Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/

(Research Article)

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A novel hybrid passive filter-ANN control approach for harmonic distortion suppression in electrical transmission network

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Global Journal of Engineering and Technology Advances, 2025, 25(03), 247-255

Publication history: Received 11 November 2025; revised on 18 December 2025; accepted on 20 December 2025

Article DOI: https://doi.org/10.30574/gjeta.2025.25.3.0355

Abstract

The lack of control of the occurrence of harmonic distortion results to the power system equipment overheating thereby increasing in energy loss, premature aging of the equipment, inaccuracy and reliability issues in sensitive and critical electronic devices. The harmonic distortions are majorly caused by non-linear loads and injection of renewable energy devices mainly, solar system network which are necessary for day-to-day activities. Hence, the paper utilized a standalone 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 330kV transmission network situated in the North central region of the country. The total harmonic distortion (THD) metrics were utilized for the determination of the performance of the filters utilized sequentially in mitigating the impact of the harmonic's distortion on the current and voltage signals. From the outcome of the simulation, the utilization of the hybrid filter had the best performance as it reduced the THD of the current signal to 1.072% and 1.213% for the Benin kebbi and Kainji bus stations respectively and voltage signal to 1.772% and 1.993% for the Benin kebbi and Kainji bus stations respectively

Keywords: Harmonic Distortion; Transmission; Passive Filter; ANN. Hybrid Filter; THD

1. Introduction

The occurrence of harmonic distortion on the power system network especially on the transmission and distribution lines can be defined as the presence of undesired components of frequency known as harmonics which are the multiple integers of the fundamental frequency [1]. The presence of non-linear loads are the primary causes of harmonic distortion in power system network in that these loads draw frequency, voltage and current signals that fails to represent the perfect sine wave and introduces these waves into the power system network. Variable frequency drives (VFDs), un-interrupted power supplies (UPSs), battery charging devices, inverters of all the DC power generation systems such as solar, wind and rectifier systems constitutes these non-linear loads that increases the presence of harmonic distortions in the power system network [2, 3].

The presence of harmonic distortion in power system network can increase the temperature of the transformers, windings in the generation plants and motors, leading to the occurrence of overheating and sudden power failure in these devices [4]. The occurrence of harmonic distortion in the power system network can be amplified by the combination of the capacitance and inductance of the network at the harmonic frequencies. Additionally, the occurrence of harmonic distortion especially in the current signal increases the resistance of a power system lines, resulting in power flow congestion leading to losses and invariably rise in power system instability. Increase in distortion of harmonics can result to increase in inaccurate measurements from energy meters and can also interfere sensitive

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communication and electronic devices. The presence of nonlinear loads and harmonics combination can give rise to voltage instability and fluctuations [5, 6].

The major area of study in this paper is the Nigerian transmission system. The Nigerian power system network is one of the complex networks in the world. According to the reports presented in [7], Nigeria operates a 330 kV system of 58 buses comprising of transmission and generation systems. This power system is beset with lingering problems, which include severe power losses, as well as very low transfer capability of the transmission network to evacuate power from generating stations to the load at the distribution level. The majority of the generation stations utilize asynchronous (induction) generators whose stability needs to be determined consistently. These induction machines experience transient disturbances which affect their performances [8] because the occurrence of harmonic distortion can cascade to the generation devices that has not been designed to withstands faults. Industrially, 330 kV system is transmitted in industrial operations and the occurrence of harmonic distortion can damage the motors currently in operation. Hence, from the findings in [9] it is imperative to always investigate the magnetic characteristics of industrial motors using transient analysis to improved starting torque and reduced torque ripple and to ensure that the torques are always enhanced and stabilized.

One of the fundamental effects of the occurrence of harmonic distortion is to minimize the transient stability of the power system network. Since the generation stations in the Nigerian power system network are of multi-machines in nature, the occurrence of transient instability could damage the operation of the generation plants quickly. One of the major disadvantages of network enlargement is the deterioration in the damping torque of the whole system which mitigates against the system in the form of fluctuations and dynamic instability [10]. With the ongoing expansions and growth of the electric utility industry, including deregulation in Nigeria, numerous changes characterized by additional generating stations, increase in transmission lines and loads are experienced thereby pushing the transmission systems closer to their stability and thermal limits and hence, causing the transfer of reactive power during steady state operating conditions to constitute a major problem of voltage instability [11]. Hence, several transient and steady-state stability improvements avenue have been utilized for the improvement of power system network with emphasis on the deployment of FACTS device as in the "application of FACTS devices in a multi-machine power system network for transient stability enhancement: A case study of the Nigerian 330 kV 48-bus system" [12]. However, the efficient way of mitigating the effect of the occurrence of harmonic distortion is the use of active and/or passive filter.

The power system network under study is a 330 kV transmission network located in the North-central region. The power system network of the location is obtained and modeled in SIMULINK to obtain the rate and level of harmonic distortion on the current and voltage signals of the network. Additional total harmonic distortion (THD) metrics is utilized in measuring the level of distortion for each of the signals and transmission lines. Then a passive filter boosted with artificial neural network (ANN) model is utilized in the mitigation of the harmonic distortion.

2. Literature review

The major components that constitute harmonic distortion is the utilization of non-linear loads which are majorly house hold electronics. These non-linear loads inject distortions in the form of sine and cosine wave Fourier series into the current and the voltage signals waves. The Fourier series sine wave for current signal is shown in equation 1 [13].

$$i_t = I_{dc} \sum_{k=1}^{\infty} i_k \sin(kwt + \theta_k) \quad (1)$$

The Fourier series cosine wave model is shown in equation 2 [14].

$$i_t = I_{dc} \sum_{k=1}^{\infty} i_k \cos(kwt + \theta_k - 90^0) \quad (2)$$

For the voltage signal, the sine and cosine waves are shown in the equations 3 and 4 respectively.

$$v_t = V_{dc} \sum_{k=1}^{\infty} v_k \sin(kwt + \theta_k) \quad (3)$$

$$v_t = V_{dc} \sum_{k=1}^{\infty} v_k \cos(kwt + \theta_k - 90^0) \quad (4)$$

Where i_i and v_t represent the current and voltage sine and cosine Fourier model respectively, I_{dc} and V_{dc} represent average current and voltage or dc current and voltage value, i_k and v_k represent the current and voltage harmonics peak value, w represents the fundamental frequency and θ_k, the harmonic distorted phase angle.

With the introduction of period (T), the sine and cosine waves can be written in rectangular equations as shown in the equations (5-6) [15];

$$i_t = I_{dc} + \sum_{k=1}^{\infty}[a_{i,k} \cos\left(\frac{2\pi kt}{T}\right) + b_{i,k} \sin\left(\frac{2\pi kt}{T}\right)] \quad (5)$$

$$v_t = V_{dc} + \sum_{k=1}^{\infty}[a_{v,k} \cos\left(\frac{2\pi kt}{T}\right) + b_k \sin\left(\frac{2\pi kt}{T}\right)] \quad (6)$$

In the triangular modeling, for the case of current signal, it is represented in equation (7-9) [16],

$$I_{dc} = \frac{1}{T}\int_{t_0}^{t_o+T} i_t dt \quad (7)$$

$$a_{i,k} = \frac{2}{T}\int_{t_0}^{t_o+T} i_t \cos(\frac{2\pi kt}{T})\, dt \quad (8)$$

$$b_{i,k} = \frac{2}{T}\int_{t_0}^{t_o+T} i_t \sin(\frac{2\pi kt}{T})\, dt \quad (9)$$

In the triangular modeling, for the case of voltage signal, it is represented in equation (10-12),

$$V_{dc} = \frac{1}{T}\int_{t_0}^{t_o+T} v_t dt \quad (10)$$

$$a_{v,k} = \frac{2}{T}\int_{t_0}^{t_o+T} v_t \cos(\frac{2\pi kt}{T})\, dt \quad (11)$$

$$b_{v,k} = \frac{2}{T}\int_{t_0}^{t_o+T} v_t \sin(\frac{2\pi kt}{T})\, dt \quad (12)$$

Where t_0 refers to the time t=0 which is the startup of the harmonic distortion sine and cosine waves where the harmonic distortions in the voltage and current signals occur in orders. Equations 5 and 6 represents the current and voltage distortions in the first order.

Harmonic distortion occurs mainly on the transmission system and the distribution system and it has been found to be more prevalent on the distribution systems due to the close proximity to the non-linear loads generated at the consumption level. This distortion of harmonics in the power distribution network impedes the improvement of power quality especially in the distribution network [17]. For the distortion on the transmission lines, it is preferable to utilize passive filter than the active filter because, the passive filter is more economical and the single-tuned passive filter is the most reliable of the passive filter control system. The topology of the single-tuned passive filter is shown in Figure 1.

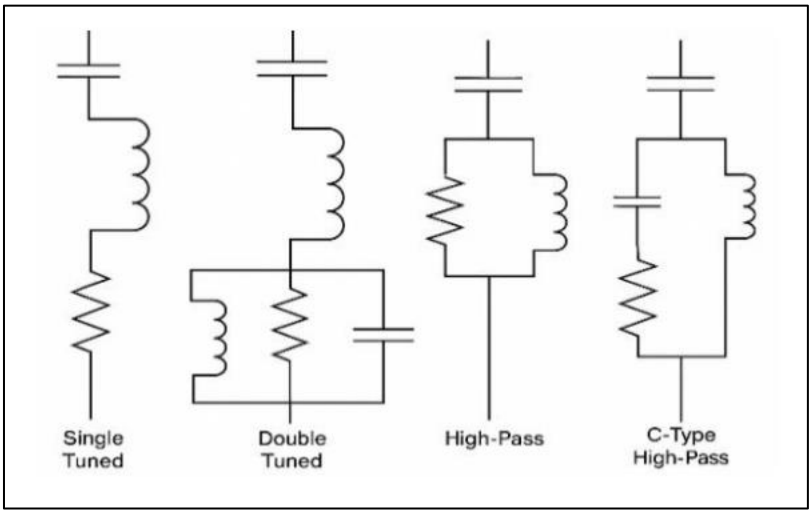

Figure 1 Topology of the various type of tuned passive filter [18]

From Figure 1, the single-tuned passive filter is the most implemented in the industries and also utilized in the high voltage transmission systems in power system network majorly due to its simplicity.

3. Materials and method

The power system network utilized in the paper is a 2-bus real time network of Nigerian 330 kV network situated at the north central region of the country. The single line diagram of the network is shown in Figure 2.

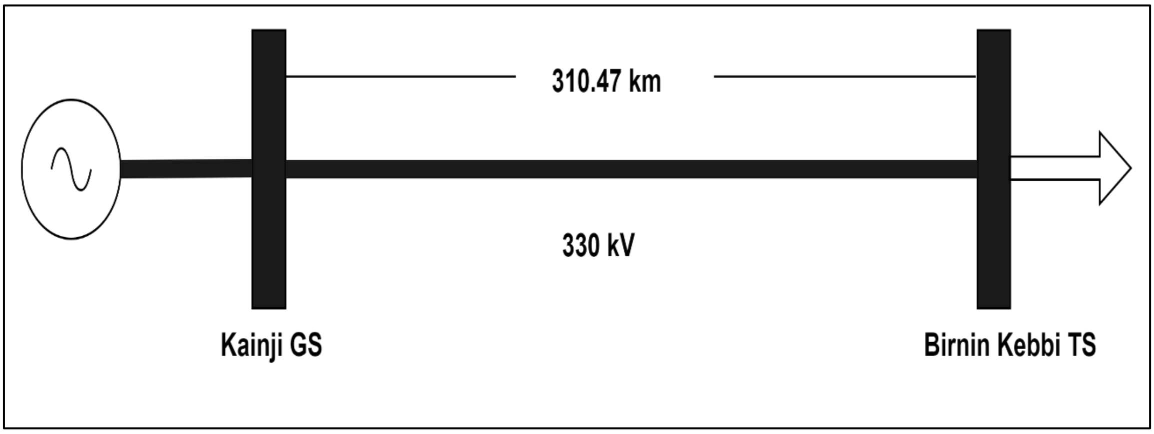

Figure 2 Single line diagram of the transmission network

The telegraph models are utilized for the generation of the voltage and current signals in the transmission system network and the models utilized are shown in equations 13 and 14.

$$\frac{\partial v(t,z)}{\partial z} + \frac{\partial i(t,z)}{\partial t} + Ri(t,z) = 0 \quad (13)$$

$$\frac{\partial i(t,z)}{\partial z} + \frac{\partial v(t,z)}{\partial t} + Gv(t,z) = 0 \quad (14)$$

For the purpose of this paper, the transmission is considered to be devoid of active and reactive losses, hence, R=G=0. Equation 13 and 14 become a wave equation as shown in 15 and 16

$$\frac{\partial^2 v}{\partial z^2} = LC\frac{\partial^2 v}{\partial t^2} \quad (15)$$

$$\frac{\partial^2 i}{\partial z^2} = LC\frac{\partial^2 i}{\partial t^2} \quad (16)$$

Where v(t,z) represents the voltage at time t and distance z, i(t,z) the current signal at time t and distance z of the transmission line, R, L, C and G represents the resistance, inductance, capacitance and conductance, all in per unit length.

Since the voltage rating of the power system model is 330 kV, passive filter is the conventional filter utilized for the harmonic distortion impact mitigation. The type of the passive filter utilized is a single-tuned passive filter with the model as shown in equation (17) [19].

$$P_{AP} = P_{RP}(\tan(cos^{-1} pf_a) - \tan(cos^{-1} pf_d)) \quad (17)$$

Where P_{AP}, represents the apparent power from the filter to the transmission line, P_{RP} the real power flow in the transmission line, pf_a and pf_d the actual (0.8), and the desired (0.85) power factors respectively. The transfer function of the filter is shown in equation 18.

$$P(jw) = \frac{1}{1+jwRC} \quad (18)$$

Where P represents the power flow, R and C the resistance and the capacitance respectively.

For the performance of the passive filter to be effective, it is boosted with ANN model. The ANN model is designed using the current and the voltage signal output of the passive filter which is in turn used as the input data to the ANN and the output being the harmonic distortion mitigated output signal. The structure of the ANN model is shown in Figure 3.

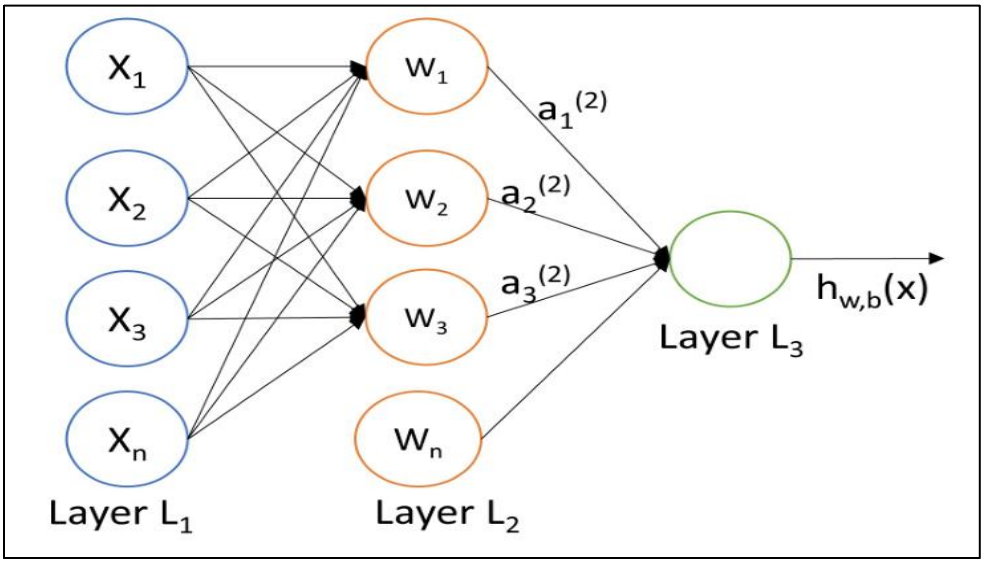

Figure 3 Structure of ANN

The input neurons are the current and voltage outputs of the passive filter making up the 2 neurons. The hidden neurons are five, with each neurons using log sigmoid model shown in equation 19

$$\log(n) = \frac{1}{1+e^{-n}} \tag{19}$$

Where n represents the input signals.

The output neurons are the output harmonic distortion mitigated current and voltage signals. The model for determining the output signals from the inputs in ANN is shown in equation 20 [20, 21].

$$O_i = \sum_i w_i x_i + b_i \tag{20}$$

Where O_i represents the output of each variable I, x_i the input of each variable I, w_i and b_i the weights and biases per variable.

The metrics utilized for the measurement of the performance of the filters is the total harmonic distortion (THD). The model for voltage and current signal is shown in equations 21 and 22.

$$THDi = (i_1 + i_2 + \cdots + i_n)^{0.5} \tag{21}$$

$$THDv = (V_1 + V_2 + \cdots + V_n)^{0.5} \tag{22}$$

Where V and i represents the voltage and current signal of the power system network and n the number of buses,

The outcomes of the performances of the hybrid filters are shown in the result section.

4. Results and discussion

The wave forms of the current and voltage signal for Birnin kebbi transmission station (TS) is shown in Figure 4.

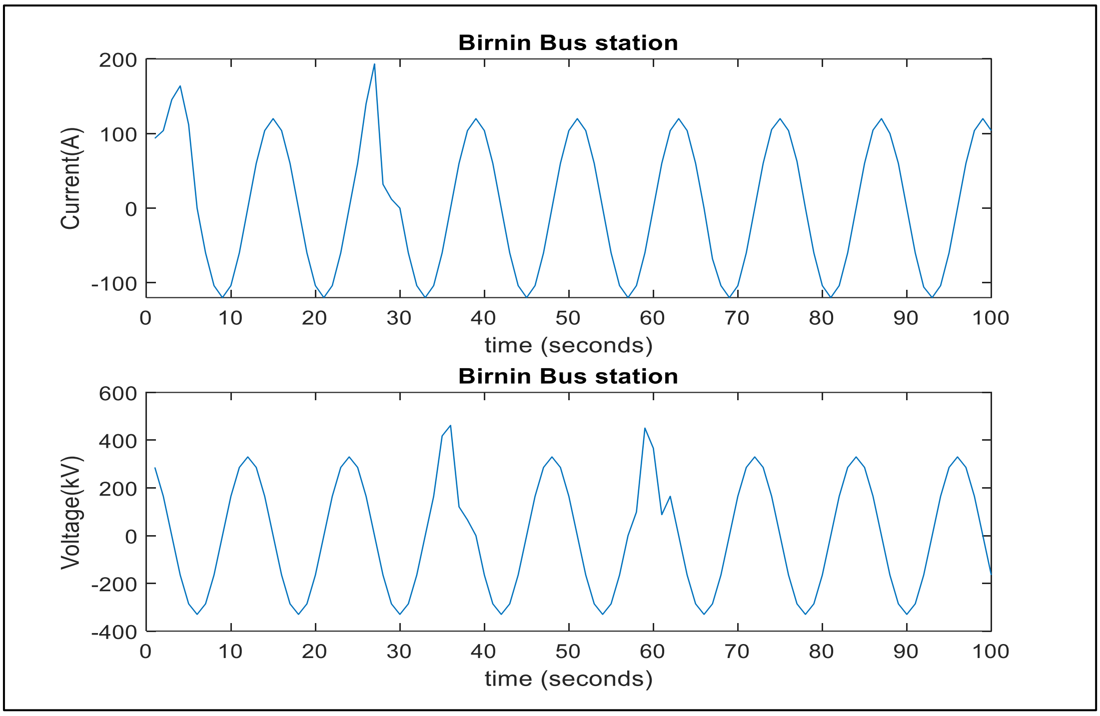

Figure 4 Harmonics of the current and voltage signal for Birnin Kebbi station

The distortions of the current and voltage signals are clearly visible as shown in Figure 4 for the Birnin kebbi transmission station. The current and the voltage wave forms have clear ripples and the same instance also occur in Figure 5 for the Kainji station. These ripples are attributed to the presence of non-linear loads.

The waves of the voltage and current signal for Kainji generation station (GS) is shown in Figure 5.

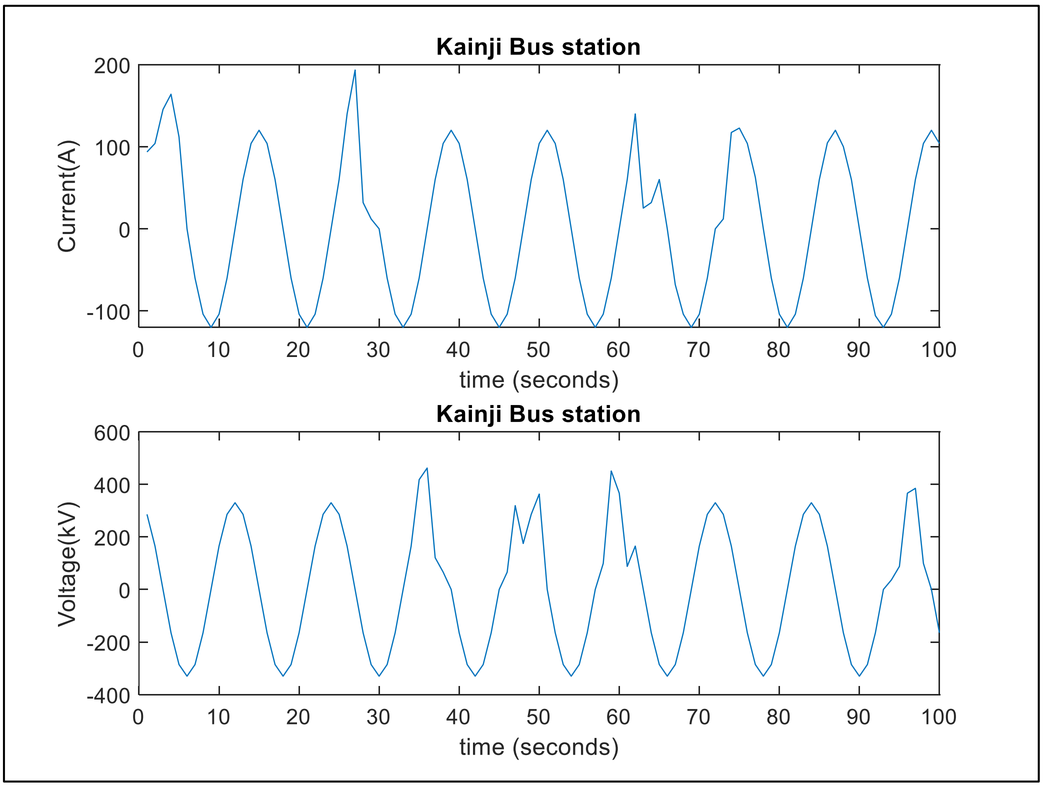

Figure 5 Harmonics of the voltage signal of the Kainji station

In Figure 5, it is observed that the harmonic distortion order that occurred is a 5th order for the current signal and 7th order for the voltage signal. This was the same outcome for Birnin kebbi transmission station.

The comparative analysis of the THD of the current signals for with, and without filters is shown in Figure 6.

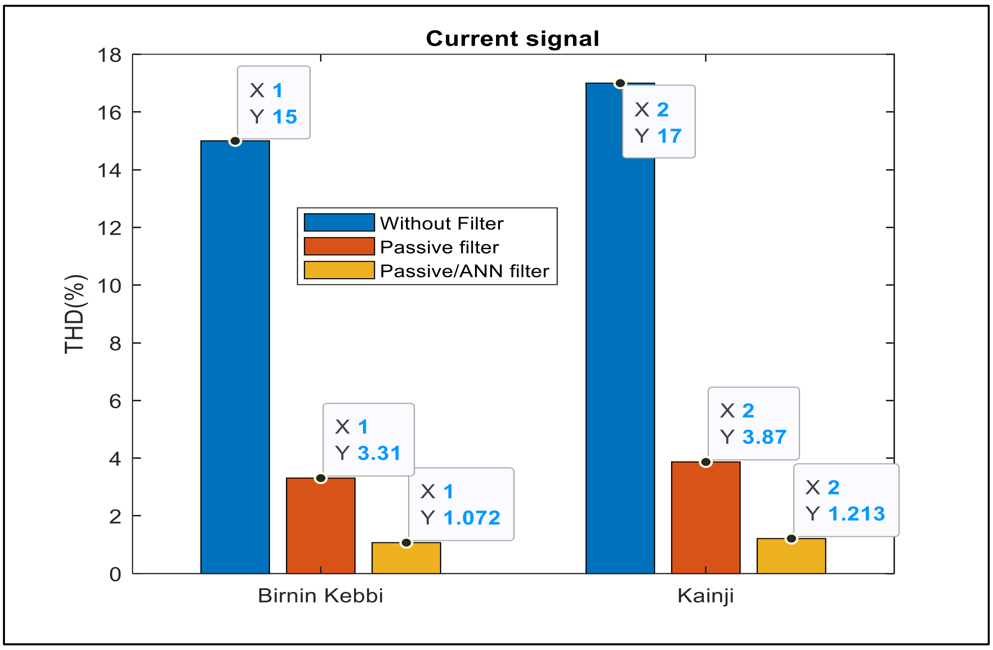

Figure 6 THD of the current signals

The impact of the hybrid of passive filter and ANN control model is clearly observed on the THD of the current signal as shown in Figure 6. For Birnin Kebbi, the hybrid filter mitigated the impact of the harmonic distortion to 1.072 % from 15 % (of the system with filter) and for the Kainji generation station, the hybrid filter mitigated the harmonic distortion impact to 1.213 % from 17 % (of the system without filter). Hence, the implementation of the hybrid filter is more effective than the stand-alone passive filter.

The comparative analysis of the THD of the voltage signals for, with and without filters is shown in Figure 7.

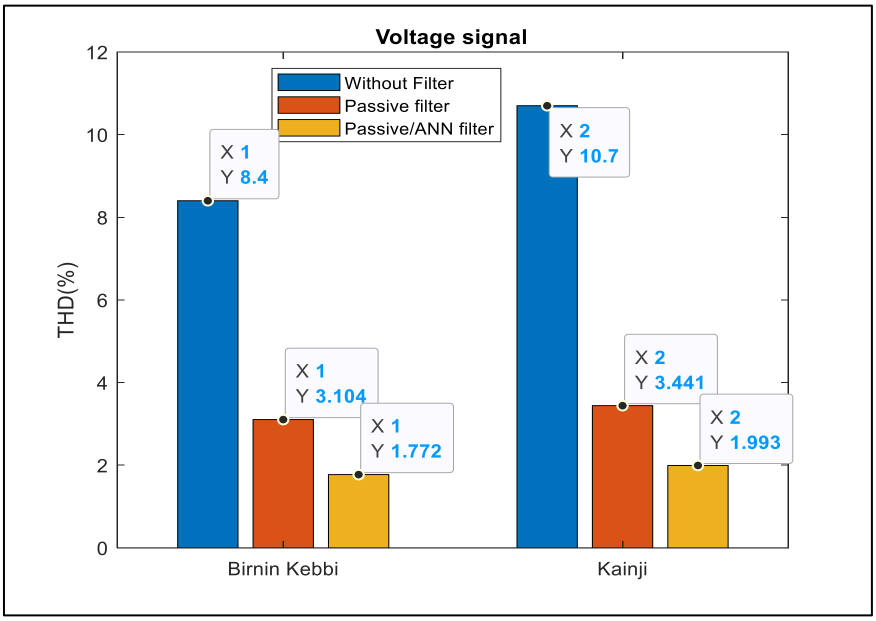

Figure 7 THD of the voltage signals

From Figure 7, it can be deduced that the boosting of the passive filter with ANN model had the highest performance. The THD of the voltage signal is reduced to 1.772 % and 1.993 % for Birnin Kebbi and Kainji stations respectively.

5. Conclusion

In this paper, stand-alone, single-tuned passive filter was utilized for the mitigation of the impact of harmonic distortion on a real time Nigerian 330 kV transmission network. The performance of the stand-alone filter was compared to a hybrid of passive filter and ANN model. The wave plots of the current and voltage signals of the systems showed that the current signal of the buses had 5^{th} order while the voltage signal had 7^{th} order. The utilization of the hybrid filter reduced the THD of the current signal to 1.072 % and 1.213 % for the Birnin kebbi and Kainji bus stations respectively while the voltage signal was reduced to 1.772 % and 1.993 % for the Birnin kebbi and Kainji bus stations respectively.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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