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Original Research Article

HARMONIC MITIGATION IN AN AC POWER SYSTEM USING 33kV TRANSMISSION LINE AS A CASE STUDY

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Authors' contributions

This study was a collaborative effort among all authors. Each author reviewed and approved the final version of the manuscript for publication.

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ABSTRACT

Background: This research aims to analyse, mitigate, and model harmonics in a power system using MATLAB Simulink to build a 33kV transmission line model. The paper presents the control of harmonics in a 33kV transmission line using SAPF in mitigating harmonic current in the power system.

Methods: Hourly readings of kW, kVar, kV and I of each feeder were obtained from the Transmission Company of Nigeria (TCN), and these results serve as source data for this research. Readings of an average of 3hours interval for 6 days was used as a test case.

Results: The simulation was conducted for the system under two different scenarios: one where the power system was connected to SHAF and another where it was not. By utilizing bus data readings from August 1, 2018, the total harmonic distortion (THD) without the SHAF connection was found to be 80.44%. However, when SHAF was connected, the THD dropped to 3.67%. Additionally, using bus data from August 2, 2018, the THD for the system without SHAF was 84.34%, while with SHAF connected, it was reduced to 3.23%. Using the load data from the 3rd and 4th of August 2018 to run the simulation, the THD values were 92.73% and 101.12%, respectively, when the

SHAF was disconnected, while the THD readings dropped to 3.70% and 4.63% when the SHAF was connected to the system.

Conclusion: This paper has presented an analysis of harmonics in a power system and also presented method to mitigating it using a SHAF. A 33kV transmission line was used as a case study, a model of the transmission line was developed and used to evaluate the presence of harmonics on the line, which are due to the presence of non-linear load connected to the network.

Key words: Harmonics, Total harmonic distortion (THD), power factor, Fast Fourier Transform (FFT), Shunt Active filter (SHAF).

INTRODUCTION

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. With modern test equipment, harmonics can be measured up to the 63rd harmonic source. (George, J.W., 2001). The recent deregulation of Nigerian power sector has led to an increased concern on power quality among all the stakeholders. Power quality has been severely affected by harmonic distortion of current and voltage with its attendant unpleasant consequences. This is attributable to the ever increasing use of power electronic devices and equipment such as variable speed drives, uninterruptible power supplies (UPS) and static power converters as well as large number of industrial loads connected to its transmission infrastructure and other non-linear loads or devices such as arc furnaces, saturated transformers, fluorescent lightings and cyclo-converters (Holey D M Chandrakar V K, 2016; Almeida C F Kagan N 2011). Data from the National Control Centre (NCC), Oshogbo revealed a staggering frequency profile and high harmonic distortion of both voltage and current. Components other than the fundamental voltage and current were found to exist in the distorted waveform as integer multiples of the fundamental frequency. The Nigerian power grid feels the impact of this harmonic distortion at all network buses which contributes to the heightened forced outages, unnecessary trips on circuit breakers, protective relay signal degradation, excessive heating within transformers, rotating machinery, and intricate grid failure alongside the disruption of fragile electronic components everywhere in the grid.

Also the technology behind the modern AC circuit and power system built has grown rapidly, and loads connected to them area changing from simple, non-electronic loads such as tungsten lamps, motors, relays, and resistive heaters to electronic ones such as fluorescent lamps, motors, relays, and restive heaters to electronic ones such as fluorescent lamps, motors with solid-state drivers and industrial drives. These electronic loads (also known as non-linear loads which draw a non-sinusoidal current even when the supply voltage is perfectly sinusoidal) are the major sources of excessive current harmonics which leads to power quality PQ pollution introduced into the power system.

Power quality (PQ) problems in power systems or in an AC circuit are not new, advances in semiconductor device technology have fueled a revolution in power electronics over the past decade, and there are indications that this trend will continue. However, power electronics based equipment's which include adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers, electronic ballasts are responsible for the rise in power quality related problems. These nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system.

Thus to improve the performance of the power system as well as the power quality, it is required to eliminate harmonics from power utility system (Grady, W. Mack, and Surya Santoso, 2011) One of the method used for elimination is the use of shunt active power filter (SAPF) in which a reference current is generated to remove distortion from the harmonic currents. Shunt active power filter continuously monitor the harmonics current and reactive power flow in the network and generate reference current from distorted current waveform. Thus dynamic closed loop action of SAPF helps the reduction of harmonics and compensation of reactive power in real time basis with little time delay. SAPF can be used with different current control strategy such as d-q method, fuzzy logic controller, p-q method, neural networks etc. which is helpful in removing effective harmonic from power system. Applications of power electronics loads are continually overtaking industry space from other types of loads, especially because of their ability to help the conservation of energy and provide better control over traditional and new processes (D. A. Paice, 2006). According to Electric Power Research Institute (EPRI), it is estimated about 60% of all electrical power will be processed in some way by solid state methods. The inherent nonlinear nature of the power electronic load places harmonic current/voltage demands and extraneous losses upon the electrical power system. A situation that has raised waveform distortion levels in distribution networks even further is the application of capacitor banks used in industrial plants for power factor correction and by power utilities for increasing voltage profile along distribution lines. The resulting reactive impedance forms a tank circuit with the system inductive reactance at a certain frequency likely to coincide with one of the characteristic harmonics of the load. This condition will trigger large oscillatory currents and voltages that may stress the insulation. On other hand, developments in the digital electronics/communications and in process control have increased the number of the sensitive loads that require ideal sinusoidal voltages for their proper operation [Dusan Graovac, Vladimir A. Katic and Alfred Rufer, 2007]. This situation imposes a serious challenge to industry and utility engineers to pinpoint and to correct excessive harmonic waveform distortion levels on the waveforms because its steady increase happens to take place right at the time when the use of sensitive electronic equipment is on the rise. Harmonic studies from the planning to the design stages of power utility and industrial installations will prove to be an effective way to keep networks and equipment under acceptable operating conditions and to anticipate potential problems with the installation or addition of nonlinear loads, in order to keep power quality under limits proposed by the standards it is necessary to include some sort of compensation [Francisco C. De La Rosa 2006].

Distortion of sinusoidal voltage and current waveforms caused by harmonics is one of the major power quality concerns in electric power industry. Considerable efforts have been made in recent years to improve the management of harmonic distortions in power systems. Standards for harmonic control have been established. Instruments for harmonic measurements are widely available. The area of power system harmonic analysis has also experienced significant advancement as given by [A. Guillemin (2006),]. Well accepted component models, simulation methods and analysis procedures for conducting systematic harmonic studies have been developed.

In this thesis however, emphasis are on harmonic analysis and mitigation on a power system wherein an improved Shunt Active Power Filter using the instantaneous active and reactive power theory (p-q) control strategy to compensates for both reactive current and harmonics current generated by non-linear load in power system. And also a model was developed to minimize the effect of harmonics on the overall network by compensating the line current. The system was simulated and shown on an oscilloscope. On the basis of the above discussion and review of related literatures, it can now be stated that the major purpose of this thesis is to present the possibilities, detailed features, as well as selected solutions and applications of the power electronics arrangements useful to the improvement in quality of delivery of the electric energy in electric power system

MATERIALS AND METHODS

Data Collection

For this research, data were obtained from the Transmission Company of Nigeria (TCN) Benin transmission station, the data's were carefully studied, and necessary validation was made to ensure data are in relevant to the case study. The kV, kW, kVAR, hourly readings from the 33 kV transmission line within the period of 6 days was analyzed. The 33kV bus has 9 outgoing feeders (GUINNESS(Q10), NEKPENEKPEN(Q20), IKPOBA DAM(Q30), Switching STN(Q40), G.R.A(Q50), ETETE(Q60), SPARE(Q70), SPARE(Q80), 33kV Bus Load), and for the purpose of this research, bus readings from 1 of the feeders (NEKPENEKPEN(Q20)) at 4 hours interval will be used.

i. Similar to other research in power systems, the analysis in this context consists of the following steps
ii. Analysis of harmonics and determination of models for their representations
iii. Mathematical model to represent harmonics.
iv. Development of a 33kV transmission line model to represent other components in the system including external networks.
v. Simulation of harmonics mitigation using shunt active filters (SHAF).

Single line diagram of 33kV distribution line

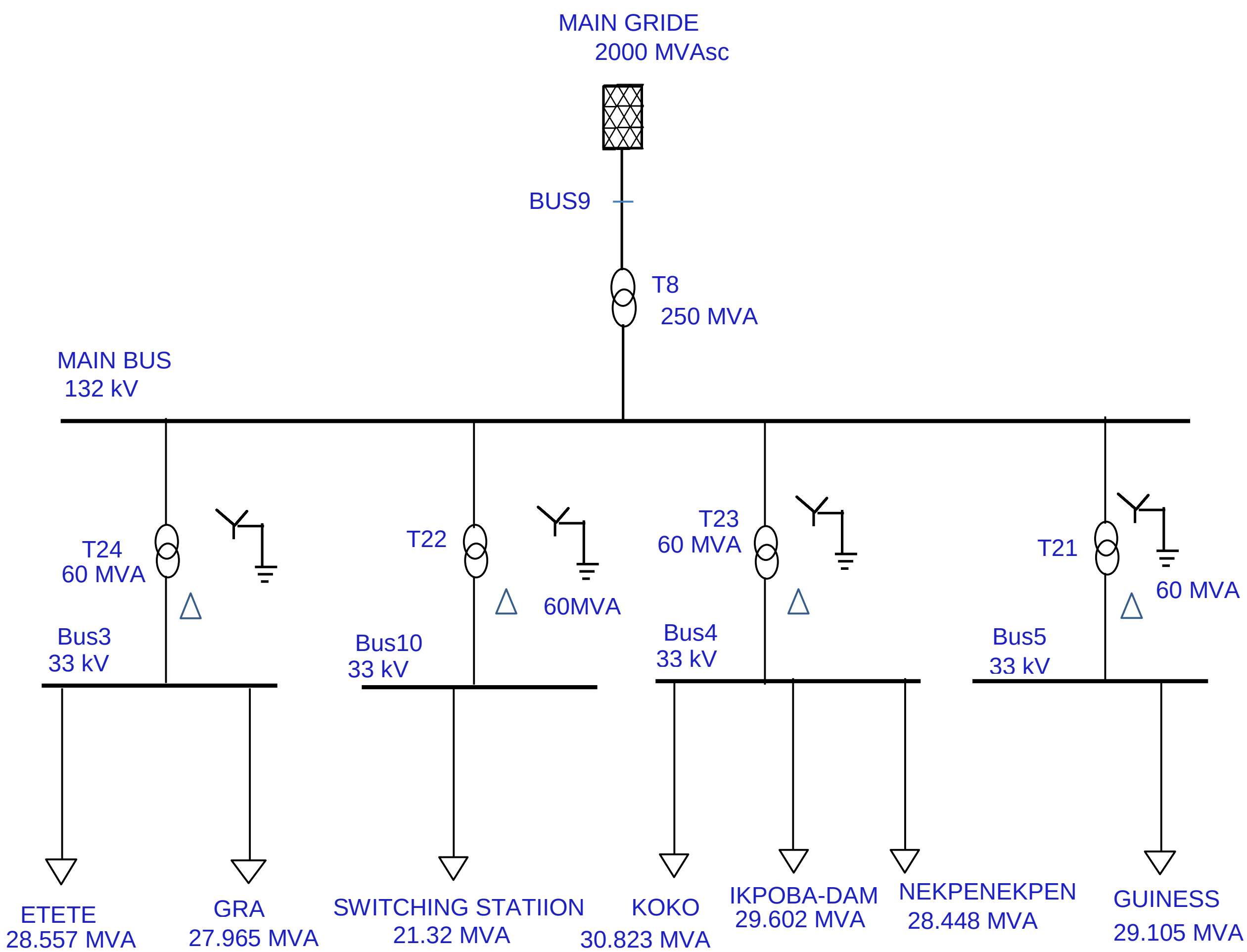

Fig 1 Single line diagram of Transmission Company of Nigeria (TCN) Benin 33kV Feeders (Source: TCN Benin substation)

Harmonic Mitigation Techniques

D-Q harmonic filtering technique

The d-q synchronous reference frame is based on park transformation theory and it transforms a three phase (3-Ø) load current into a synchronous reference current so as to eliminate the harmonics in the source current. The main advantage of this method was that it takes only the load current under consideration for generating reference current irrespective of the source current and voltage distortion. A Phase lock loop (PLL) was used for maintaining synchronism between the reference current and voltage for better performance of the system. The current in the d-q frame i_d and i_q can be transformed from the positive sequence and negative sequence using a PLL (phase locked loop). The reference current signal can be achieved by the AC component in d-q frame through a counter-transformation. The D-Q transformation, commonly referred to as the Park transformation, is a mathematical approach that converts three-phase time-domain signals to a two-axis rotating reference frame. This transformation is widely used in the study and control of electric power systems, particularly for harmonic filtering and controlling AC equipment. According to Park's transformation, the relation between three phase source current (a-b-c) and the d-q reference co-ordinate current is given in equation 3.1

$$\begin{bmatrix} i_{ld} \\ i_{lq} \\ i_{l0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\mu & cos(\mu - \frac{2\pi}{3}) & cos(\mu + \frac{2\pi}{3}) \\ -sin\mu & -sin(\mu - \frac{2\pi}{3}) & -sin(\mu + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{ld} \\ i_{lq} \\ i_{l0} \end{bmatrix} \quad 1.1$$

Where, 'μ' is the angular deviation of the synchronous reference frame from the 3-phase orthogonal system which is a linear function of fundamental frequency. $\boldsymbol{i_d}$ is the current component aligned with the direct axis of the rotating reference frame, $\boldsymbol{i_q}$ is the current component that is orthogonal to the direct axis (90 degrees phase shift), while $\boldsymbol{i_0}$ is the zero-sequence component (which is zero in balanced three-phase systems). The harmonic reference current can be obtained from the load currents using a simple Low Pass Filter (LPF). The currents in the synchronous reference system was decomposed into two components denoted by i^{-} and $i^{\sim}$ as shown in equation 3.2 and 3.3

$$i_{ld} = i_{ld}^{-} + i_{ld}^{\sim} \quad 1.2$$

$$i_{lq} = i_{lq}^{-} + i_{lq}^{\sim} \quad 1.3$$

After filtering, one of the DC terms or component (i_{ld}^{-} and i_{lq}^{-}) was suppressed as well as the alternating term which was continually appearing at the output of the extraction system and also responsible for harmonic pollution in the power system. The SHAF reference currents i^* was given by equation 3.4

$$\begin{bmatrix} i_{fd}^* \\ i_{fq}^* \end{bmatrix} = \begin{bmatrix} i_{fd}^{\sim} \\ i_{fq}^{\sim} \end{bmatrix} \quad 1.4$$

Where $\begin{bmatrix} i_{fd}^* \\ i_{fq}^* \end{bmatrix}$ is the SHAF reference currents and $\begin{bmatrix} i_{fd}^{\sim} \\ i_{fq}^{\sim} \end{bmatrix}$ the components To further find the filter currents i_f^* in the three phase system which cancels out the harmonic components, the inverse Park transformation was used as shown by equation 3.5

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\mu & -sin\mu \\ cos(\mu - \frac{2\pi}{3}) & -sin(\mu - \frac{2\pi}{3}) \\ cos(\mu + \frac{2\pi}{3}) & sin(\mu + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{fd}^* \\ i_{fq}^* \end{bmatrix} \quad 1.5$$

Where i_{fa}^*, i_{fb}^* , i_{fc}^* represents the transformed 3-phase (3-Φ) reference current generated by the SHAF from the d-q harmonic current component.

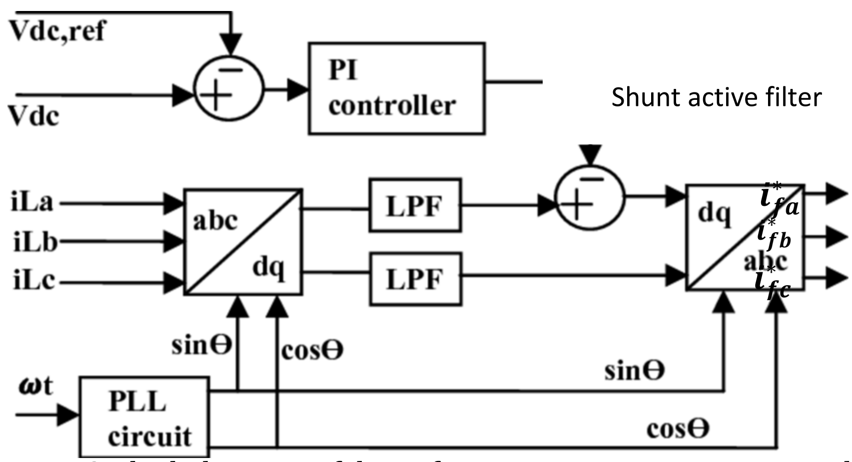

Figure 2 Block diagram of d-q reference current generation technique

Harmonic Components

A method to represent any non-sinusoidal periodic function $u(t)$ using an infinite series of cosine and sine functions and coefficients as shown in eqn. 1 was first proposed by Baron Jean Fourier in 1822

$$u(t) = A_0 + \sum_{h=1}^{\infty} [A_0 \cos(h\omega_0 t) + B_0 \sin(h\,\omega_0 t) = A_0 + \sum_{h=1}^{\infty} C_h \cos(h\omega_0 t) + \Psi_h \quad 1$$

Where (t) is a period function of frequency f_0, angular frequency $\omega_0 = 2\pi f_0$, and period

$$T = \frac{1}{f_0} = \frac{2\pi}{\omega_0} \quad 2$$

C_1 cos $(h\omega 0t)$+ Ψ_1 represents the fundamental component, and $C_h \cos(h\omega_0 t)$+ Ψ_h represents the hth harmonic component of the amplitude C_h, frequency $h\omega_0$ and phase Ψ_h relative to the fundamental. Generally, for power systems, the fundamental frequency is either 50Hz or 60Hz. Power systems in Nigeria are typically operated at 50Hz, thus harmonic frequencies will appear as multiples of 50Hz (100Hz, 150Hz, 200Hz, etc.). The Fourier series coefficients C1, C_2,Ch and relative phases Ψ_1,Ψ_2,… Ψ_h make up the harmonic spectrum of the waveform and are found using eqn. 3.2 through to eqn.3.6.

$$A_0 = \frac{1}{T}\int_0^T u(t)\,dt = \frac{1}{2\pi}\int_0^{2\pi} u(t)dx \text{ where } x = \omega_0 t \quad 1.6$$

$$A_h = \frac{2}{T}\int_0^T u(t)\,cos(h\omega_0 t)\,dt = \frac{1}{\pi}\int_0^{2\pi} u(t)\cos(hx)dx \quad 1.7$$

$$B_h = \frac{2}{T}\int_0^T u(t)\, sin(h\omega_0 t)\, dt = \frac{1}{\pi}\int_0^{2\pi} u(t)\, \sin(hx) dx \qquad 1.8$$

$$C_h = \sqrt{A\frac{2}{h} + B\frac{2}{h}} \qquad 1.9$$

$$\Psi_1 = \tan^{-1}\frac{A_h}{B_h} \qquad 2.0$$

Conversely, if the harmonic spectrum of a given current or voltage waveform u(t) is known the original waveform can be constructed using the Fourier series summation:

$$u(t) = \sum_{h=1}^{\infty} U_h \cos(h\omega_0 t + \Psi h) \qquad 2.1$$

Where U_h is the h^{th} harmonic peak current or voltage, Ψ_h is the h^{th} harmonic phase, ω_0 is the fundamental angular frequency, $\omega_0 = 2\pi f_0$, and f_0 is the fundamental frequency, typically 50Hz.

Model of the 33kV transmission line

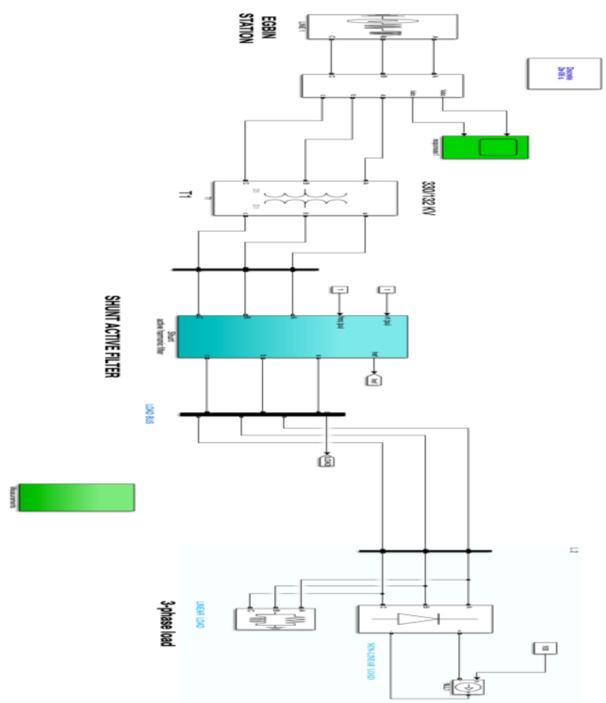

Fig 3 Developed model of a 33kV distribution line network with a shunt active filter connected between the load and the sending end

RESULTS AND DISCUSSION

MATLAB simulation of the designed 33kV transmission line model and the SHAF model for harmonic compensation is discussed in this chapter with emphasis on the harmonic content of the load current. The simulation results of the system model for 6 days of readings at four (4) hours interval are presented and analyzed in the corresponding sections. The Power system model without any compensation connected to it was first simulated and results presented, then the system performance with the shunt active filter connected to the overall network after simulation is also presented and analyzed. The performance of SHAF in compensating harmonic current or reducing the total harmonic distortion (THD) is compared for the overall system. Using the above method we are able to validate the effectiveness of the proposed SHAF compensation scheme.

Results of harmonic mitigation of the power system

Harmonics analysis of the Power system with the compensator disconnected (SHAF contact open)

From the result obtained, a distortion in current and voltage waveform is seen during the simulation carried out for the 4 hours interval from feeder readings for 6 days as obtained from the transmission company of Nigeria (TCN) Benin City transmission station. At the end of the simulation, the result were compared to show the effect of SHAF in mitigating harmonic content in the 33kV transmission line

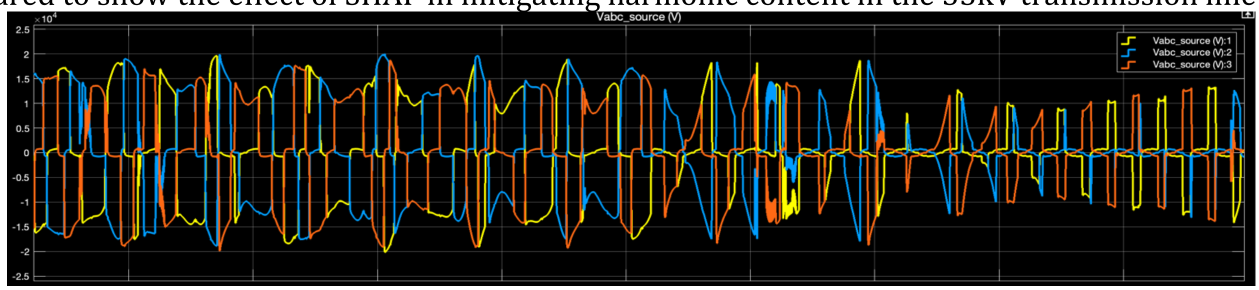

Fig 4 Source voltage waveform from simulation using day 01-03-2018 bus readings.

The source voltage waveform shows considerable distortions when the SHAF was not connected to the system. To visualize the harmonic distortion, the simulation time was set at 0.2 second

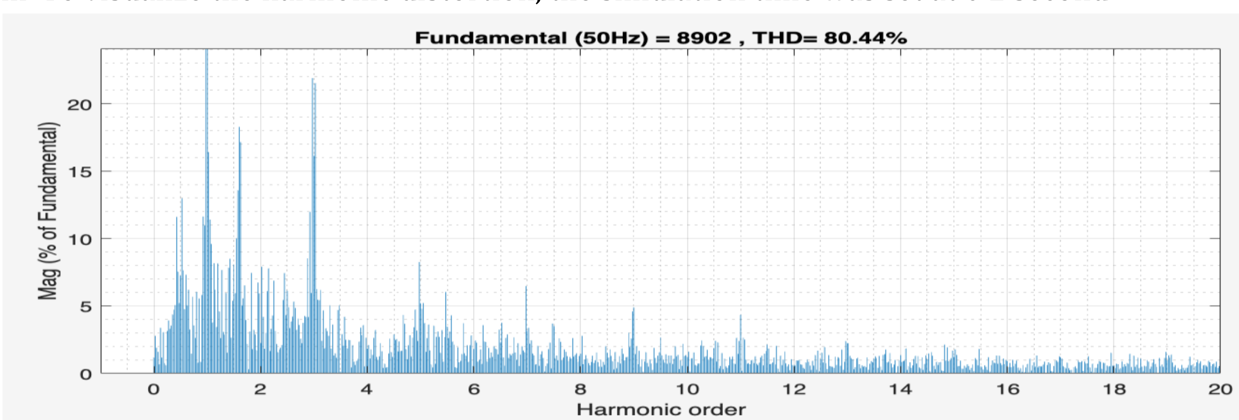

Fig 5: Showing total harmonic distortion (THD) of the load voltage when the SHAF was not connected to the power system.

Simulation with SHAF connected (Circuit breaker closed)

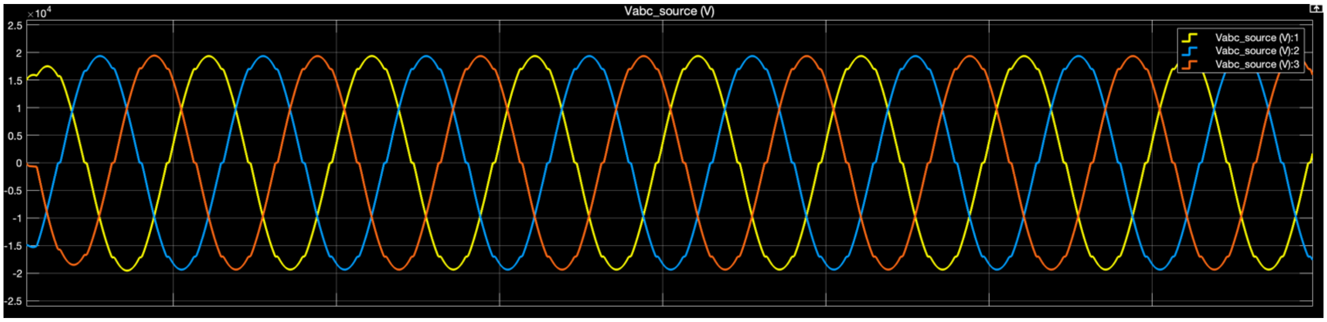

Fig 6: Showing Source voltage wave form of the developed system when connected to SHAF

Figure 6 shows the waveform of the source voltage when the SHAF was connected to the power system. It shows a pure sinusoidal waveform of the source voltage devoid of any distortion. This clearly shows the compensation effectiveness of the SHAF

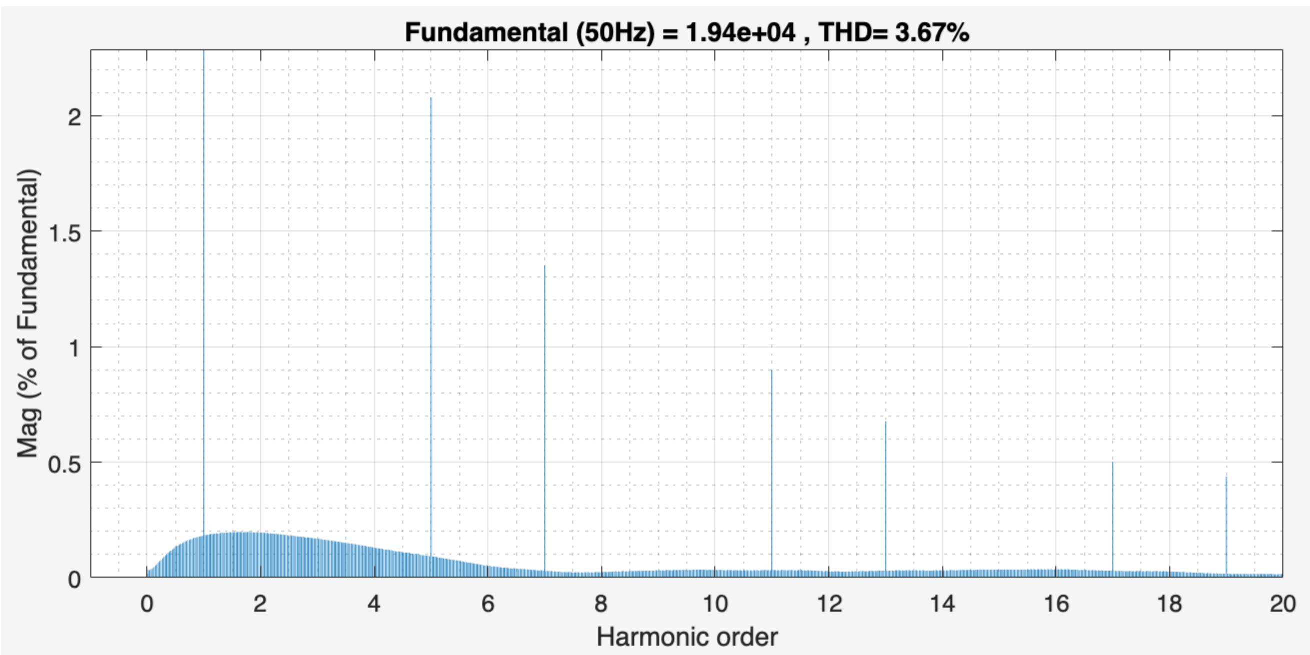

Fig 7: Showing total harmonic distortion (THD) of the source voltage when the SHAF was connected to the power system. From fig 5, the THD of the source voltage when SHAF was connected to the power system was 3.67% which showed a great reduction in the harmonics content in the system. As shown in fig 6, the THD of the source voltage when the SHAF was not connected to the system was 80.44%.

From the Simulation carried out, the THD values of the source voltage for each daily reading when the SHAF is not connected to the system and when it was connected shows a reduction in the THD, confirming that the SHAF is able significantly reduce the harmonic signal in the system. From the table below the THD percentage shows an acceptable THD value not exceeding 5.0% as stated according to the IEEE 519

Standard (IEEE Std 519-2014). The table below however shows the THD of the system before and after connecting the SHAF.

Table 1 Showing the total harmonic distortion (THD) of the source voltage when the SHAF is connected and disconnected, as well as at different load condition.

THD		
Date	SHAF not connected	SHAF connected
01-03-2018	80.44%	3.67%
02-03-2018	84.34%	3.23%
03-03-2018	92.73%	3.70%
04-03-2018	101.12%	4.63%
05-03-2018	45.10%	2.77%
06-03-2018	39.06%	5.08%
07-03-2018	58.43%	3.78%
08-03-2018	99.90%	4.12%
09-03-2018	92.68%	3.11%
10-03-2018	60.66%	3.86%

CONCLUSION

This paper has presented an analysis of harmonics in a power system and also presented method to mitigating it using a SHAF. A 33kV transmission line was used as a case study, and a model of the line was developed and used to evaluate the presence of harmonics on the line, which are due to the presence of non-linear load connected to the network. This was done using MATLAB/Simulink platform. The various harmonics in the lines of the network which were obtained as results are presented. Results were generally discussed and analysed for various scenario and times of loading/restoration of 33kV feeders in the network. Simulation and tests were conducted aiming to mitigate harmonics in a Power line using shunt active filter (SHAF) for compensation. The effectiveness of d-q theory in estimating compensation reference current is demonstrated. The simulation results were analysed and discussed. Finally, a detailed THD analysis on source current and voltage spectrums is carried out to validate the harmonic filtering performance of the proposed SHAF topology. The results showed that the distortion in the line current and voltage of the Power line caused by nonlinear load connected at the load side of the line, has been compensated. Based on the results, the proposed SHAF topology is capable of responding effectively to the harmonics caused by the three-phase diode rectifier load. The total harmonic distortion of the source current without compensation is high; about 10.64% for the current in each phase. When compensation was made and harmonics filtered with the proposed SHAF, the total harmonic distortion was reduced considerably below IEEE standard.

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