REDUCTION OF HARMONIC DISTORTION IN 40MVA 132/33KV POWER TRANSFORMER USING PASSIVE FOURIER FILTERING TECHNIQUE

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Abstract

This paper presents the reduction of harmonic distortion in power transmission system using passive Fourier filtering technique The aim was to minimize the percentage of harmonic on the 19 bus, 40MVA, 132/33KV Abuja injection feeder. This method is characterization of the feeder to determine the harmonic percentage which is 6.0277 and did not satisfy the International Electrical Electronics Engineering (IEEE) requirements for harmonic tolerance in power transmission system. To solve the problem, Fourier passive filter was developed and then implemented on the power system using Simulink. The result showed that voltage harmonic was reduced to 0.82% after validation. The result when integrated on the 19bus feeder injection system showed that the average harmonic was 4.943 which is good as it satisfied the IEEE standard. The results when comparatively analyzed showed that with the passive filter, the percentage mitigation of harmonic achieved is 17.99%.

Keywords: Harmonics, Power Transmission System, Fourier Filtering, Voltage, Injection System

1. INTRODUCTION

The need to improve quality of power supply in Nigerian power system has led to the recent power deregulation within the sector (Ogbu, 2015). However, despite the success, certain technical problem like harmonics continues to affect the quality of power supply.

According to (Nwohu et al., 2019) harmonic is a positive integer which is a multiple of the fundamental frequency, and are generated by nonlinear loads. Harmonics impact on this present-day power system was as a result of the increase adoption of power electronics for power system control and protection. These electronic devices further increase the rate of harmonic impact on the power flow and have remained a very big challenge (Amoo et al., 2011; Almeida and Kagan, 2011). As a result, the impact of harmonic distortion on the national grid has continues to affect the quality of power and also has contributed to the issues power flow transient instabilities, false trips on the circuit breakers, poor frequency profile, poor metering calibration and high rate of losses in the transmission lines (Gul and Gundogdu, 2015).

Interestingly, in Nigeria, researches have been done to address this problem by the power system planning engineers but the results remained a very big issues waiting to be addressed both in the transmission and distribution section of the power system architecture (Adeshina and Fakolujo, 2015). While line reactors and under-frequency relays exist in the distribution section to solve the issues of load flow instability, no filtering devices was installed for the purpose of mitigating the impact of harmonics. This research seeks to address this problem in the Nigeria power sector using passive harmonic filter. The filter will be developed as a passive processing element and deployed on the case study power system, to help remove harmonic and improve quality of power supply.

2. OVERVIEW OF HARMONICS IN POWER SYSTEM

Harmonics are one of the major concerns in a power system. Harmonics cause distortion in current and voltage waveforms resulting into deterioration of the power system. The first step for harmonic analysis is the harmonics from non-linear loads. The results of such analysis are complex (Li et al., 2016). Over many years, much importance is given to the methods of analysis and control of harmonics. Harmonics present in power system also has non-integer multiples of the fundamental frequency and have a periodic waveform. The harmonics are generated in a power system from two distinct types of loads (Ewald et al., 2018).

The first category of load is described as linear loads. The linear time-invariant loads are characterized such that application of sinusoidal voltage results in sinusoidal flow of current (Maaswood et al., 2013). A constant steady-impedance is displayed from these loads during the applied sinusoidal voltage. As the voltage and current are directly proportional to each other, if voltage is increased it will also result into increase in the current. An example of such a load is incandescent lighting (Keerthipala and Chong, 2015).

According to Wilson and Mucoke (2019), even if the flux wave in air gap of rotating machine is not sinusoidal, under normal loading conditions transformers and rotation machines pretty much meet this definition. Also, in a transformer the current contains odd and even harmonics including a dc component. More and more use of magnetic circuits over a period of time may get saturated and result into generation of harmonics. In power systems, synchronous generators produce sinusoidal voltages and the loads draw sinusoidal currents. In this case, the harmonic distortion is produced because of the linear load types for sinusoidal voltage is small (Li et al., 2016).

Elias et al. (2019) posited that non-linear loads are considered as the second category of loads. The application of sinusoidal voltage does not result in a sinusoidal flow applied sinusoidal voltage for non-linear devices. The non-linear loads draw a current that may be discontinuous.

Harmonic current is isolated by using harmonic filters in order to protect the electrical equipment from getting damaged due to harmonic voltage distortion. They can also be used to improve the power factor (Li et al., 2016). The harmful and damaging effects of harmonic distortion can be evident in many different ways such as electronics miss-timings, increased heating effect in electrical equipment, capacitor overloads, etc. There can be two types of filters that are used in order to reduce the harmonic distortion i.e. the active filters and the passive filters (Ewald et al., 2018).

3. DESIGN METHOD

The methodology used for this study is the experimental method. The approach allowed for the technical investigation of the 19us, 132/33KV power transformer and then analyzes to find out the challenges which impacts on the quality of power supply. To solve the problem identified, harmonic filtering system was developed using passive Fourier techniques and then implemented on the power transmission network using Simulink. The results were obtained from simulation and analyzed based on the International Electrical Electronics Engineering (IEEE) and Nigerian Electricity Regulatory Commission (NERC) standards for harmonic percentage in power transmission network.

3.1 Model of the 40MVA, 132/33kv Transmission Network

The feeder is a 40MVA, 132/33KV transmission substation connected as a mesh to the national grid via four high voltage circuits which are the Abuja 132KV Line I, Abuja to Suleja 132KV Line II, Minna to Suleja 132KV Line I and Minna to Suleja 132KV Line II. The primary supply source is from Shiroro power generating plant in Niger state.

The Abuja circuits emanated from the Ketampe 330/132KV transmission station in the Abuja area, while the Minna circuits emanate from Minna 132KV transmission substation. The Suleja 132/33KV substation has three power transformers rated as follows: 7.5MVA 132/11KV transformer TR1 feeding five 11KV feeders (Gauraka, Dikko, Minna Road, NNPC and Water Works 11KV feeders); 45MVA 132/33KV transformer TR2 feeding two 33KV feeders (Abuja Steel and Field Base 33KV Feeders); and 60MVA 132/33KV transformer TR3 feeding two 33KV feeders which are Jere and Kantoma 33KV feeders.

The Suleja Network has three 33/11KV Injection substations which is located at Kantoma, Jere and Field Base respectively. Kantoma 33/11KV Injection substations have two power transformers with each rated 15MVA with four 11KV feeders which are RafinSanyi, Dawaki, Hassan and Madalla respectively.

The field base 33/11KV injection substation has one power transformer which is rated 15MVA with two feeders namely Suleiman Barau and Tommy; while Jere 33/11KV Injection substation has two power transformers which are rated 7.5MVA feeding three feeders namely SabonLugbe, SabonDikko and Nasara 11KV feeders respectively. All the other major network equipment like circuit breakers, isolators and buses were also modeled and simulated on the MATLAB programming environment used to implement the system. The single line model of the test bed is presented in figure 1;

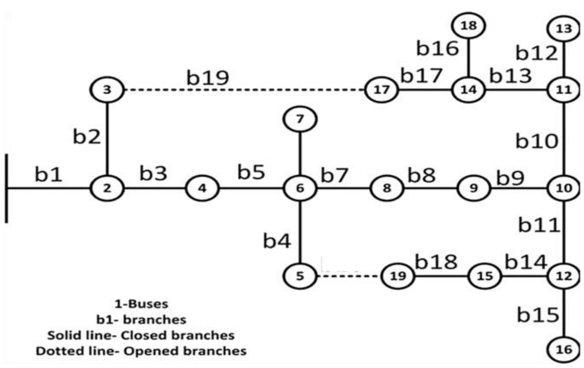

Figure 1: Single line diagram of the Abuja 132/33KV (Source: TCN)

3.2 Model of the harmonic problem formulation on the 132/33KV transformer

The figure 1 presented the model of the Abuja 132/33kv transmission network, the impact of harmonic on the transformer was presented using the model (Ganesan and Subbraman, 2020);

$$f(t) = \frac{1}{2}a_o + \sum_{k=1}^{\infty} * (a_k cos2\pi kt + b_k sin2\pi kt) \quad (1)$$

Where K is frequency of the k_{th} order of harmonic, a and b are coefficient of the nth harmonic, the continuous Fourier transform is given as equation 1 (Ganesan and Subbraman, 2020);

$$x(f) = \int_{-\infty}^{\infty} * x(t)e^{-j2\pi ft}dt \quad (2)$$

Where x(t) is a function; $e^{-j2\pi ft}$ is the sinusoid. The discrete transform is therefore given as equation 3;

$$X_k = \sum_{n=0}^{N-1} * x_n e^{\frac{-2\pi Kn}{N}} \quad (3)$$

Where k_{th} is the frequency, n is sample frequency and N is number of samples.

$$\frac{k}{N} \triangleq F, n \triangleq t \; and \; b_n = \frac{2\pi Kn}{N} \quad (4)$$

3.3 Total Harmonic Model

The total harmonic voltage distortion in the 33KV feeder is defined considering the harmonic current, voltage and root mean square value and the order of harmonic in the system (Gul and Gundogdu, 2015).

$$THDv = \left[\sqrt{\frac{\sum_{h=2}^{\infty} * V_h^2}{V1}}\right] \quad (5)$$

$$THD_V = \sqrt{\{((V_{RMS}/V_1)^2] - 1\}} \quad (6)$$

Where V_h is the harmonic voltage at harmonic frequency h in RMS; V_1 is the rated fundamental voltage in RMS, and h is the harmonic order.

H=1 corresponds to the fundamental frequency. Similarly, to determine the total harmonic current in the system, the same equation 5 is adopted is adopted and substitute voltage with current as shown in equation 7 (Gul and Gundogdu, 2015);

$$THD_I = \left[\sqrt{\frac{\sum_{h=2}^{\infty} * I_h^2}{I1}}\right] \quad (7)$$

$$THD_I = \sqrt{\{((I_{RMS}/I_1)^2] - 1\}} \quad (8)$$

Where I_h is the harmonic current at harmonic frequency h_f in RMS and I_1 is the rated fundamental current in RMS. The data collected for the feeder is presented in the next chapter where all results were discussed.

3.4 Development of the Harmonic Filter

The passive Fourier filter developed is a double tuned passive filter designed considering the operation frequency of the transformer, power (P), and width (B), the voltage (V), reactive power (Qc) and quality factor (Q) as presented in the models below;

$$Q = \frac{nX_l}{R} \quad (9)$$

$$n = \frac{fn}{f1} \quad (10)$$

$$B = \frac{fn}{Q} \quad (11)$$

$$Qc = \frac{V^2}{Xc} * \frac{n^2}{n^2-1} \quad (12)$$

$$P \approx \frac{Q_c}{Q} * \frac{n}{n^2-1} \quad (13)$$

$$w = 2\pi f_1$$

Where f_1 is the fundamental frequency, f_n is tuning frequency, n is the order of harmonic, V is the nominal line to line voltages, X_l presents the inductor reactance at fundamental frequency, X_c is the capacitive reactance at frequency of $\frac{1}{C\omega}$, w is the angular frequency.

3.5. The filter development

The filter was developed base on resistor (R) and capacitor (C) components which only allows only cutoff frequency defined by the model in equation 14;

$$F_C = \frac{1}{2\pi RC}\ Hz \quad (14)$$

With the model in the equation 14, the pass band of the filter can be controlled using the reference frequency. To determine the value of C, the model in equation 5 was used as equation 15, where n is the number of the capacitor used and F_l is the cutoff frequency.

$$C_n = \frac{1}{2\pi F_l R} \quad (15)$$

While the value of R is determined as equation 16;

$$R_n = \frac{1}{2\pi F_l C} \quad (16)$$

The figure 2 presented the equivalent circuit diagram of the filter with the respective parameters presented in table 1;

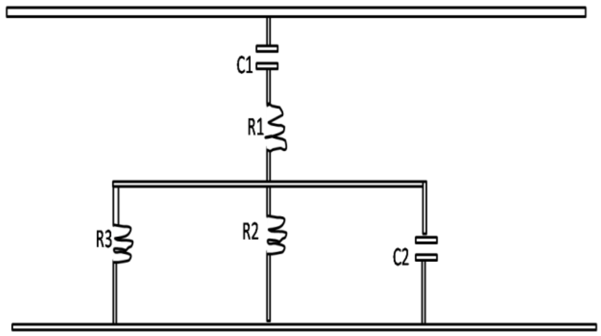

Figure 2: Equivalent circuit of the filter

The filter size was determined as 150Mvar using the RLC parameters in the table 1

Table 1: Specification of the filter

Parameters	**Values**
Transformer Power	40MVA
Number of Buses	2
Frequency	50.0Hz
Cutoff frequency margin	$\pm$0.5% (50)Hz
Total reactive power	600.0Mvar
Capacitance	20 X 10^6uf
Load capacity	35MVA
Inductance	0.5H

4. SYSTEM IMPLEMENTATION

The system was implemented using power system toolbox and signal processing toolbox. These toolboxes were designed using the models develop for the case study power transformer, discrete Fourier transform of the waveform and the Fourier passive filter developed to present the improved power system network as shown in figure 3;

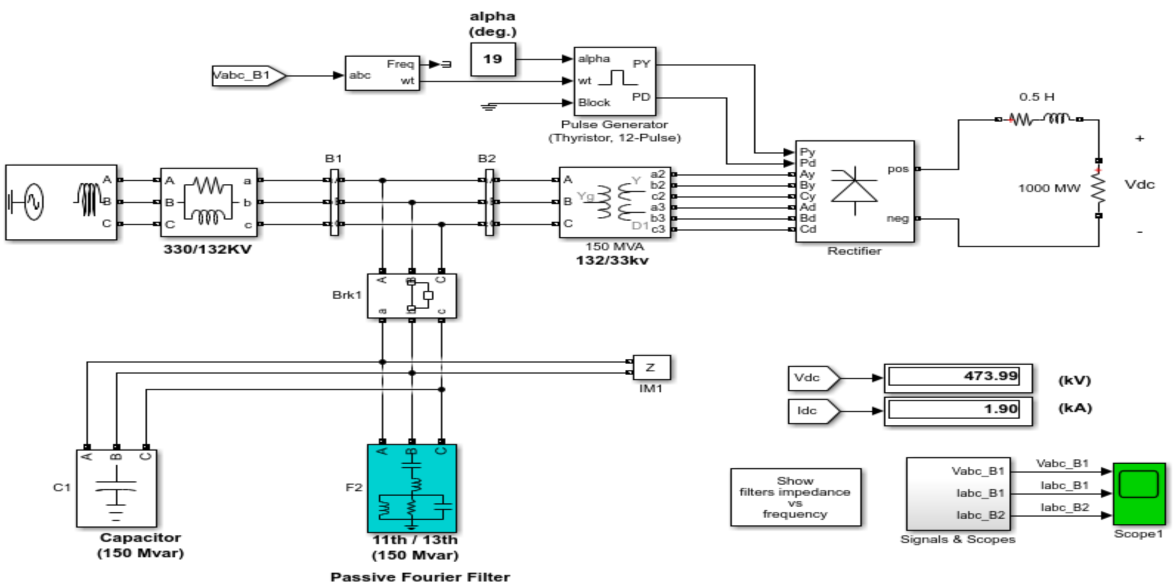

Figure 3: Simulink model of the power system network

The Simulink model in figure 3 shows how the filter was implemented on the case study 132/33KV transformer to mitigate harmonic percentage on the quality of power supply by the transformer. The Simulink showed how the model Of the Abuja 132/33KV which was feed from the 330/132KV incoming was connected to the 150Mvar filter developed in figure 2 and then utilized to mitigate harmonics.

5. RESULTS AND DISCUSSION

This section presented the performance transformer which was configured with the harmonic filter developed and simulated with the data collected from the 132/33KV Abuja feeder transformer as shown in the table 2;

Table 2: Harmonic analysis of the feeder with filter

Harmonic Orders	**Voltage harmonic distortion (%)**
1	0.20
2	0.08
3	0.02
4	0.17
5	0.10
6	0.12
7	0.01
8	0.02
Average	0.82

The table 2 presented the data analysis of the simulated feeder transformer to study the harmonic content with the passive filter. The data was analyzed using the FFT tool as shown in the figure 4;

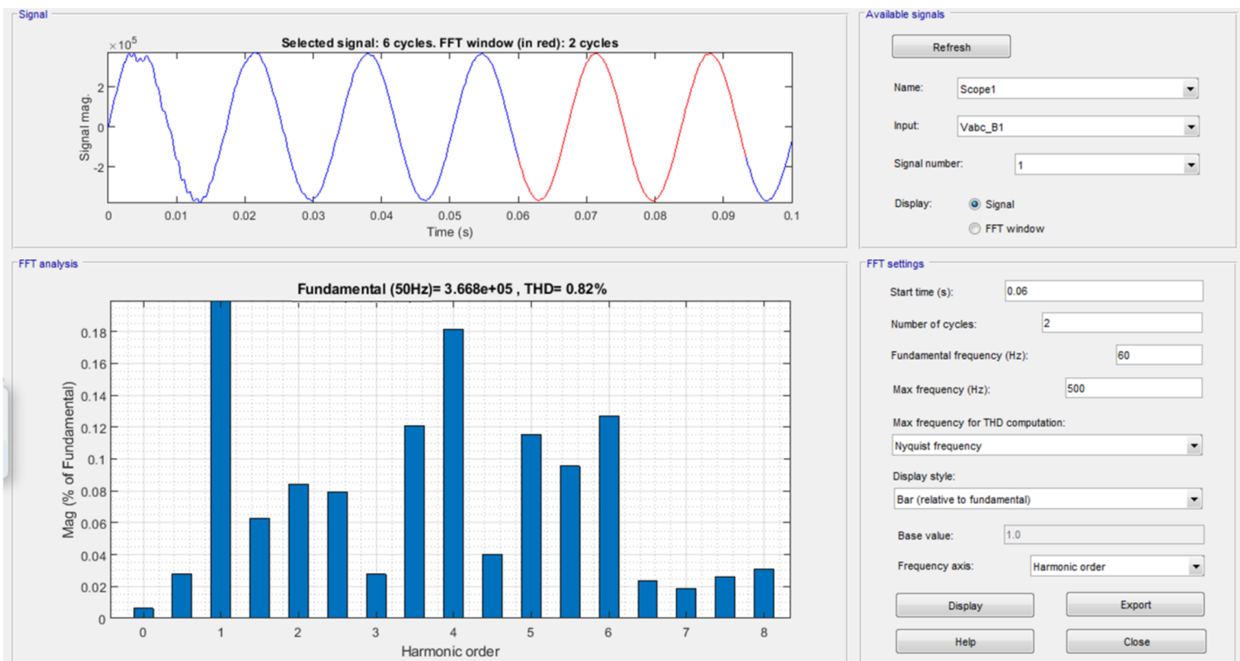

Figure 4: Harmonic performance of the 33KV transformer

From the result presented in the figure 4, it was observed that the total harmonic in the transformer is 0.82%. This result is very good as it satisfied the requirement of the national grid code, IEC and IEE standard for harmonic content in power transmission systems.

5.1 Filter Validation Result

To validate the result, the tenfold cross validation technique in Xu et al. (2008) was used which iteratively evaluated the performance of the transformer with the installed filter in tenfold and then compute the average harmonic result as presented in the table 3;

Table 3: Validation Result

S/N	Voltage harmonic distortion (%)
1	0.820
2	0.811
3	0.805
4	0.817
5	0.809
6	0.812
7	0.816
8	0.814
9	0.820
10	0.810
Avg.	0.816

From the result in the table 4.3, the validated result of the 33KV transformer was computed and the average result is presented as 0.816 which is very good performance.

5.2 Performance of the Abuja 132/33KV System with filter

The filter was deployed on the 132/33KV Abuja Suleja transmission power system after the validation and the performance was measured and presented in the table 4;

Table 4: Performance of the feeder with the integration of Passive filter

Bus ID	VIHD
Field Base 11kV	9.389
Jere 11kV Bus	7.495
Jere 11kV Bus 1	6.929
Suleja Main Bus	6.832
Suleja Transfer Bus	6.757
Bus4	4.216
Abuja Steel Bus1	4.699
Field Base 11kV	2.417
FieldBase 33kV Inj S/S	3.891
Jere 11kV Bus 1	2.061
Jere 33kV Inj. S/S	5.028
Kantoma 11kV Bus 1	6.053
Kantoma 11kV Bus 2	6.052
Kantoma 33kV Inj. S/S	6.179
Suleja 11kV Bus	5.224
Suleja 33kV Bus 1	6.219
Suleja 33kV Bus3	4.778
Suleja Main Bus	2.306
Suleja Transfer Bus	2.306
Average	4.943

The table 4 presented the result of the system integration which showed how the passive filter developed was integrated on the 132/33KV Abuja feeder for the mitigation of harmonic. The result showed that the average harmonic content on the feeder is 4.943 which satisfied the IEEE standard for harmonic mitigation in power system network. Similarly the table 4 presented the performance of the passive filter on the 132/33KV feeder network. The filter was used to mitigate the impact of voltage harmonic on the power quality or each bus. The result showed that the harmonic voltage for all the bus were mitigated and Bus4; Abuja Steel Bus1; Field Base 11kV; Field Base 33kV Inj S/S; Jere 11kV Bus 1; Suleja 33kV Bus3; Suleja Main Bus; Suleja Transfer Bus respectively was able to satisfy the IEEE requirements for quality of service. The reason other bus was not able to satisfy the requirement even though the percentage of harmonic voltage was reduced is due to aging and poor maintenance impact on the bus which affected the effectiveness of the passive filter.

6. CONCLUSION

Harmonic distortion is a major challenge in the Nigerian power sector. This distortion cannot be inevitable due to the massive employment of power electronics such as the converters and FACTS controllers. Form the reviewed in the course of this study, it was identified that out the various epistemologies employed in the past to combat those challenges (Harmonic). However, despite the success achieved, there are still problems of non-linearity experienced on the power system and the end effect affects the domestic load at home and also the major power system devices used for the power supply. The study also pointed out that some of the existing system reduced harmonic at low order and not high order, while the rest is vice versa. The study developed a system which was able to reduce the percentage of harmonic from 6.0277 to 4.94 which gives improvement of 17.99 in percentage.

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