quality enhancement.

Harmonic filters are applied to either eliminate or attenuate harmonic distortions so that harmonic components of current or voltage source will not unduly interfere with the power system (Sankaran, 2002). Different studies have been conducted on the improvement of power quality in power system networks using varieties of shunt passive harmonic filters. achieved (Elmi and Salman, 2023; Muhammad *et al.,* 2022; Neelina *et al.,* 2020; Desai *et al.*, 2019; Adejumobi *et al.,* 2017; Almutairi and Hadjiloucas, 2017; Reginald and Thomas, 2015; Memon *et al.*, 2012; Young-Sik and Hanju, 2011). Despite the series of promising outcomes achieved by the researchers, more investigations are still greatly needed in the area of industrial electricity distribution networks where penetration of non-linear loads is extensively high to examine the effectiveness of shunt passive filters in curtailing harmonic distortions in the networks.

Therefore, the goal of this study is to apply shunt passive filters for harmonic mitigation in an electrical distribution network considering the power network layout of a typical bottling company, 7-Up Industry Plc, as a sample case.

Materials and Methods

Harmonic Measures for Power Quality Analysis

Total Harmonic Distortion (THD) is an index for quantifying the current and voltage total harmonic distortion injected into a power system network by nonlinear loads. Voltage and current harmonic distortion (V_{THD} and I_{THD}) respectively measure the total deviation or variation in voltage and current at harmonic frequencies to the value at fundamental

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

$$V_{HD} = \frac{V_h}{V_1} \times 100\% \quad (2)$$

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

$$I_{HD} = \frac{I_h}{I_1} \times 100\% \quad (4)$$

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

Design of Passive Harmonic Filter Single Tuned Passive Filter

This filter comprises a capacitor and an inductor connected in series. A typical single tuned filter configuration is shown Figure 1.

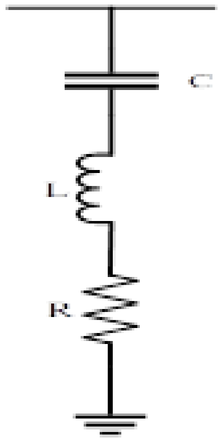

Figure 1: A typical single tuned filter model

The resistance, R, in Figure 1 is the intrinsic resistive component of the series reactor usually employed to prevent overheating of the filter. Any harmonic component whose frequency falls within that of the single tuned passive filter will find a low impedance path through the filter (De la Rosa, 2006). The component values of the filter are determined from Equations (5) and (6):

$$C = \frac{Q}{2\pi f V^2} \quad (5)$$

$$L = \frac{1}{(2\pi f_n)^2 C} \quad (6)$$

Where C, L, Q, V, f, f_n respectively are capacitance, inductance, filter reactive power at the fundamental frequency, filter voltage level, fundamental frequency and tuning frequency.

The single tuned filter impedance is expressed by Equation (7):

$$Z = R + j\,(X_L - X_C) \quad (7)$$

Where X_C and X_L are capacitive and inductive reactances expressed by Equations (8) and (9), respectively:

$$X_C = \frac{1}{j\omega c} \quad (8)$$

$$X_L = j\omega L \quad (9)$$

With ω as the angular frequency.

Since single tuned passive filter inductive and capacitive reactances are equal at resonant frequency, Equation (10) is obtained:

$$\omega_n = \sqrt{\frac{L}{C}} \quad (10)$$

Where ω_n, n respectively are tuned angular frequency and tuning index.

The index of tuning, n, is given as equation (11):

$$n = {}^{f_n}/_{f} \quad (11)$$

The resonant frequency, f_o, of a single tuned passive filter and quality factor, Q_o, which gives a measure of tuning sharpness are respectively expressed by Equations (12) and (13) (Das, 2018):

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (12)$$

$$Q_o = \frac{X_o}{R} = \frac{\sqrt{L/C}}{R} \quad (13)$$

Where, X_o is the capacitive or inductive reactance at the tuned frequency.

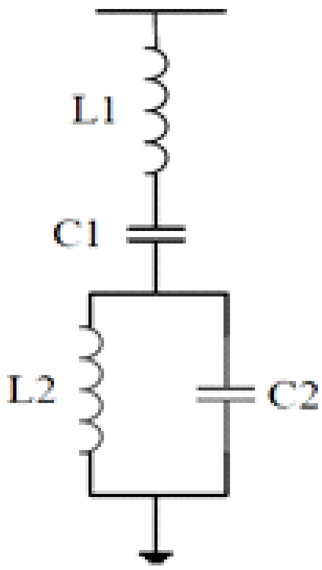

Figure 2: Double tuned filter

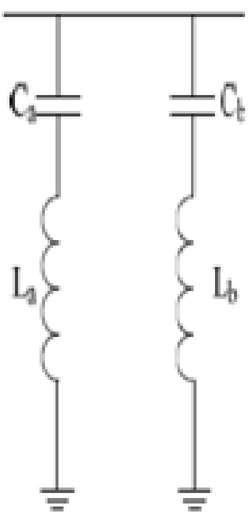

Figure 3: Parallel Single Tuned Filter

$$\omega_s = \frac{1}{\sqrt{L_1C_1}} \quad (14)$$

$$\omega_p = \frac{1}{\sqrt{L_2C_2}} \quad (15)$$

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

The resonant frequencies of each of the parallel filters circuit in Figure 3 are given by Equations (16) and (17), respectively:

$$\omega_a = \frac{1}{\sqrt{L_aC_a}} \quad (16)$$

$$\omega_b = \frac{1}{\sqrt{L_bC_b}} \quad (17)$$

Since the double tuned filter and the parallel single tuned filters are equivalent, Equation (18) is obtained:

$$\omega_a\omega_b = \omega_s\omega_p \quad (18)$$

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

$$C_1 = C_a + C_b \quad (19)$$

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

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

$$L_2 = \frac{\left(1-\frac{w_a^2}{w_s^2}\right)\left(1-\frac{w_a^2}{w_p^2}\right)}{C_1 w_a^2} \quad (21)$$

$$C_2 = \frac{1}{L_2 w_p^2} \quad (22)$$

Test Network

The test network considered in this study is 7-Up Industry Plc power distribution network. The Industry is a typical Nigerian bottling company located in the heart of Ibadan, Oyo State, Nigeria. A dedicated 33 kV line which was stepped down to 11/0.415 kV via a power transformer of 33 MVA rating supplies the company with four 500 kVA back-up generators. The power distribution network layout of the company is shown in Figure 4 with the energy needs of the key loads provided in Table 1.

Implementation Software

MATLAB/Simulink software was used as a simulation environment in this study. The software provides an interactive environment for simulation of dynamical systems of varying degrees, therefore, enabling rapid construction of virtual prototypes to explore design concept to model a non-linear system. Figure 5 shows the Simulink model of the 7-Up Industry Plc power distribution network

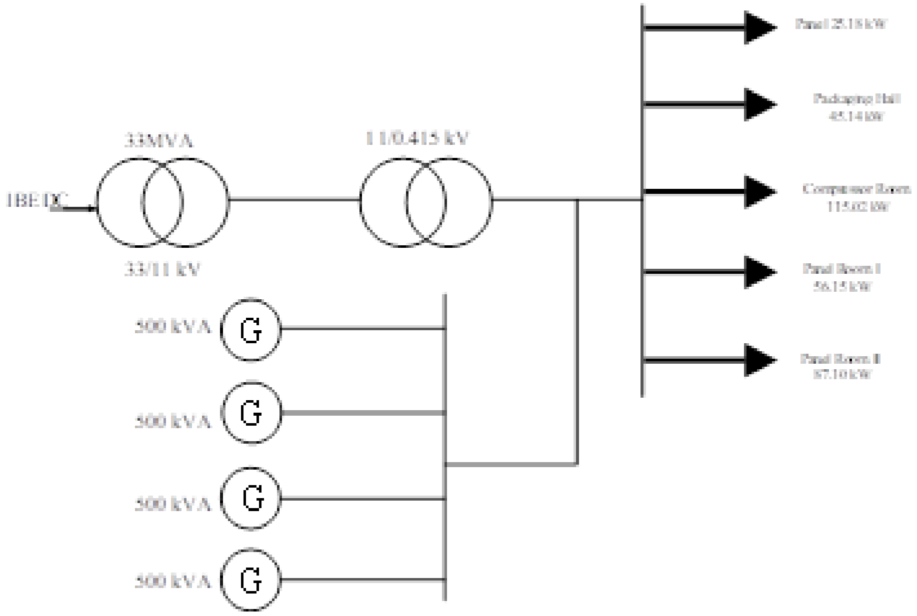

Figure 4: The power distribution layout of 7-Up Industry Plc

Table 1: Power Requirements of 7-Up Industry 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

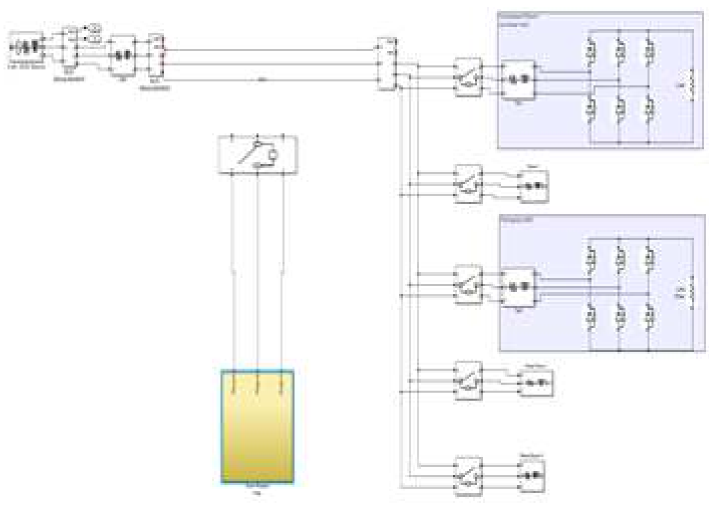

Figure 5: Simulink model of 7-Up Industry Plc power distribution network

Results and Discussion

Simulation Results of 7-Up Industry Plc Distribution Network without Filter Application

The simulation results of the Simulink model of the distribution network of 7-Up Industry Plc depicted in Figure 5 without the shunt passive filter application are shown in Figures 6 to 9 which give the voltage waveform, current waveform, voltage harmonic spectrum and current harmonic spectrum respectively. The voltage and current signals of the company's power network as reflected in Figures 6 and 7,

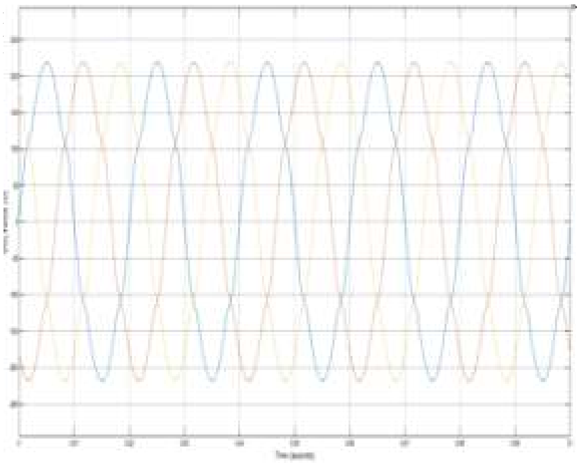

Figure 6: 7-Up Industry Plc power distribution network voltage signal without filter

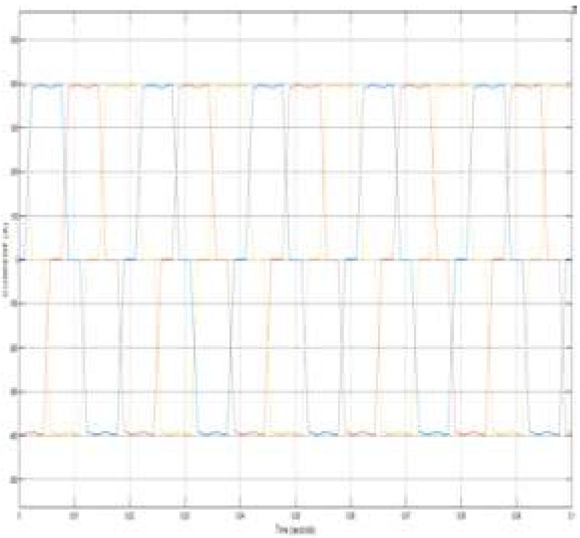

Figure 7: 7-Up Industry Plc power distribution network current signal without filter

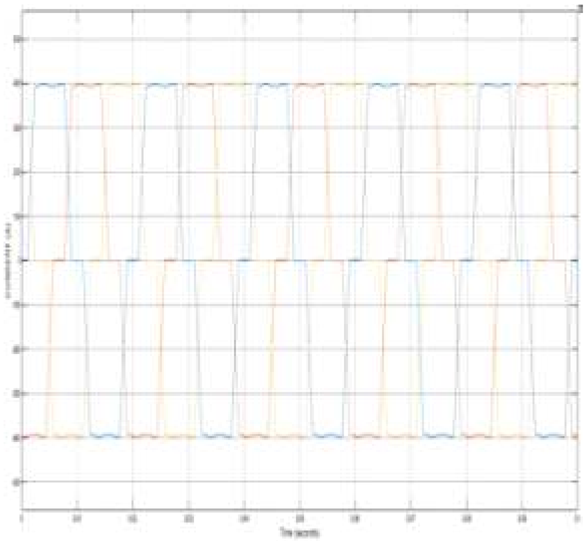

Figure 7: 7-Up Industry Plc power distribution network current signal without filter

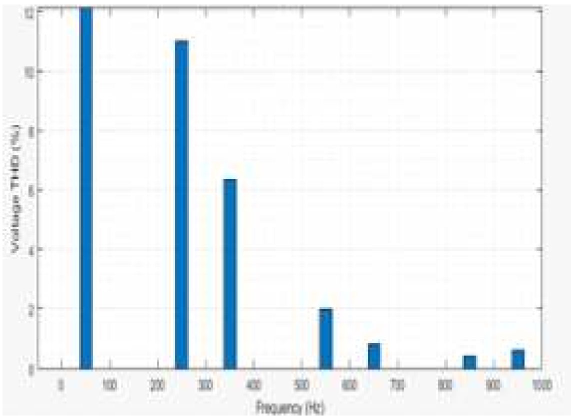

Figure 8: Harmonic spectrum of 7-Up Industry Plc power distribution network voltage without filter

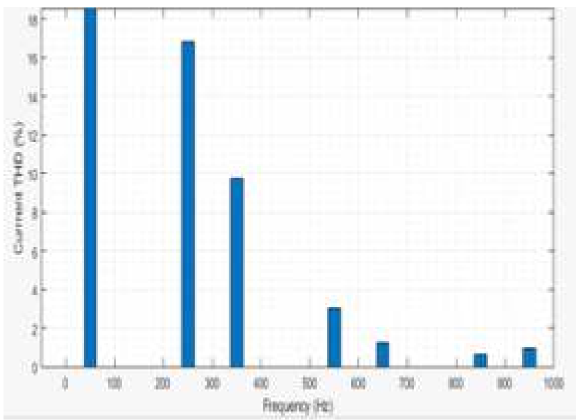

Figure 9: Harmonic spectrum of 7-Up Industry Plc power distribution network current without filter

Simulation Results of 7-Up Industry Plc Distribution Network with Shunt Passive Filter

Figures 10 to 13 present the results of simulation of Simulink model of the distribution network of 7-Up Industry Plc in Figure 5 with shunt passive filter (SPF) applied. Figures 10 and 11 respectively show the network's voltage and current signals during simulation while the harmonic spectra of the voltage and current are respectively depicted in Figures 12 and 13. The signals in Figures 10 and 11 respectively revealed that there was a substantial reduction in the amount of harmonic distortion present in the considered network. The V_{THD} obtained from Figure 11 was 0.7802%, giving a 5.304% reduction compared with Figure 6, while the I_{THD} was 2.448%, producing a reduction of 17.342% compared with Figure 7.

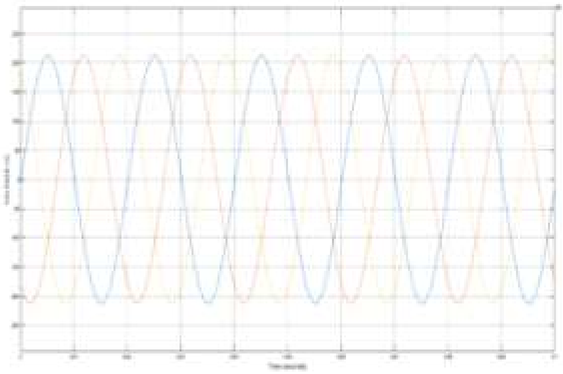

Figure 10: 7-Up Industry Plc power distribution network voltage signal with SPF

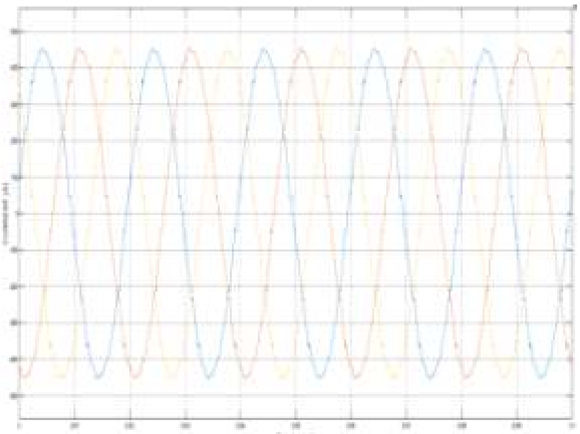

Figure 11: 7-Up Industry Plc power distribution network current signal with SPF

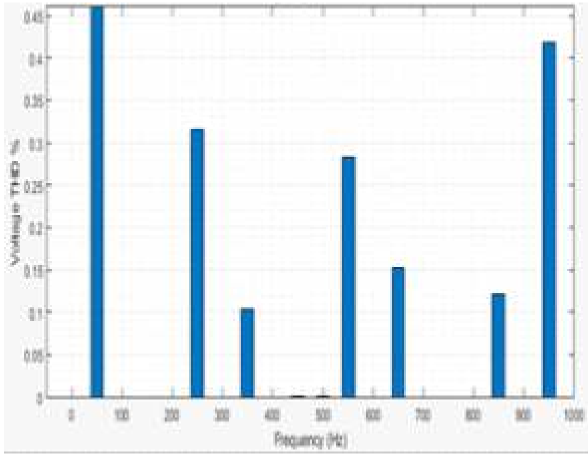

Figure 12: Harmonic spectrum of 7-Up Industry Plc power distribution network voltage with SPF

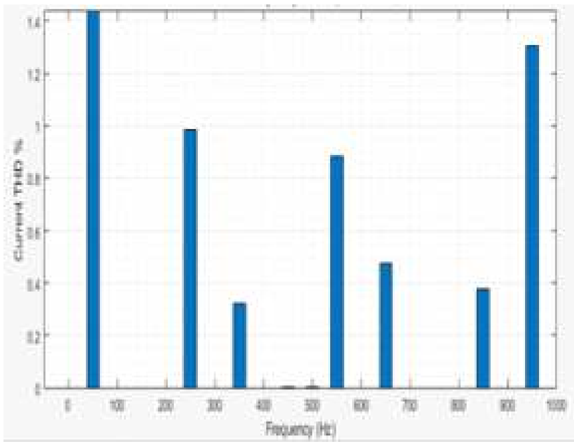

Figure 13: Harmonic spectrum of 7-Up Industry Plc power distribution network current with SPF

Comparison of the 7-Up Industry Plc Power Distribution Network Voltage and Current Total Harmonic Distortion with and without Shunt Passive Harmonic Filter

Figures 14 and 15 are the bar charts showing the comparison of the 7-Up Industry Plc power distribution network voltage and current total harmonic distortion with and without SPF. From Figures 14 and 15, the shunt passive filter mitigated harmonic distortion on the 7-Up industry Plc power network layout appreciably, compared to the case when SPF was not applied. The application of SPF reduced the V_{THD} from 6.084 to 0.7802%, while mitigating I_{THD} from 19.79 to 2.448% respectively. These results are indications that shunt passive harmonic filter is a suitable and appropriate mitigating method for the considered network.

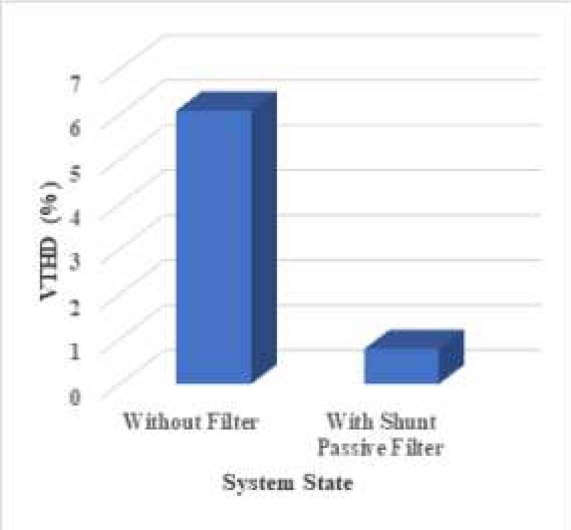

Figure 14: Performance comparison of SPF for voltage harmonic mitigation

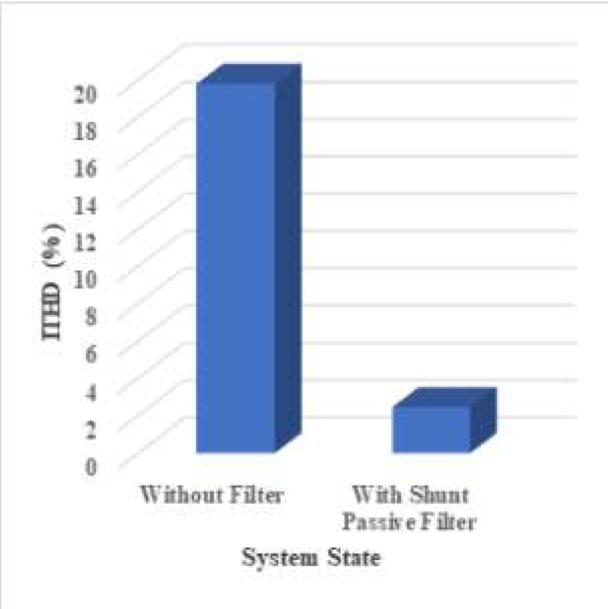

Figure 15: Performance comparison of SPF for Current harmonic mitigation

Conclusions

Harmonics penetration in a power distribution network deteriorates the quality of electricity delivered to the consumers and consequently can disrupt the optimum operating conditions of associated electrical equipment. Therefore, this study assessed the harmonic mitigation capability of shunt passive harmonic filter on an electrical distribution network of a typical bottling company of 7-Up Industry Plc. High penetration level of harmonic distortion on the modelled 7-Up Industry Plc power network layout was observed without any filter being applied. The observed voltage and current harmonic distortions in the test system were appropriately mitigated with the use of shunt passive filters. This study established that application of shunt passive filter is a suitable approach for power quality enhancement of the considered network.

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