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Performance Evaluation of a Hybrid Passive Filter and AI-Based Optimization Techniques for Harmonic Distortion Mitigation in the Nigerian Power Network

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Abstract

Non-linear loads are the primary causes of harmonic distortion in power system network and these loads are essential house hold equipment that are essential for daily living and for comfort. However, the occurrences of harmonic distortions result to the power system failure leading to blackouts. This paper determined the impact of distortion on the current and voltage signals of Nigerian 330 kV system in the North Central region and utilized the machine learning controlled passive filter for the mitigation of the impact of the harmonic distortion. The case study region had 6 buses and the total harmonic distortion (THD) for these buses were obtained. The THD of the current signal for without, with standalone passive filter and RNN-controlled passive filter were (16.21 %, 4.73 % and 1.89 % for bus 1), (17.55 %, 4.41 % and 2.01 % for bus 2), (18.72 %, 3.88 % and 1.91 % for bus 3), (15.93 %, 3.12 % and 1.89 % for bus 4), (17.51 %, 4.83 % and 1.19 % for bus 5) and (17.04 %, 4.81 % and 1.03 % for bus 6). The outcome voltage signals obtained were (13.21 %, 4.33 % and 2.72 % for bus 1), (14.81 %, 3.73 % and 2.13 % for bus 2), (16.44 %, 4.34 % and 2.92 % for bus 3), (12.92 %, 3.93 % and 2.72 % for bus 4), (15.24 %, 4.53 %, and 2.12 % for bus 5) and (14.55 %, 4.41 % and 2.02 % for bus 6) respectively. It was observed that the RNN-controlled filter had a better performance than the standalone passive filter.

Keywords: Power System Network; Harmonic Distortion; Current and Voltage Signal; Passive Filter; Machine Learning; RNN And THD

1. Introduction

The electrical power system network is a complex system that ensures the interconnection of the power system components to ensure that the flow of electricity commences from the power source to the power destination [1]. The designed power system network is meant to carry out power generation, transmission and distribution to the consumers [2]. The components of the power system network include [2]. The generation of electrical power can be conventional (coal, thermal and nuclear power plant) and renewable source (solar system, wind turbine, biomass designed generator and hydro-electric generation system). The generating plant generates electricity at low voltage rating between 11 kV-15 kV [4, 5]. The transmission systems transmit electricity at high voltages for a longer distance and the generated power would be sent to a step-up transmission to increase the voltage rating so as to ensure that all customers especially those at a longer distance from the generation plant have access to electricity. The transmitted power is usually between 66 kV to 765 kV voltage rating and it locates various designed substations before locating the distribution stations [6, 7]. The distribution system receives electricity from the transmission system and steps the voltage down to lower voltages between 11 kV and 415 V. This is to ensure safe delivery to the end-users through designed feeders [8, 9].

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Lots of works have been carried out in the field of power systems stability and improved power transfer capability. [10] utilized FACTS such as IPFC, UPFC and TCSC to improve the available transfer capacity of the power flow in the Nigerian 330 kV transmission network by reducing the power flow congestion to ensure that a large amount of power generated is transferred to the end-users. In High impedance fault (HIF) detection and location in the Nigerian 330 kV transmission network using adaptive neuro-fuzzy inference system [11], the detection and location of HIF in the South-South region of Nigerian 330 kV transmission power system was carried out and the results show the effectiveness of the ANFIS model developed in the detection and location of HIF at minimal deviation errors. The authors in “detection and classification of high impedance fault in Nigerian 330 kV network using ANN: a case study of the southeast transmission network” [12] outlined the detection and classification of HIF occurrence using ANN model in the South eastern Nigerian 330 KV network on the following transmission line; Alaoji GS to Owerri TS, Alaoji GS to Onitsha and from Onitsha TS to New Heaven TS. The HIF classification outcome presented after inserting the ANN model in the power system model indicated a perfect HIF classification. Further works on improving real-time power quality using ANFIS-controlled hybrid active filter for total harmonic distortion (THD) reduction [13], was carried out. Standalone active filter and active filter with ANFIS boost were utilized for the mitigation of THD in a real time 33 kV network located in Nigeria and it was proven that the hybrid of active filter and ANFIS controller was more suitable for the purpose of mitigating the THD than the stand-alone active filter. The authors in [14] utilized a stand-alone single-tuned passive filter and a hybrid of a passive filter and ANN model control mechanism for the mitigation of the impact of harmonic distortion on the Nigerian 330 kV transmission network situated in the North central region of Nigeria. The outcome of the simulation showed that the hybrid filter had the best performance as it reduced the THD of the current signal considerably. Comparative analysis of ANN and ANFIS models to locate three phase HIF occurrences in the power system network of the 330 kV transmission network in southern Nigeria was also conducted [15]. The HIF location point distances were projected and shown for the three locations with error deviation from the actual distance obtained and plotted. The results showed that the ANFIS model had a better point location of HIF occurrence than the ANN model.

2. Review of Related Literature

The current, voltage and frequency signals generate a perfect sinusoidal wave when the power system network is devoid of any fault occurrence. However, when undesired higher frequency signals which are multiples of fundamental frequency inter-jects with the clean signals, it hampers the smooth flow of the signals resulting in signal distortion [16, 17]. This undesired signal is attributed to be caused by the presence of non-linear loads with sources from modern electronics such as power supplies that are of switch mode, VFDs and LED lights [18]. The electronics generate un-sinusoidal signals that draws current, voltage and frequency signals in non-sinusoidal pattern resulting to smooth signal disruption which has a negative impact on the power system generation plants and other power system equipment as a result of overheating, failures and reduction in equipment reliability [19, 20].

The occurrence of the unwanted signal is always measured and quantified using the THD via determining the percentage unwanted harmonic content in the power system signals and compared to the fundamental frequency [21]. THD is utilized in determining how far the existing signal waves deviate from a perfect signal waveform and the occurrence of high THD without mitigation process would result to power equipment damages and failures [22]. To prevent the impact of the occurrence of the harmonic distortion on power system network signals, it is necessary to utilize the filters to eliminate the unwanted distortion signals and the types of signals filters that exists are active filter and passive filter. [13] utilized an ANFIS-controlled active power filter to mitigate the occurrence of harmonic distortion on the power system network with emphasis on reducing the THD values of voltage and current signal. In this work and considering the Nigerian 330 kV in the North central region, a hybrid of passive filter and machine learning model is utilized for the mitigation of the harmonic distortion in the power system network. The line diagram information from the National Control Center (NCC) in Osogbo is modeled in Simulink and filters are implemented for harmonic distortion mitigation. The THD is utilized in determining the level of the presence of harmonic distortion before and after the implementation of the hybrid filter in the power system network.

3. Materials and Method

The power system network design is centered on Ohms law with the equation shown in equation 1 [23].

$$V = ZI \qquad (1)$$

where V represents the voltage phasor of the power system network, I represents the current signal of the network and Z represents the impedance shown in equation 2.

$$Z = R + jX \tag{2}$$

where R and X represent the resistance and reactance of the power system respectively.

For the power equations (AC systems) the apparent power is shown in equation 3.

$$Z = P + jQ \tag{3}$$

where P represents the real power and Q represents the reactive power. The equation for the real power is shown in equation 4 while the equation for the apparent power was shown in equation 5.

$$P = IV\cos\theta \tag{4}$$

$$P = IV\sin\theta \tag{5}$$

where θ represents the phase angle of the power system network.

Some of the occurrences that hinders the smooth power flow process are faults and harmonic distortion largely due to the installations and utilizations of non-linear loads, solar system as a power source and the use of transformers. Harmonics in power system signals are represented as sinusoidal waves that contains fundamental frequency of integer multiples. The harmonic distortion waveform of current signal (It) is shown in equation 6.

$$I_t = \sum_{h=1}^{\infty} I_h \sqrt{2}\sin(hwt + \theta_h) \tag{6}$$

where h represents the harmonic order.

Machine learning is an area of data science and artificial intelligent system that can be implemented and utilized as a control mechanism to power filters in ensuring increase in power quality of the power system network [24]. The machine learning models comprise of supervised learning, unsupervised learning and reinforced learning. This paper utilizes regression neural network (RNN) as a hybrid to the passive power filter in reducing the impact of the occurrence of harmonic distortion on the voltage and current signals. The performance of the utilization of standalone passive filter and the hybrid filter is carried out using current and voltage THD metrics. The real time power system network studied is the Nigerian 330 kV North central network and the line diagram of the network is shown in Figure 1.

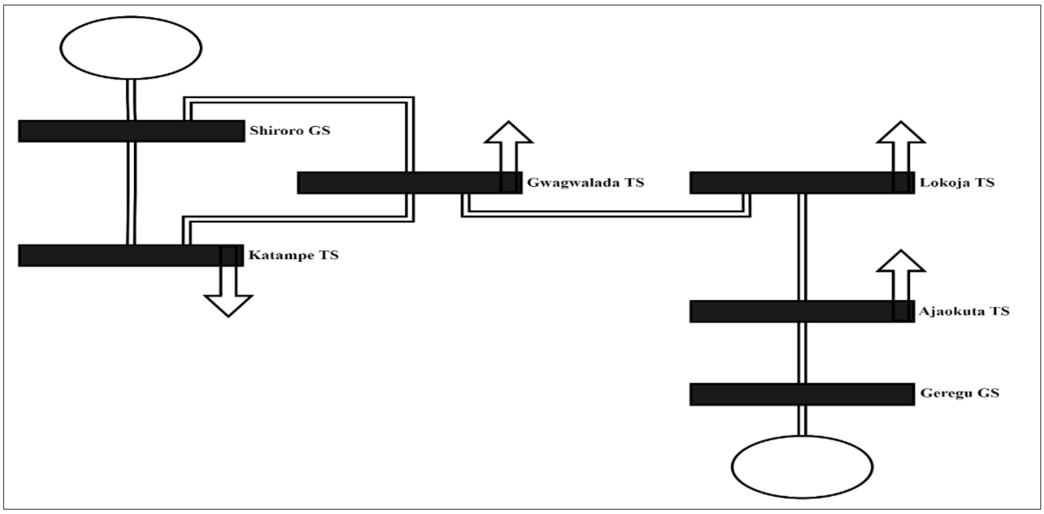

Figure 1 Power system network line diagram

The bus numbering is as presented in table 1.

Table 1 Bus numbering

Bus Number	Bus Location
1	Shiroro GS
2	Katampe TS
3	Gwagwalada TS
4	Lokoja TS
5	Ajaokuta TS
6	Geregu GS

The line diagram is modeled in SIMULINK environment and depicted in Figure 2.

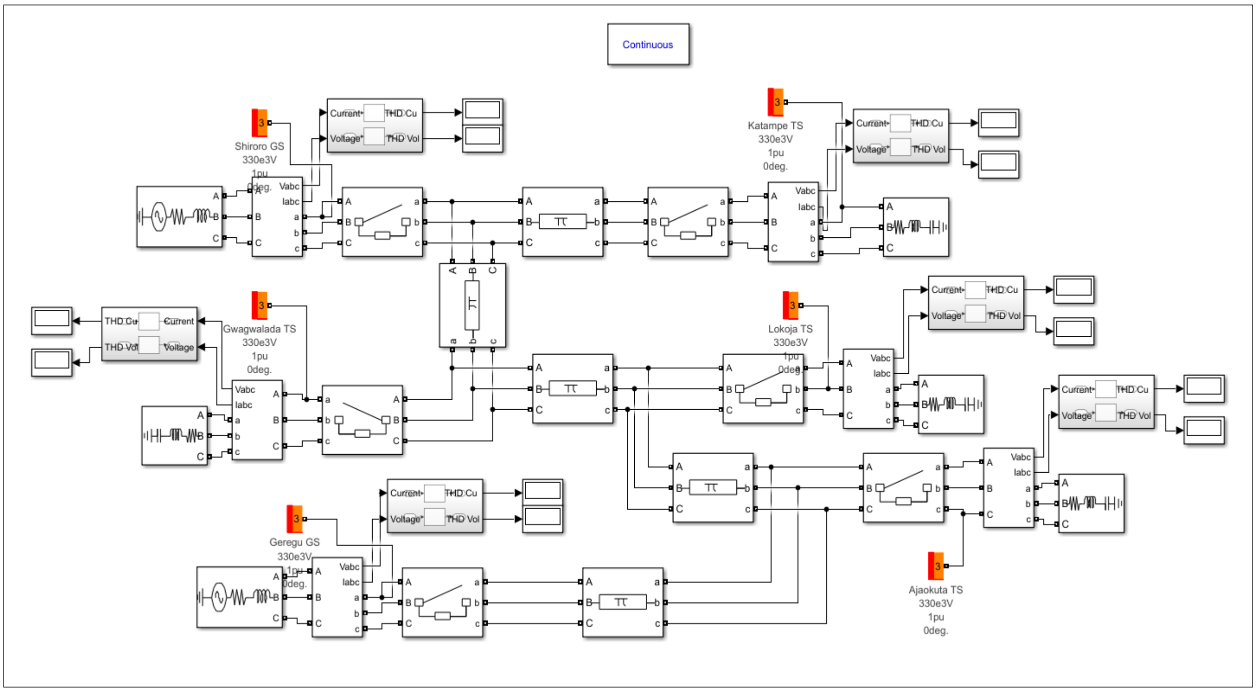

Figure 2 SIMULINK representation of the Power system line diagram

The power system network displayed in Figure 1 and Figure 2 comprises of six (6) buses and five (5) transmission lines. the line data utilized for the model of the power system network in SIMULINK is given in Table 2.

Table 2 Line data of power system network

Line number	From bus	To bus	Distance (kM)	Resistance (ohms)	Reactance (ohms)
1	1	2	167	2.441	3.181
2	1	3	144	1.814	2.117
3	2	3	192	1.552	1.551
4	3	4	127	1.281	2.774
5	4	5	83	1.094	1.816
6	5	6	72	1.213	2.011

The type of passive filter utilized was a passive-series single-tuned harmonic filter (LC) and the expression for the single-tuned frequency f_t is given in equation 7 while the reactive power from the filter is as depicted in equation 8.

$$f_t = \frac{1}{2\pi\sqrt{LC}} \qquad (7)$$

$$Q_R = \frac{V^2}{X_c} - X_l \qquad (8)$$

where X_C and X_l represents the reactive capacitance and reactive inductance respectively.

The model for the regression neural network (RNN) which is the machine learning model employed is given in equation 9.

$$y = \propto_2 (W_2 \propto_1 (W_1 x + \infty_1) + \infty_2) \qquad (9)$$

where $\propto_2$ and $\propto_1$ represents the output and hidden activation for linear and non-linear functions respectively. RNN in this case is used as a feed forward system and the outcome of the passive filter is utilized as the input to the model. the RNN structure is as shown in Figure 3.

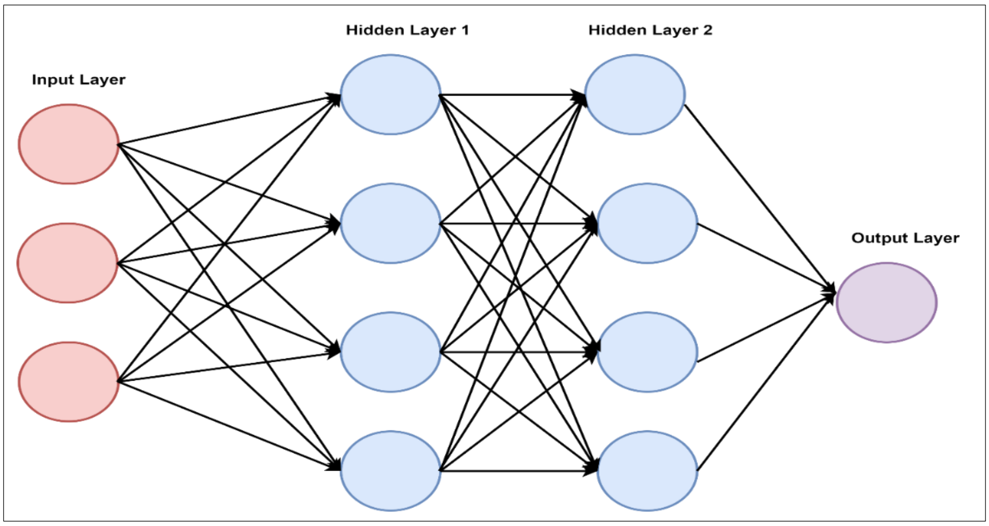

Figure 3 Generalized Structure of the RNN Model

The input layer has two neurons which represent current and voltage signals, the hidden layer has four hidden neurons and the output layer has two neurons which are voltage and current signals.

The outcomes of the impact of the RNN controlled passive filter are presented in the result section. The performance of the hybrid filter is measured with the voltage and current THD and the model outcomes are shown in equations 10 and 11.

$$THD_V = (V_1^2 + V_2^2 + \cdots + V_n^2)^{0.5} \qquad (10)$$

$$THD_i = (I_1^2 + I_2^2 + \cdots + I_n^2)^{0.5} \qquad (11)$$

4. Results and Discussion

The barchart of the voltage and current THD for with and without filters (without filter, standalone passive filter and passive-RNN filter) for bus 1 is depicted in Figure 4 where it is observed that combined RNN and passive filter mitigated healthily against THD than the standalone passive filter and the system without the filters.

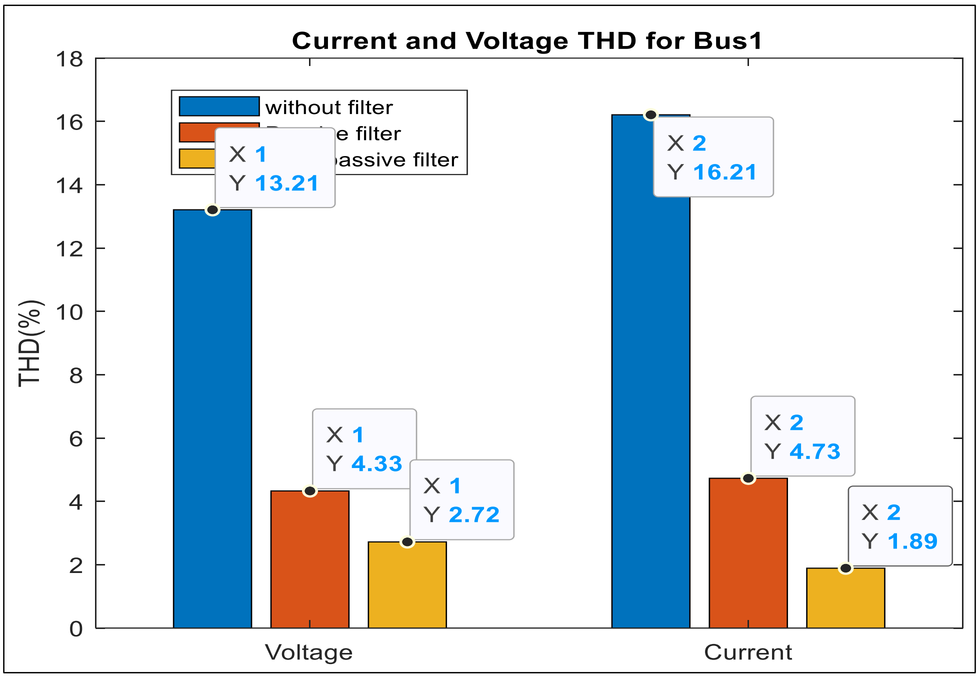

Figure 4 THD of the voltage and current signal for bus 1

The barchart of the voltage and current THD for with and without filters (without filter, standalone passive filter and passive-RNN filter) for bus 2 is shown in Figure 5.

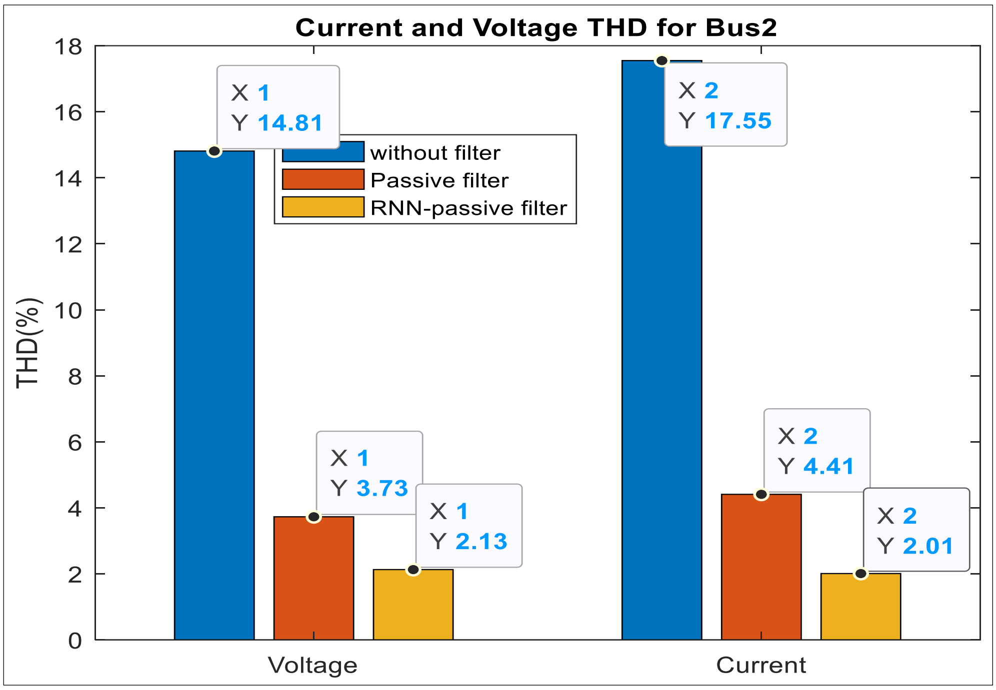

Figure 5 THD of the voltage and current signal for bus 2

The barchart of the voltage and current THD for with and without filters (without filter, standalone passive filter and passive-RNN filter) for bus 3 is also illustrated Figure 6.

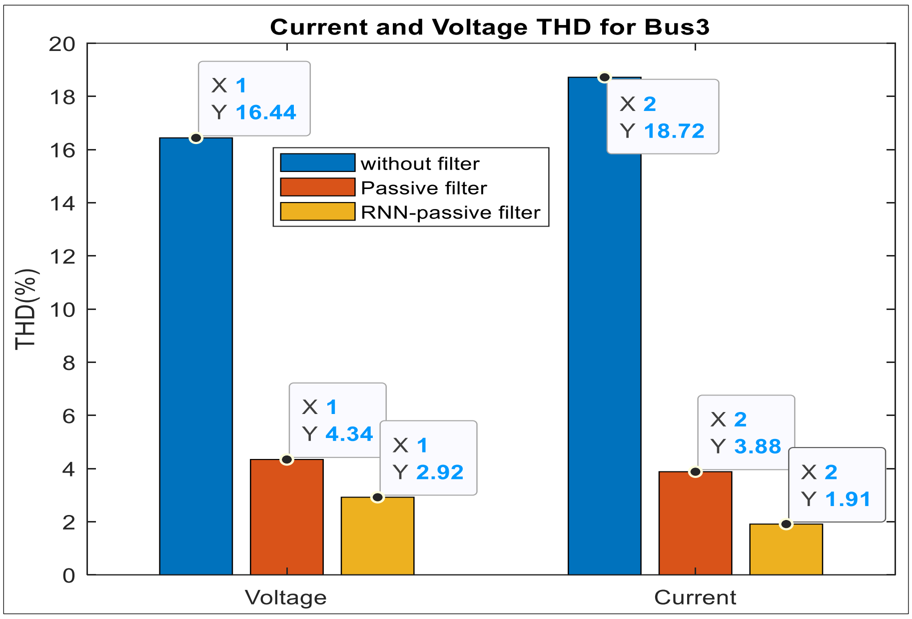

Figure 6 THD of the voltage and current signal for bus 3

The barchart of the voltage and current THD for with and without filters (without filter, standalone passive filter and passive-RNN filter) for bus 4 is shown in Figure 7.

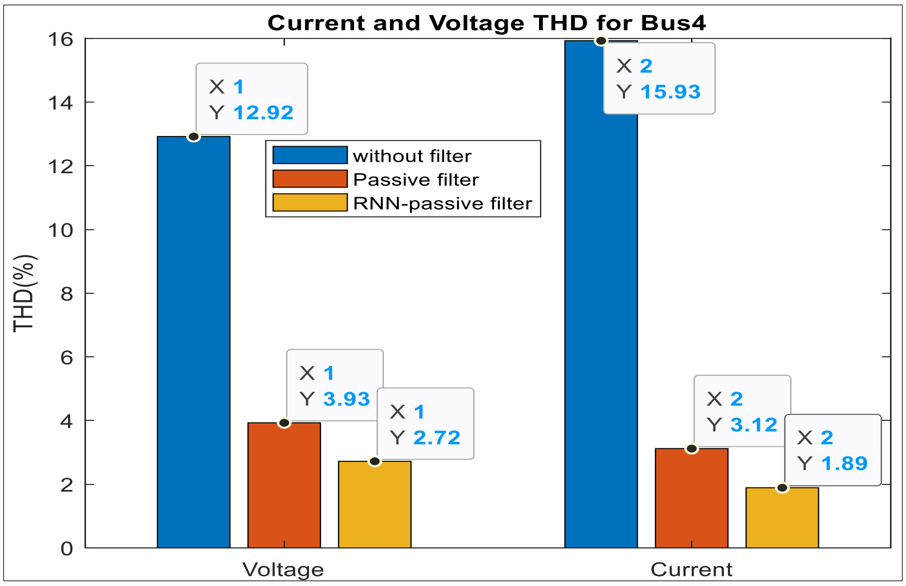

Figure 7 THD of the voltage and current signal for bus 4

The barchart of the voltage and current THD for with and without filters (without filter, standalone passive filter and passive-RNN filter) for bus 5 is depicted in Figure 8.

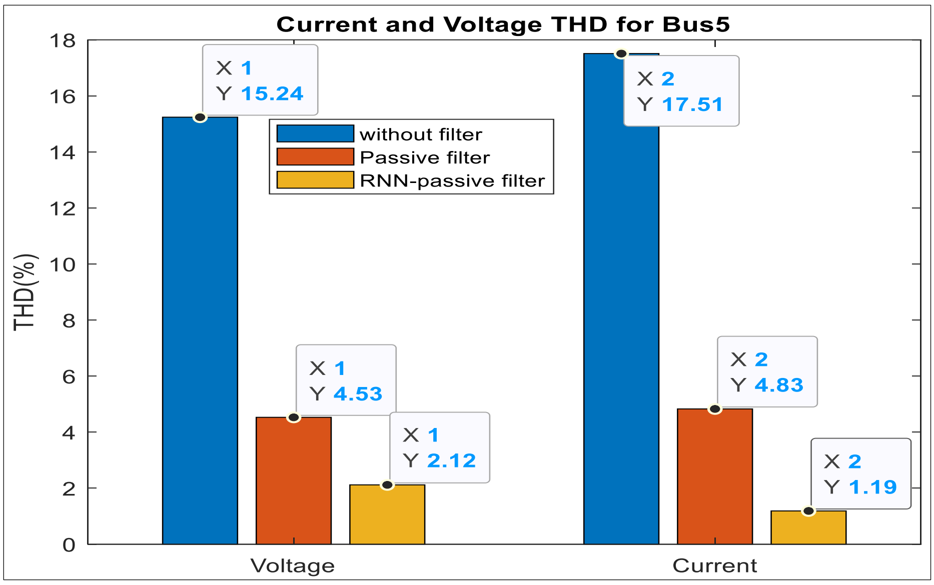

Figure 8 THD of the voltage and current signal for bus 5

The barchart of the voltage and current THD for with and without filters (without filter, standalone passive filter and passive-RNN filter) for bus 6 is shown in Figure 9.

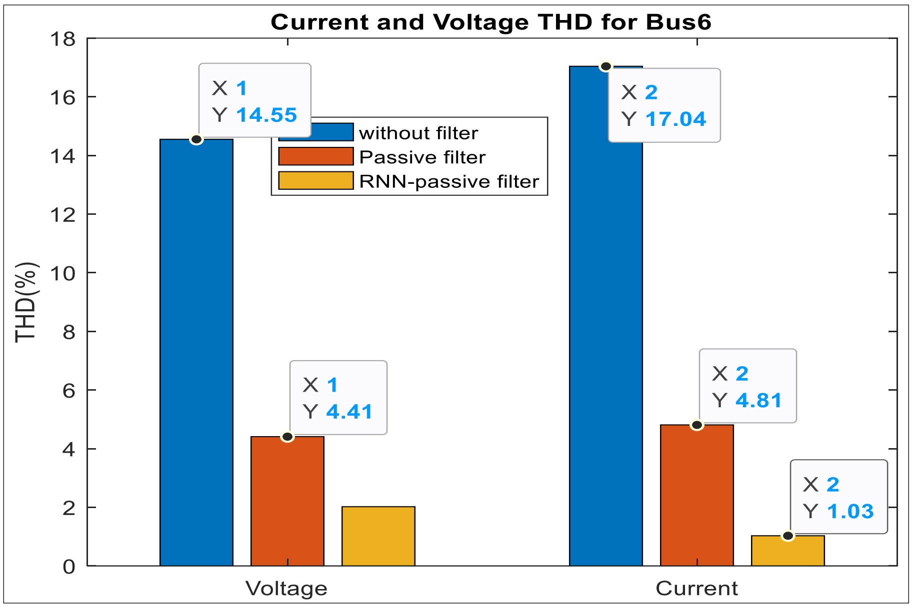

Figure 9 THD of the voltage and current signal for bus 6

Figure 4 to figure 9 show the barchart of the THD of the current and voltage signals for the six buses. It is observed that the THD of the system without filter exited the threshold of 5% and the impact was more on the current signal. The implementation of standalone passive filter mitigated the harmonic distortion impact to generate THD of voltage and current signals to be a bit below 5% and the implementation of the hybrid filter mitigated the impact of the harmonic distortion less than 2%.

5. Conclusion

The impact of the occurrence of harmonic distortion on the power system network leads to the shutdown of the generation plants and obstruction to the power flows on transmission and distribution system. The machine learning controlled passive filter was utilized in mitigating the impact of the occurrence of harmonic distortion on voltage and current signals on the Nigerian 330 kV north central region. It was found that the THD of the power system network without filter exceeded 13% for all the buses and the utilization of standalone passive filter reduced the harmonic impact to less than 5%. The most excellent filter was the hybrid of passive filter and machine learning with the THD obtained being not more than 2%. However, it is recommended that other machine learning be utilized as hybrid to passive filter with comparative analysis carried out to determine their performance against the RNN controlled filter.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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