THE EFFECT OF COMBINED SERIES-SHUNT PASSIVE FILTER ON HARMONIC DISTORTION AND POWER LOSSES IN AN ELECTRICAL DISTRIBUTION NETWORK

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Abstract
The persistently growing non-linear loads utilization in recent times produces harmonics that can negatively impact the performance of a power system network. Harmonics causes the system's voltage and current signals distortion and in effect results in power loss increase. This study analyzed the series-shunt passive filter (SeShPF) impact on harmonic distortion-power loss interaction in an electrical distribution network. The mathematical equations for determining the system's voltage, current and voltage-current total harmonic distortion (THD_V, THD_I and THD_{V-I}) along with the active power loss were formulated. The modelling and simulation of the Federal University of Agriculture, Abeokuta (FUNAAB) electrical distribution network for 250-seater computer laboratory facility which was used as a test case before and after the application of SeShPF were done in MATLAB/Simulink R2023a environment. The THD_V, THD_I, THD_{V-I} and active power loss for each simulation scenario were determined. The obtained results showed that without the use of SeShPF on the case network, the THD_V, THD_I and THD_{V-I} were 21.71, 30.43 and 37.38%, respectively, while the active power loss was 9703 W. In contrast, the application of SeShPF on the network reduced the THD_V, THD_I and THD_{V-I} to 0.06, 0.22 and 0.22%, respectively, whereas the active power loss was minimized to 35 W. This study showcased the SeShPF as a potential candidate for mitigating electricity distribution network harmonics and power loss.

Keywords: active power loss, harmonics, MATLAB/Simulink, non-linear load, passive filter, total harmonic distortion.

Introduction

An electricity distribution system is a key segment of power system that ensures efficient electrical energy delivery from generation stations to end-users. However, a vast integration of non-linear loads such as uninterruptible power supplies, variable speed drives, computers, rectifiers among others in distribution networks has made power quality issues, particularly harmonic distortion, a major bottleneck. A 50 or 60 Hz is the fundamental frequency at which power systems are intended to function. Non-linear loads, however, introduce harmonics which are integer multiples of these fundamental frequencies (Adebisi *et al.*, 2025; Ogundele *et al.*, 2023; Aziz *et al.*, 2021; Ulinuha and Sari, 2021). It is very important in power systems to take cognisance of the frequency components of the base waveform that can negatively impact the effective functionality of the entire system. This is because harmonics, if left unaddressed, are capable of causing undesirable effects such as voltage waveform distortion, inefficiency, unreliability and equipment failure (Riaz *et al.*, 2021; Ulinuha and Sari, 2021; Sinvula *et al.*, 2019; Adejumobi *et al.*, 2017; Park *et al.*, 2017; Ye, 2017; Neagu *et al.*, 2016; Ghorbani and Mokthari, 2015; Bamigbola *et al.*, 2014; Hussein *et al.*, 2010).
Aside the various deleterious effects of harmonics that have been previously highlighted, one other major detrimental effect of this pollutant is huge power loss it causes (Okuo *et al.*, 2025; Ogundele *et al.*, 2023; Riaz *et al.*, 2021; Ulinuha and Sari, 2021). Harmonic distortion-power loss connection

in an electrical distribution network is crucial in the understanding of the system functionality. The system losses, which are mostly due to resistive elements of transformers and conductors, become extremely high with increase in higher frequency components of the current waveform. These higher frequency current components which are harmonics can cause additional losses by increasing the conductors' skin effects, core losses and eddy current losses as well as causing instability of voltage and interference with smooth protective devices operation (Neagu *et al.*, 2016; Ye, 2017; Benedict *et al.*, 1992). Soares *et al.* (2021), Park *et al.* (2017), Ghorbani and Mokthari, (2015), Vuletic and Todorovski (2015) and Navani *et al.* (2012) established that a technical loss in a power distribution network increases as voltage and current harmonics increase, implying that harmonic distortion increases the distribution system technical loss. The goal of power quality is the supply's purity, which means there should not be any distortion in voltage or current waveform (Javad *et al.*, 2019; Adebisi *et al.*, 2017; Santoso *et al.*, 2012; Singh, 2009; Grady and Santoso, 2001). Therefore, an effective mitigation strategy for harmonics must not only take into consideration the distortion caused but also the power losses generated.

Varieties of harmonic mitigation strategies have been proposed in power system. Koupaie (2024), Aziz *et al.* (2021), Zobaa *et al.* (2018) and Nair and Sankar (2015) dealt with modification of power network structures and deployment of harmonic reduction transformers to suppress harmonic emission from non-linear loads. More so, Adebisi *et al.* (2025), Okuo *et al.* (2025) and Asiedu (2021) worked on power filters involving both passive and active filters and their hybrids for power system harmonic reduction. Observations from the various studies showed that the deployed mitigation strategies drastically reduce distortion due to harmonics while those that focused on examining the harmonic distortion impact on power losses revealed that decrease in distortion arising from harmonics minimises power system losses. Further assessment gave an indication that filtering techniques remain widely used and cost-effective solutions. Therefore, this present work assessed the combined series-shunt passive filter impact on an electrical distribution network's harmonic distortion-power loss level.

Many previous studies have considered harmonic distortion suppression and explored its connection with power loss. Koupaie, (2024) analysed harmonic distortion on a power network of an Iranian cement factory. The work delved into harmonic causes and impacts on the network while implementable solutions for harmonic problems redress were detailed. Comparative assessment of shunt passive and shunt active power filters for harmonic minimization on a Nigerian typical bottling company's electrical distribution network was dealt with by Ogundele *et al.* (2023). The study revealed that shunt passive filter demonstrated better voltage and current total harmonic distortion mitigation capability over shunt active filter on the network. Alasali *et al.* (2022) worked on an optimization of a hybrid active power filter for harmonic minimization. The outcomes indicated that the filter's parameters were optimized better for harmonic suppression by Whale optimization algorithm compared to other optimization algorithms employed.

Harmonic effect on a 25kVA oil-filled distribution transformer's temperature and power loss was investigated by Thakur *et al.* (2022). The outputs revealed that harmonic distortion is positively correlated with the transformer's temperature and power loss. Riaz *et al.* (2021) examined harmonic distortion effect on an industrial power plant under the influence of an harmonic filter. The work used a fluke energy analyzer for the analysis of the harmonic distortion. It was established that not only did the filter reduced harmonic distortion but also the power factor was enhanced. Aziz *et al.* (2021) presented a review on harmonic mitigation methods for electrical power systems. The findings revealed that, when it comes to harmonic filtering, the hybrid harmonic filter outperforms other filtering options due to its efficiency, particularly in high-power applications. From the previous studies, it was observed that most of the works emphasized the harmonic distortion impact on power quality and the necessary mitigation measures taken to reduce its negative effects. It was also noticed that only few of the articles considered the relationship between harmonic distortion and power loss with focus on transmission networks and transformers. This paper closes this gap via quantitative analysis of harmonic distortion and power loss relationship in an electrical distribution network fortified with a SeShPF.

Methodology

Total Harmonic Distortion (THD)

One of the very useful indices for figuring out a waveform's harmonic content is total harmonic distortion (THD). It is an indicator of a waveform's effective value (Santoso *et al.*, 2012; Baggini and Hanzelka, 2008). It can be used for both voltage and current distortion level quantification as expressed by Eqs. (1) and (2) (Adebisi *et al.*, 2025, Okuo *et al.*, 2025; Ogundele *et al.*, 2023):

$$THD_V = \frac{\sqrt{\sum_{h=2}^{h_{max}} V_h^2}}{V_1} \quad (1)$$

$$THD_I = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_1} \quad (2)$$

where THD_V, THD_I, V_h, V_1, I_h and I_1 are respectively the voltage total harmonic distortion, current total harmonic distortion, voltage at harmonic order h, fundamental voltage, current at harmonic order h and fundamental current.

The alternate forms of Eqs. (1) and (2) are respectively expressed by Eqs. (3) and (4) (Okuo *et al.* 2025) while Eq. (5) gives the combined expression relating both voltage and current (Okuo *et al.*, 2025; Alasali *et al.*, 2022):

$$V^2 = V_1^2(1 + THD_V^2) \quad (3)$$
$$I^2 = I_1^2(1 + THD_I^2) \quad (4)$$
$$THD_{V-I} = \sqrt{THD_V^2 + THD_I^2} \quad (5)$$

where V and I are respectively the system voltage and current.
The Eq. (5) is important for investigating cumulative voltage and current harmonic distortion effects on reliability and power quality of a power system network (Alasali *et al.*, 2022; Peng *et al.*, 1990).

Harmonic Distortion-Power Loss Interaction in an Electrical Distribution Network

In an electrical distribution network, non-linear loads inject harmonic active power which is a product of harmonic voltage and current of the same order. Although, this power is lower in magnitude compared to underlying active power but it is capable increasing the utility supply system losses. Eqs. (6) to (11) establish the connection between power loss and harmonic distortion (Ghorbani and Mokthari, 2015; Lundquist, 2001):

$$P_{lh} = RI^2 \quad (6)$$
$$THD_I.I_1 = \sqrt{\textstyle\sum_{h=2}^{\infty} I_h^2} \quad (7)$$
$$I^2 = \textstyle\sum_{h=2}^{\infty} I_h^2 + {I_1}^2 \quad (8)$$
$$I^2 = {I_1}^2(1 + {THD_I}^2) \quad (9)$$
$$P_{lh} = R{I_1}^2(1 + {THD_I}^2) \quad (10)$$
$$P_{lh} = R{I_1}^2(1 + {THD_{V-I}}^2 - {THD_V}^2) \quad (11)$$

where P_{lh} and R are respectively the harmonic based power loss and conductor resistance.
The total harmonic based power loss for a three-phase three-wire system, $P_{lh3\phi}$, is expressed by Eq. (12):

$$P_{lh3\phi} = 3R_P \textstyle\sum_{h=1}^{\infty}(I_{ah}^2 + I_{bh}^2 + I_{ch}^2) + R_N \sum_{h=1}^{\infty}(I_{Nh}^2) \quad (12)$$

where R_p and R_N are the phase and neutral resistances respectively, I_{ah}, I_{bh}, and I_{ch} are the phases A, B and C harmonic currents respectively and I_{Nh} is the neutral current at harmonic order h.

The neutral wire power loss can be considerable and may result in overloading due to the zero-sequence currents and unbalanced loads (Ghorbani and Mokhtari, 2015; Lundquist, 2001).

Design of Passive Filter

Passive filters come in shunt, series and hybrid forms and are made up entirely of passive components including resistors, capacitors and inductors. These filters are usually connected in series with switch gears, busbars, motor control systems, and large switchboards (Asiedu *et al.*, 2021; Zobaa *et al.*, 2018; Hussein *et al.*, 2010). When passive filters are connected to a system in series, they become series passive filters while passive filters configured in parallel are known as shunt passive filters (Okuo *et al.*, 2025; Asiedu *et al.*, 2021; Zobaa *et al.*, 2018; Hussein *et al.*, 2010).
Passive filter designs in single or double-tuned mode are excellent solutions for applications that require elimination of harmonics of particular order. The series and shunt passive filters combination was considered in this work with single tuned filter as the reference filter. The basic tuned filter configuration is depicted in Figure 1 while Figure 2 shows the combined series-shunt passive filter schematic.

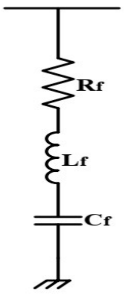


Figure 1: The basic tuned filter configuration

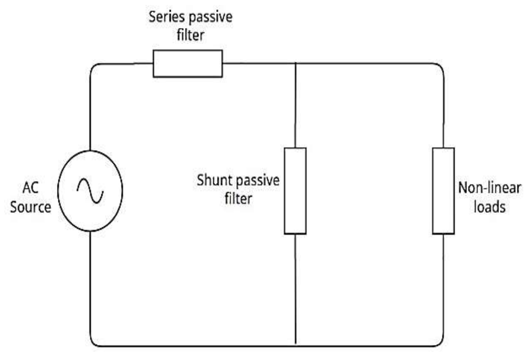


Figure 2: The schematic diagram of a SeShPF

The tuned passive filter design demands appropriate capacitor size selection on the basis of power factor standpoint (Okuo *et al.*, 2025; Adebisi *et al.*, 2017; Tali *et al.*, 2014). The power factor enhancement requires that the capacitance, C_f, of the filter is sized for a defined reactive power value

Q_C. As such, Q_C and C_f are connected by the expression of Eq. (13) (Okuo *et al.*, 2025; Adebisi *et al.*, 2017; Tali *et al.*, 2014):

$$C_f = \frac{Q_c}{2\pi f V^2}\left(1 - \frac{1}{h^2}\right) \quad (13)$$

where V, f and n are respectively the supply voltage, fundamental frequency and harmonic order.

The filter reactor, L_f, produced series resonance at the harmonic frequency f_h (hf) governed by Eq. (14):

$$X_C = X_L \quad (14)$$

where X_C and X_L are respectively the capacitive and inductive reactances expressed by Eqs. (15) and (16):

$$X_C = \frac{1}{2\pi f_h C_f} \quad (15)$$

$$X_L = 2\pi f_h L_f \quad (16)$$

The Eqs. (15) and (16) application in Eq. (14) produced Eq. (17) from which inductance of the filter is obtained:

$$L_f = \frac{1}{4\pi^2 f_h^2 C_f} \quad (17)$$

The filter's quality factor Q determines the tuning sharpness from which its resistance R_f is derived according to Eqs (18) to (20) (Okuo *et al.*, 2025; Adebisi *et al.*, 2017; Tali *et al.*, 2014):

$$R_f = \frac{2\pi f_h L_f}{Q} \quad (18)$$

$$R_f = \frac{\sqrt{\frac{L_f}{C_f}}}{Q} \quad (19)$$

$$R_f = \sqrt{\frac{L_f}{Q^2 C_f}} \quad (20)$$

The Q has a range of values from 20 to 100 with better mitigation achievable at higher Q values (Okuo *et al.*, 2025; Adebisi *et al.*, 2017; Memon *et al.*, 2016; Tali *et al.*, 2014).

Test Case

The electrical distribution network of FUNAAB's 250-seater computer laboratory facility was employed as this study's test case. The facility is supplied via 33 MVA transformer which steps down a dedicated 33 kV feeder to 11/0.415 kV. A back-up comprising a 300 kVA generator is also provided for the facility. The electrical distribution network layout of the facility is depicted in Figure 3 while the loads' power demands are presented in Tables 1 and 2.

Choice of Simulation Software

In this work, MATLAB/Simulink software was deployed for modelling and simulation of the FUNAAB's 250-seater computer laboratory facility distribution network along with its loads. Simulink is a robust graphical programming environment for dynamic systems analyses. Using basic function blocks, it enables systematic construction of complex systems for straight-forward analysis (Ejiofor *et al.*, 2019). Being very useful for time domain to frequency domain signal transformation, the fast Fourier transform application was used the THD derivation in this work. Figure 4 shows the Simulink configurations of the FUNAAB's 250-seater computer laboratory facility distribution network before and after SeShPF use.

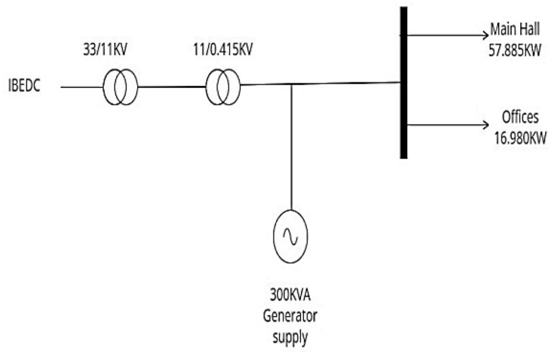


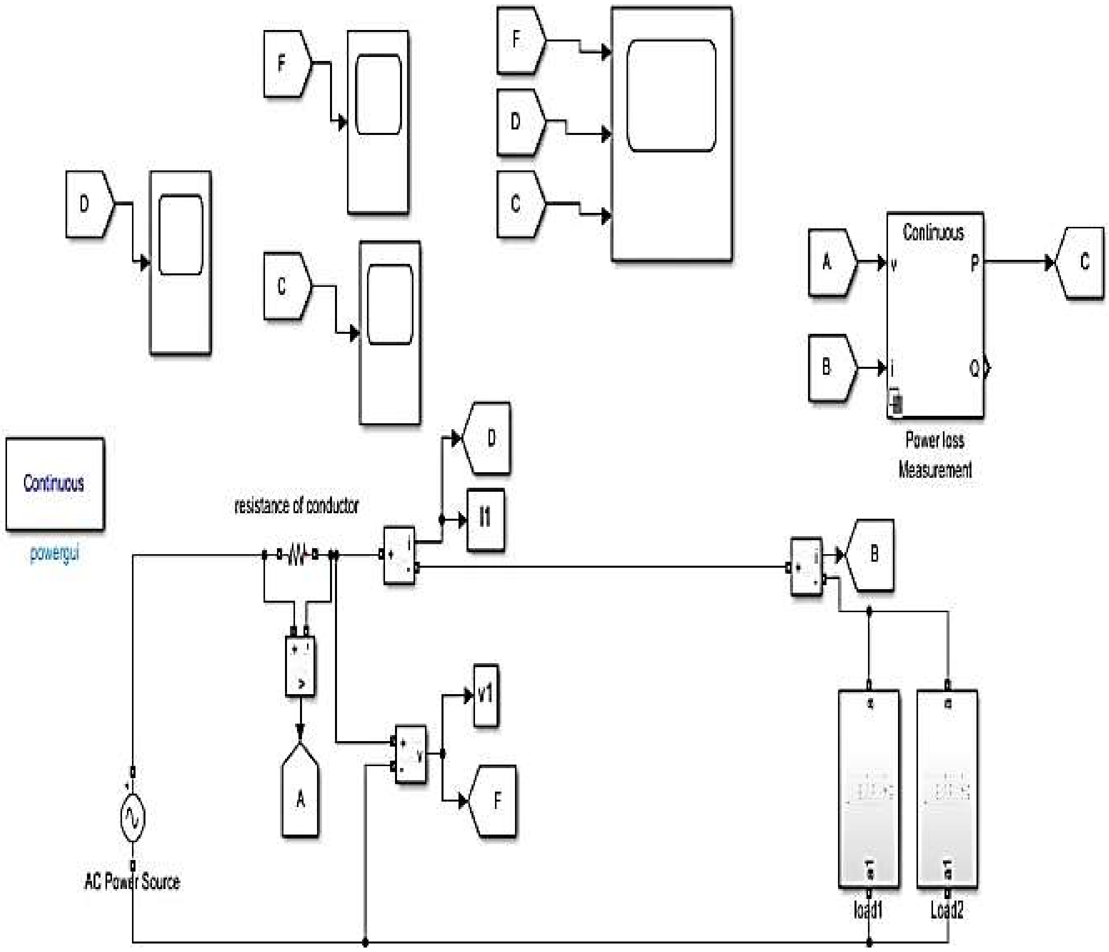
Figure 3: FUNAAB's 250-seater computer laboratory electrical distribution network layout

Table 1: FUNAAB's 250-seater computer laboratory facility main hall loads' power demands

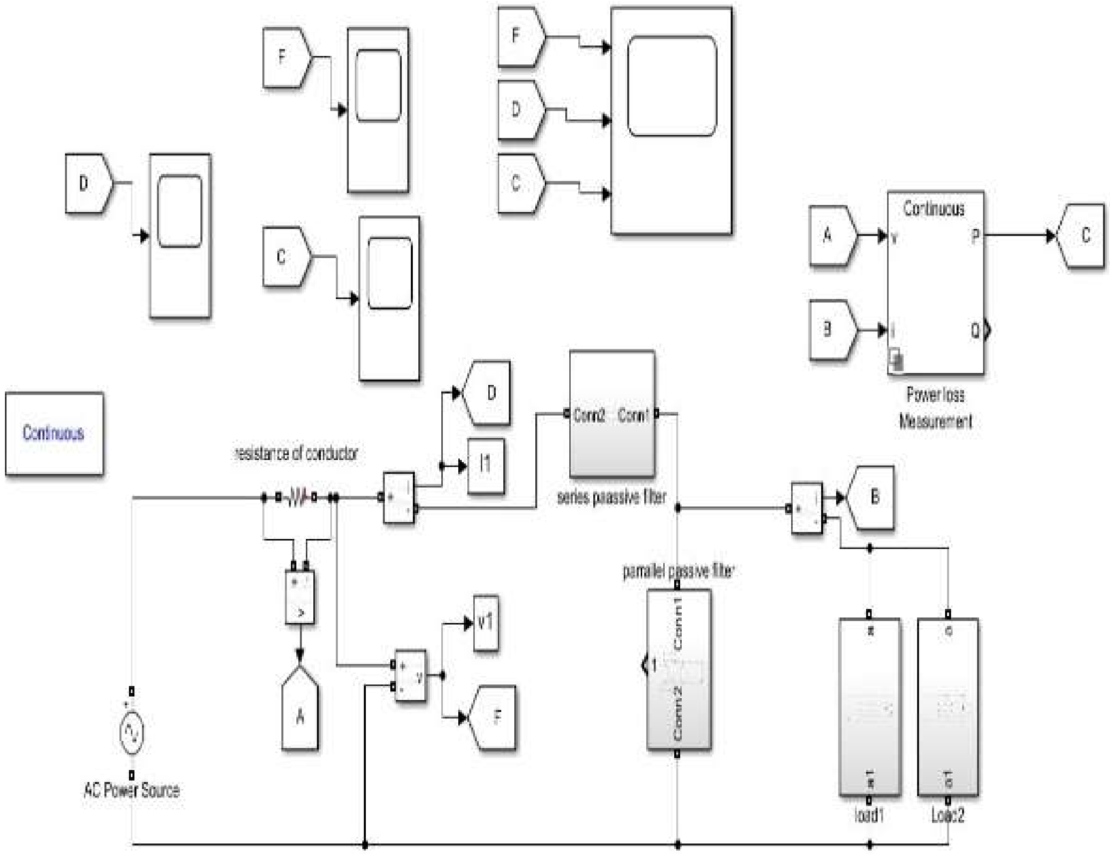
Loads	**Load Type**	**Unit**	**S(VA)**	**P(W)**	**Q(VAr)**
Split Air conditioner	Non-linear	6	42,750.00	34,200.00	25,650.00
CCTV cameras	Non-linear	16	300.00	240.00	180.00
Fans	Non-linear	30	1,312.5.00	1,050.00	787.20
Compact fluorescent	Non-linear	116	4,350.00	3,480.00	2,610.00
Computers	Non-linear	291	23,643.75	18,915.00	14,186.23
Total			**72,356.30**	**57,885.00**	**43,413.60**

Table 2: FUNAAB's 250-seater computer laboratory facility offices loads' power demands

Loads	Load Type	Unit	S(VA)	P(W)	Q(VAr)
Air conditioner	Non-linear	12	18,750.00	15,000.00	11,250.00
Fans	Non-linear	12	525.00	420.00	315.00
Compact fluorescent	Non-linear	12	450.00	360.00	270.00
Computers	Non-linear	12	975.00	780.00	585.00
Printers	Non-linear	12	525.00	420.00	315.00
Total			**21,225.00**	**16,980.00**	**12,735.00**



(a)



(b)

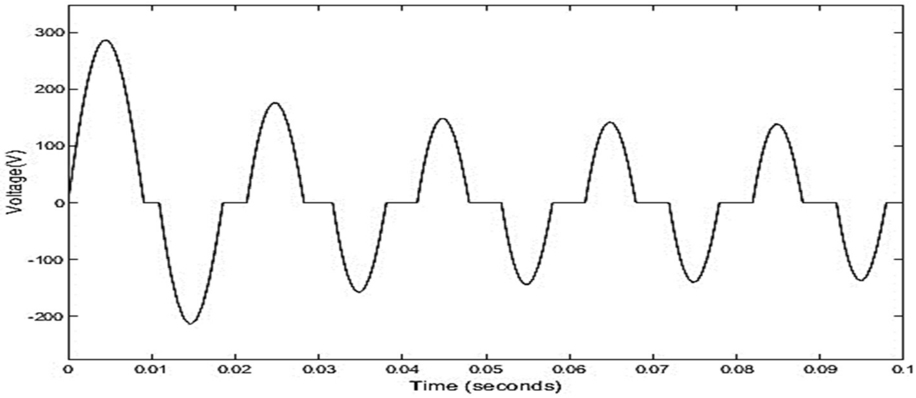
Figure 4: Simulink configuration of the FUNAAB's 250-seater computer laboratory facility distribution network (a) before SeShPF application (b) after SeShPF application

Results and Discussion

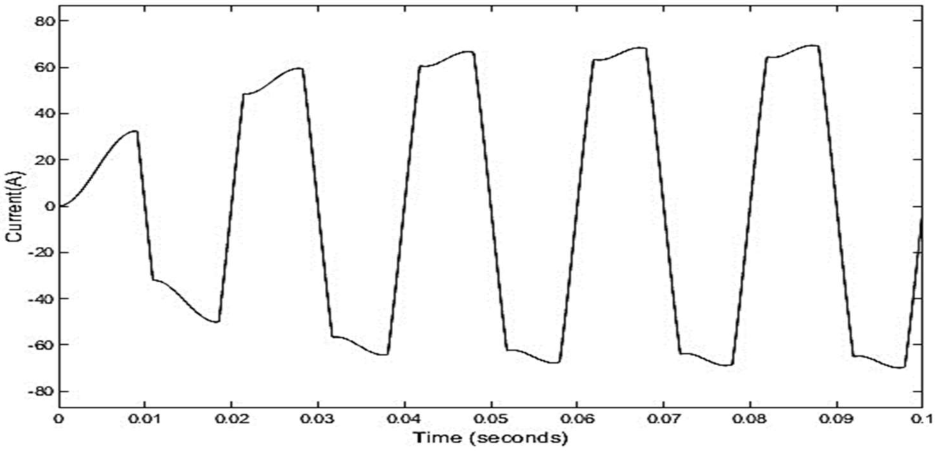
Figure 5 delineates the results of pre-filtering simulation of the FUNAAB's 250-seater computer laboratory facility distribution network. While the network's waveforms of voltage and current are respectively shown in Figures 5a and b, Figures 5c and d depict the voltage and current spectra respectively. The network's power loss waveform is presented in Figure 5e. The assessment of Figures 5a and b revealed distorted FUNAAB's 250-seater computer laboratory facility distribution network voltage and current waveforms; an indication of harmonics penetration. The THD_V and THD_I evaluation from Figures 5c and d respectively produced 21.71 and 30.43% voltage and current harmonic distortion, leading to a THD_{V-I} of 37.38%. Analysis of the obtained THD_V and THD_I showed that both values exceeded the acceptable distortion thresholds. The THD_V was above 5% stipulated by IEEE 519-2022 for distribution networks of 1-69 kV, the class to which FUNAAB's 250-seater computer laboratory facility distribution network is categorised. The THD_I on the other hand was above 16% current distortion limit according to Sabin *et al.* (2022) and Radzi *et al.* (2020). The maximum system active power loss with no filter application was 9703 W as determined from Figure 5e.

The post-filtering simulation results of the FUNAAB's 250-seater computer laboratory facility distribution network with SeShPF are presented in Figure 6. Displayed in Figures 6a and b respectively are network's voltage and current waveforms under the filtering condition whereas Figures 6c and d delineat the spectra of voltage and current respectively. Figure 6e shows the power loss waveform of the network. As observed respectively from Figures 6a and b, a much reduced system's voltage and current waveforms distortions were obtained with the SeShPF application when compared with Figure 5a and b. The THD_V and THD_I as evaluated from Figures 6c and d were 0.06 and 0.22%; producing harmonic mitigation 21.65 and 30.21% respectively when compared with Figures 5c and d. These values are well within the acceptable voltage and current distortion thresholds. The estimated THD_{V-I} was 0.22% which when compared to 37.38% obtained when no SeShPF was applied is very low. From Figure 6e, the maximum system active power loss was 35 W, giving a 9668 W reduction in loss value as compared with Figure 5e.

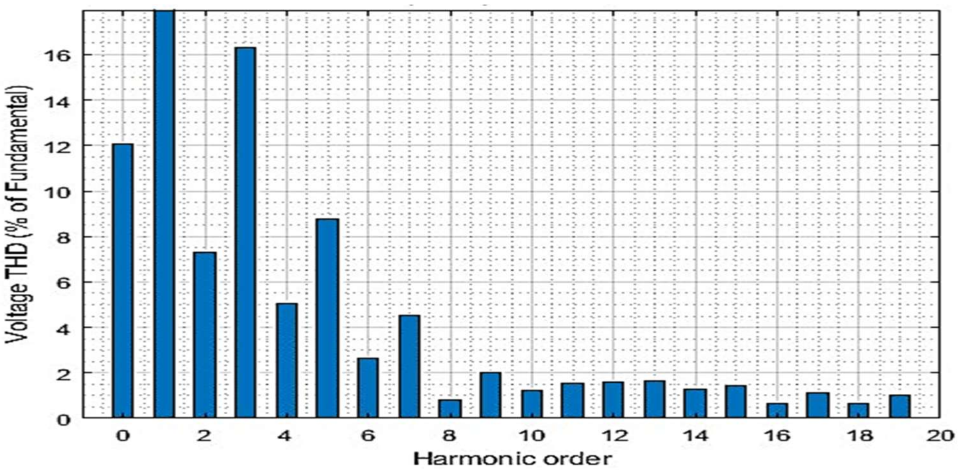
Figure 7 shows the comparison of the THD_V, THD_I and $THD_{V\text{-}I}$ before and after the SeShPF application on FUNAAB's 250-seater computer laboratory facility distribution network while Figure 8 depicts the active power loss comparison without and with SeShPF. A careful assessment of Figures 7 and 8 revealed power loss is directly correlated with harmonic distortion, that is, the system active power loss reduces as the harmonic content decreases.



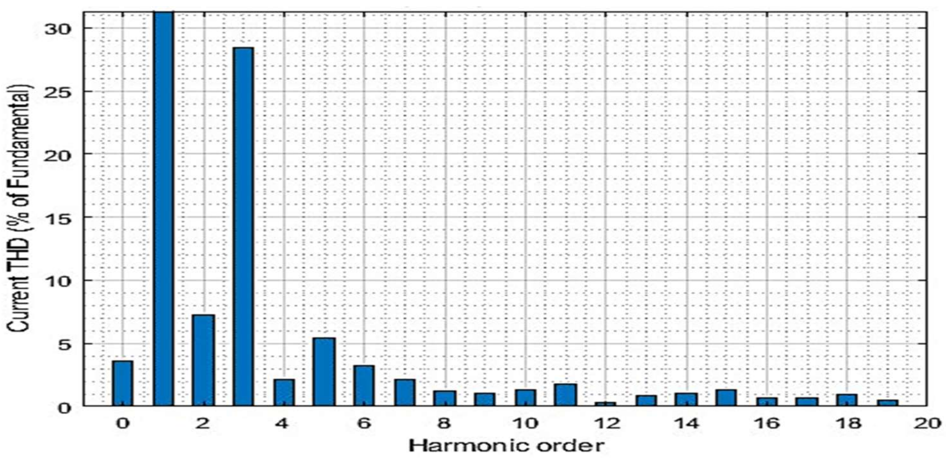
(a)



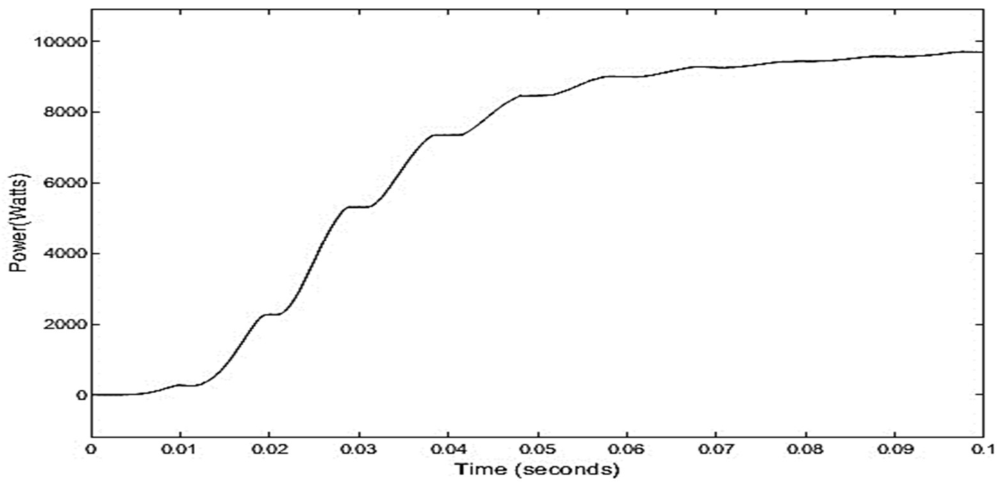
(b)



(c)

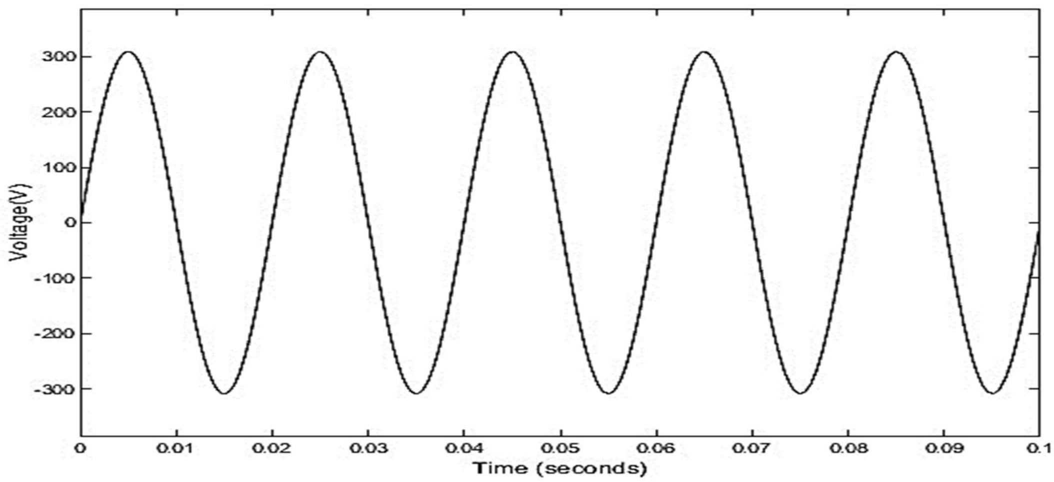


(d)

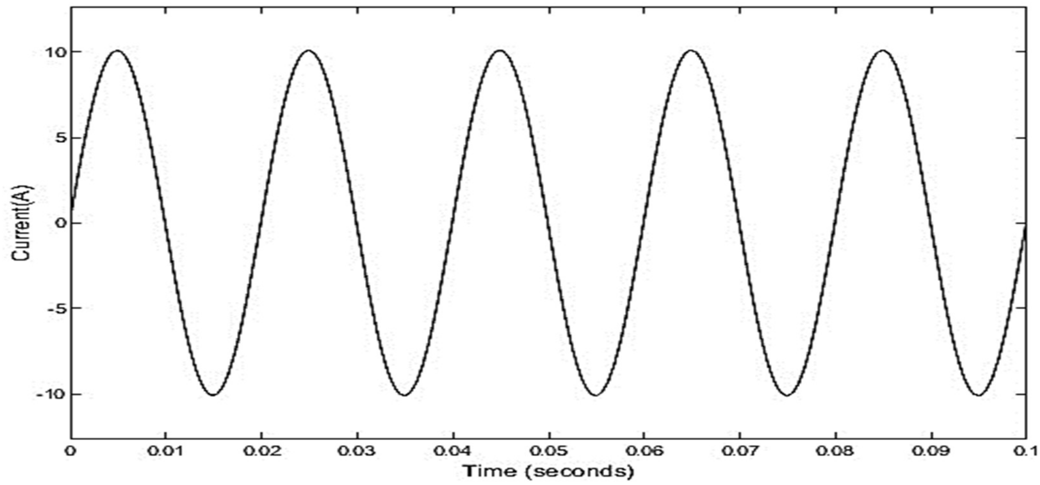


(e)

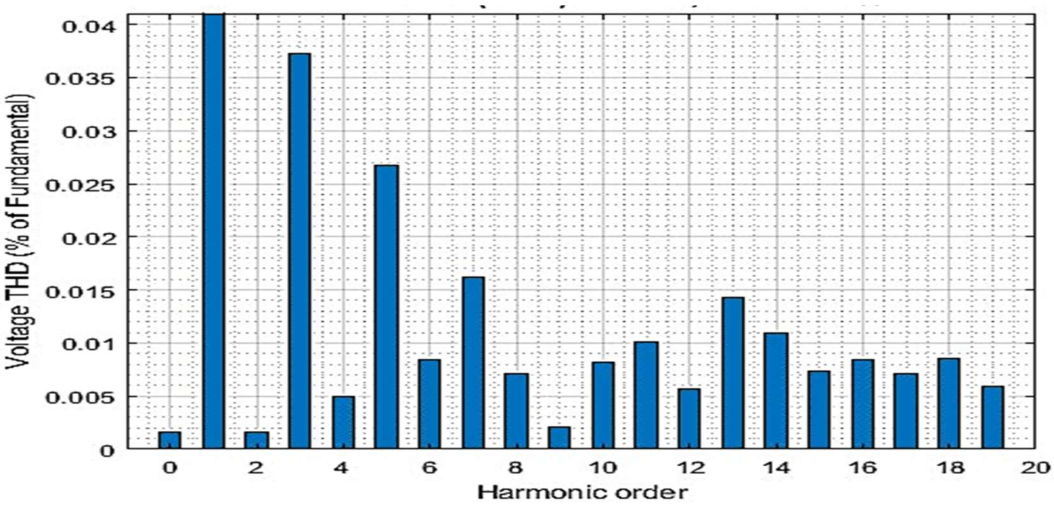
Figure 5: Pre-filtering simulation of FUNAAB's 250-seater computer laboratory facility distribution network (a) voltage waveform (b) current waveform (c) voltage spectrum (d) current spectrum (e) power loss waveform



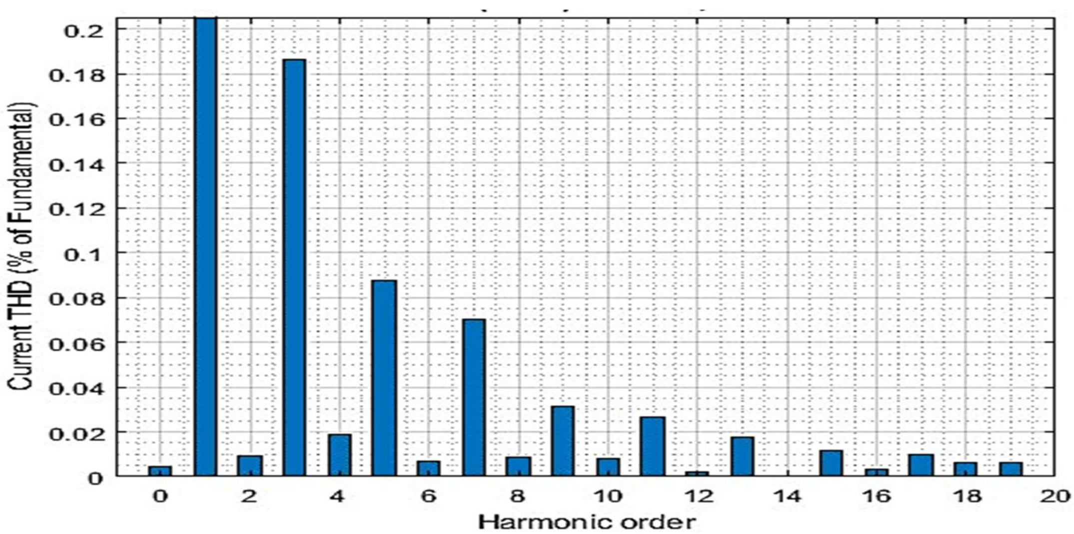
(a)


Current(A)
Time (seconds)

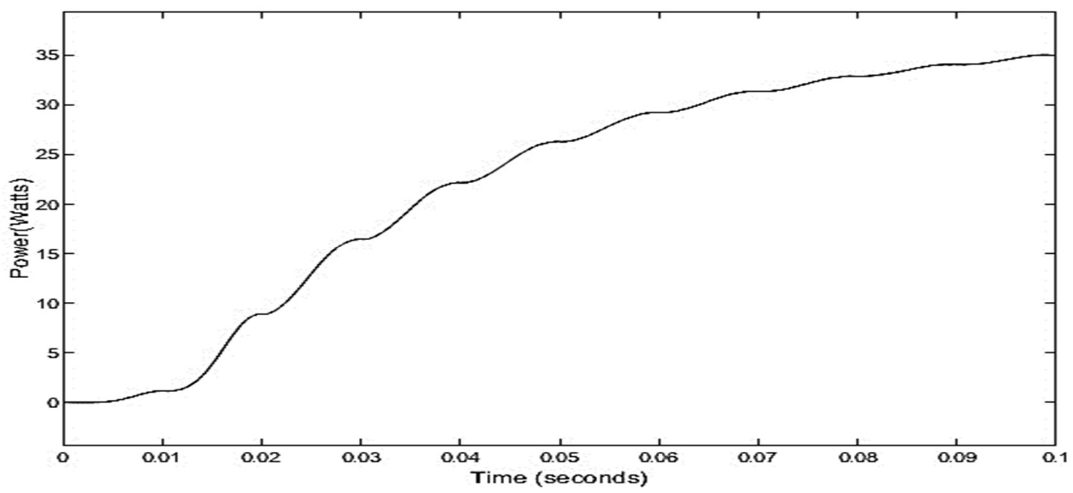
(b)


Voltage THD (% of Fundamental)
Harmonic order

(c)


Current THD (% of Fundamental)
Harmonic order

(d)



(e)

Figure 6: Post-filtering simulation of FUNAAB's 250-seater computer laboratory facility distribution network with SeShPF (a) voltage waveform (b) current waveform (c) voltage spectrum (d) current spectrum (e) power loss waveform

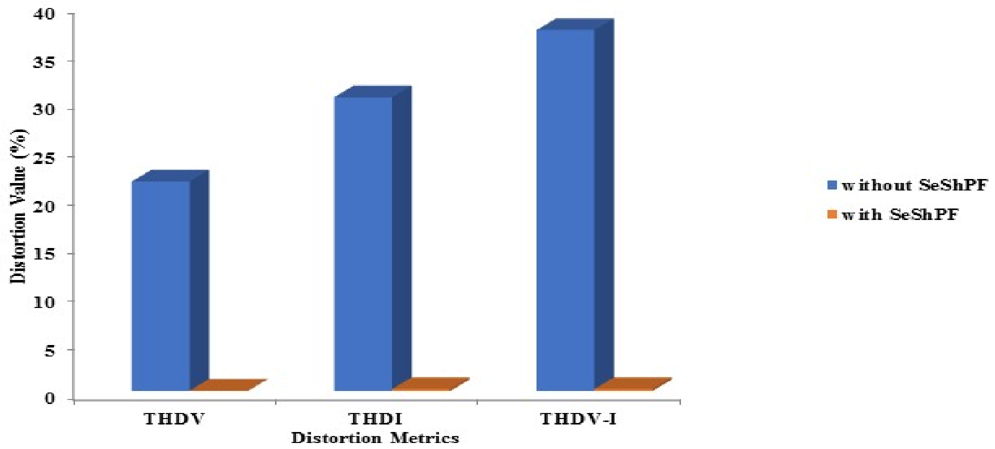


Figure 7: Comparison of distortion metrics before and after SeShPF application on FUNAAB's 250-seater computer laboratory facility distribution network

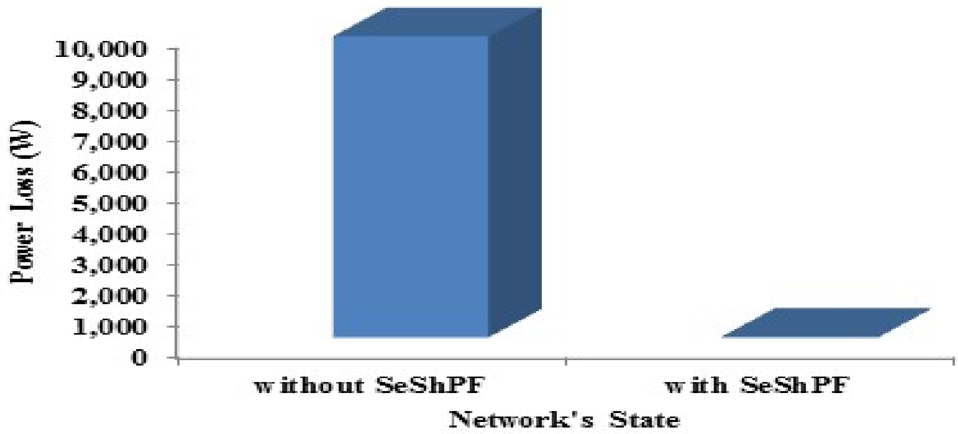


Figure 8: Power losses comparison before and after SeShPF application on FUNAAB's 250-seater computer laboratory facility distribution network

This study's outcomes aligned with the works of Ogundele *et al.* (2023), Aziz et al. (2021), Zobaa *et al.* (2018) and Adebisi *et al.* (2017) where findings revealed that a passive filter application has a significant harmonic suppression capability on a power system network. Thakur *et al.* (2022) asserted that harmonic distortion has a detrimental influence on power quality and raises power loss. This claim was consistent with this study's outputs which demonstrated that SeShPF use is capable of lowering electrical network harmonic content and power loss and consequently, enhance the power quality of the supply delivered to the end-users.

Conclusions

Power quality is threatened by harmonics, which can lead to major efficiency issues in any power network. This study dealt with the examination of harmonic distortion-power loss interaction under influence of a SeShPF with FUNAAB's 250-seater computer laboratory facility distribution network considered as a test case. The study showed that when no filter was used on the network, a high degree of harmonic penetration was observed which resulted into a high distortion level and active power loss. The SeShPF use significantly decreased the THD and the resulting system active power loss. According to the study, a power loss in an electrical distribution network is directly correlated with harmonic distortion; the effects of which are curtailed by the application of a SeShPF.

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