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MINIMIZATION OF POWER DISTRIBUTION SYSTEM HARMONICS USING HIGH VOLTAGE DIRECT CURRENT BASED THREE PHASE HARMONIC FILTER

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ABSTRACT

This paper presents the minimization of 075MVA, 11/0.45KV power distribution system harmonics using High Voltage Direct Current Link (HVDC) and three phase harmonic filter. In the study the HVDC was used to control load flow stability while the harmonic it induces on the power system was controlled with three phase harmonic filter. The three HVDC was developed with 12 pulse thyristor converted and rectifier while the filter was developed with shunt elements. These were implemented on the distribution system using Simulink and the performance evaluated based on the Nigerian Electricity Regulation Commission Standard (NERC). The result when tested showed that the HVDC was able to control the flow of active and reactive power via the 6 pulse thyristor components, while the harmonics was reduced to the satisfaction of the NERC standard for power quality in distribution network.

Keywords: Voltage, Current, distribution system, Thryristors, HVDC, NERC, filter, harmonics

1. INTRODUCTION

Over time, the increased demand of electricity and the need to improve power system performance at minimum cost and time have resulted in the application of various power electronics components to help boost performance; however, despite the success of the applications, they also induce certain quantity of harmonics, which result to which degrade in the quality of power flow.There are other many factors that result in the generation of harmonics in power systems these include the nonlinear behavior of loads, nonlinear behavior of the generating plants among others (Hasan, 2017).

Harmonics are voltage or current at a multiple of fundamental frequency of the system (Johan, 2016). This harmonic signal results in poor performance of the electrical and electronic components, transformer overheating, poor power factor and stability performance among other issues which require urgent attention to be addressed in many developing and under developed power system architecture like the Nigerian power system.

Overtime, the researchers have contributed extensively to solving these harmonic challenges in power system, employing various techniques, yet despite the success they achieved, there is still need to combat this quagmire that causes instability in power system to the lowest level. These issues have motivated the researcher to embark on this study, developing a harmonic mitigation system using high voltage direct current link-based filter system.

According to (Ge et al., 2018) the use of traditional passive filter has been tried but not that much effective because their static action and no real time action or dynamic action taken for the removal of harmonics. Active filters like the shunt types have also been employed to improve the system which gives a promising result but not convincing enough as a result of some factors like overheating and noise still experienced in some of the systems, especially when the voltage is low or unstable.

Vishwaprakash and Manilandan (2015) presented a solution using the instantaneous active-reactive power method; Maswood (2013) used thyristor rectifier-based approach; Itoh and Itsuki (2018) used current injection technique among others various techniques which have been proposed to address the issues of harmonic in power system, however the solutions never considered the issues of power stability. This will be addressed in this paper using High Voltage Direct Current Link (HVDC) and three phase harmonic filter. The HVDC will be used for power stability while the filter will be used to mitigate harmonics. Brief literature review to summarize existing techniques was presented in table 1;

TABLE 1: Brief Literature Summary

Author	Title	Work Done	Paper Gap
Maswood (2013)	Optimal harmonic injection in thyristor rectifier for power factor correction	The work focuses on minimizing voltage harmonic in power electronics using a thyristor rectifier	The work has little effect on reducing current harmonic
Nishida (2016)	Enhancing harmonic injection in thyristor rectifier	The work combats harmonic using injection technique with thyristor rectifier-	The work did not completely eliminate harmonics

Itoh and Itsuki (2018)	A novel three phase PFC rectifier using a harmonic current injection method	The work reviews some previous method on harmonic filter and uses current injection technique	The work was focussed more on current harmonic challenges, and has little contribution to voltage harmonic mitigation
Bozovi and Pejovi (2015)	A novel three phase PFC rectifier using a harmonic current injection method	The work mitigates current harmonics using current harmonic injection technique, simulation model was also designed	The work was not characterised and hence the discussions result was not justified
Nassif et al (2009)	An investigation on the selection of filter topologies for passive filter application	The work was able to reveal some of the recently published bibliographies	The passive filters are not a complete solution to harmonic and also the don't stop overheating of components

2. METHODOLOGY

The methodology focused on the minimization of harmonics on the 15MVA, 11/0.45KV Emene distribution transformer while maintaining load flow stability. The study developed a three phase harmonic filter using shunt element and installed on the transformer to mitigate harmonics. The power stability of distribution system was also controlled using HVDC system developed with thyristor elements to control excess active or reactive power flow. These two developed components (filter and HVDC) were implemented on the distribution transformer using high level programming language and the load flow was studied while measuring the harmonic content using the Nigerian Electricity Regulation Commission (NERC) standard which provided harmonic current not to exceed 5% and harmonic voltage not to exceed 15% in distribution networks.

2.1 The 11/0.45KV Distribution system and power flow formulation

The transformer study is the Emene 11/0.45KV Distribution system whose single line architecture is presented showing how incoming from the 11KV was step down to 0.45KV and distributed to the various consumers. Other component which made up the system are all represented and labelled in figure 1;

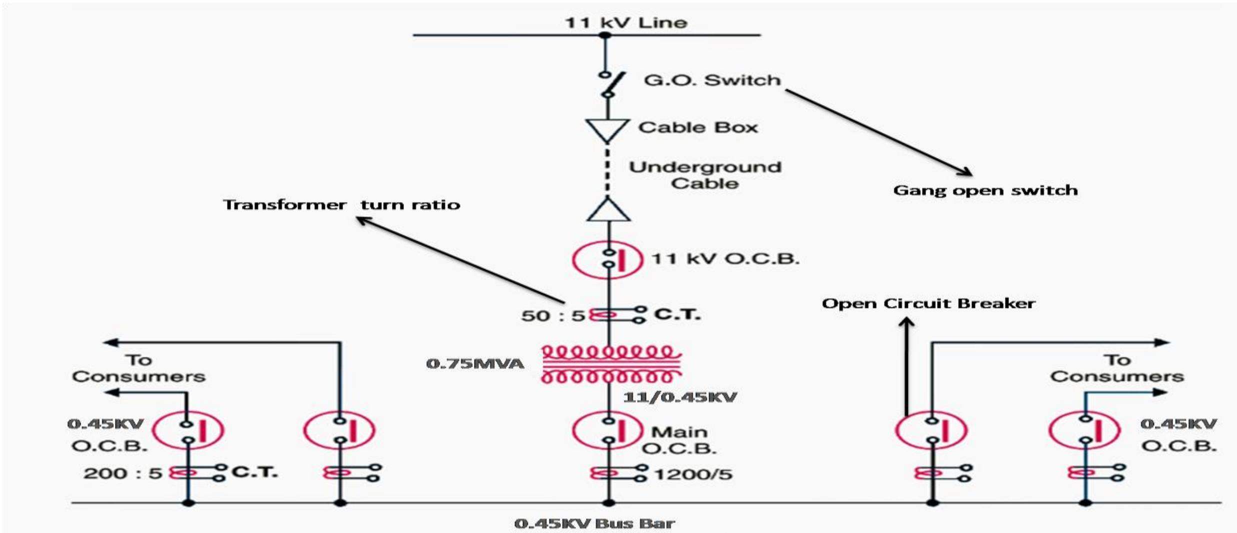

Figure 1: Single line diagram of the 11/0.45KV distribution network

The figure 1 presented the single line diagram of the distribution network, from a loadflow perspective, there are four parameters at the bus which are the voltage magnitude V, voltage angle δ, active power P, and reactive power Q. To detrmine the load flow problem a swing bus is considered at the generator with magnitude and phase angle specified as zero. The table 2 was used to classify the load flow properties in the bus with two unkown paramaters respectively.

Table 2: Classificaiton of load flow in the bus

Classification	Knowns	Unknowns
PQ (Load Bus)	P, Q	V, δ
PV (Generator Bus)	P, V	Q, δ
V δ (Swing Bus)	V, δ	P, Q

The loadflow program solves for the set of unknowns that produces power balance at the bus as.

$$P_i^{spec} + jQ_i^{spec} = P_i^{calc} + jQ_i^{calc} \qquad 1.0$$

Where;

$$P_i^{calc} + jQ_i^{calc} = V_i I_i^* \qquad 2.0$$

In other words, the power specified at the bus must equal the power flowing into the system. Since there are two unknowns at the bus, the size of the loadflow problem is 2N, where N is the number of busses. Obviously, to solve the problem, there must be two equations for every bus presenting the active and reactive power flow respectively using the kirchoffs current law for ith bus as; $P_i^{spec} + jQ_i^{spec} = P_i^{calc} + jQ_i^{calc}$

$$= V_i I_i^* = V_i \left[\sum_{j=1}^{N} y_{i,j} V_j\right]^* \qquad 3.0$$

Separating into real and imaginary components yields two equations for bus i,

$$P_i^{spec} = \sum_{j=1}^{N} |V_i| \left|y_{i,j}\right| \left|V_j\right| cos\left(\delta_i - \delta_j - \theta_{i,j}\right) \quad 4.0$$

2.2 The Harmonic Problem Formulation

To model the harmonic effect on the distributive system, first the root means square values of the system are determined based on the expressions for the RMS voltage and current as (Mashwood, 2013);

$$V_{RMS} = \sum_{H=1}^{\infty} \left(\frac{V_h}{\sqrt{2}}\right)^2 \quad 6.0$$

$$I_{RMS} = \sum_{H=1}^{\infty} \left(\frac{I_h}{\sqrt{2}}\right)^2 \quad 7.0$$

Here it is assumed that V_h and I_h are also given in RMS. From the equation 6.0 and 7.0, the total harmonic current and voltage are defined as (Mashwood, 2013);

$$THD_V = \frac{\left[\sqrt{\sum_{h=2}^{\infty} V_h^2}\right]}{V_1} \quad 8.0$$

$$THD_V = \sqrt{\{[(V_{RMS}/V_1)^2] - 1\}} \quad 9.0$$

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.

$$THD_I = \frac{\left[\sqrt{\sum_{h=2}^{\infty} I_h^2}\right]}{I_1} \quad 10.0$$

$$Q_i^{spec} = \sum_{j=1}^{N} |V_i| \left|y_{i,j}\right| \left|V_j\right| sin\left(\delta_i - \delta_j - \theta_{i,j}\right) \quad 5.0$$

$$THD_I = \sqrt{\{[(I_{RMS}/I_1)^2] - 1\}} \quad 11.0$$

Where I_h is the harmonic current at harmonic frequency h in RMS; I_1 is the rated fundamental current in RMS. The RMS voltage and current can now be expressed in the terms of THD as (Mashwood, 2013);

$$V_{RMS} = \sqrt{\sum_{h=1}^{\infty} V_h^2} \quad 12.0$$

$$I_{RMS} = \sqrt{\sum_{h=1}^{\infty} I_h^2} \quad 13.0$$

2.3 Development of the three phase harmonic filter

The tuned passive filter is developed using a resistor, inductor and capacitor (RLC) shunt element for decreasing harmonic voltage and correction of power factor. The RLC parameters were achieved from the load flow reactive power at nominal voltages, variable frequency and quality factor. The tuned passive filter involves a parallel connection of the single, double, C-type and high pass filter to the power system as;

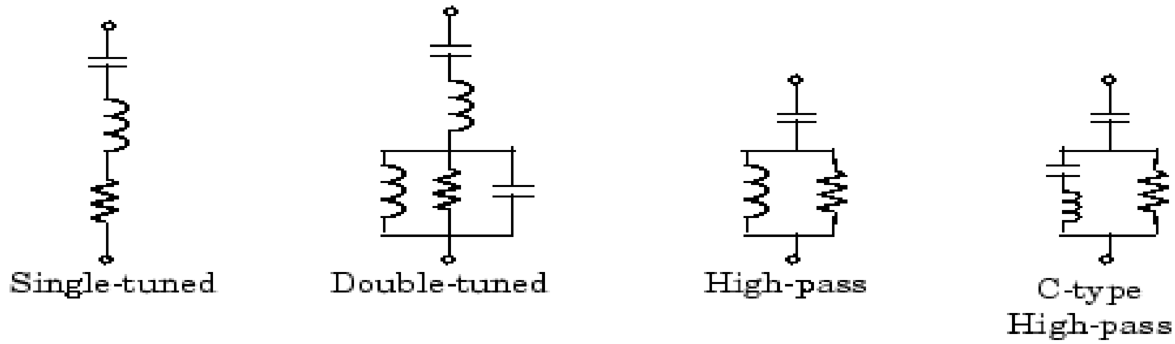

Figure 2: The four types of filter

From the four filter types respectively, the single tuned filter is the simplest and used to ensure quality factor and computation of reactive power; the quality factor is presented as the tuning frequency $Q=nX_l / R$ which is used to determine the tuning frequency and sharpness of the filter. The double tuned filter is made of series of LC circuit and parallel RLC circuit. If for instance f1 and f2 are the fundamental frequencies. They are approximately tuned in series and parallel in the geometric frequencies as Fm = Gf1f2. The quality factor of the double tuned filter are based on the quality of the L elements connected parallel in mean frequencies Fm = Q = R/L*R*3.142Fm. The high pass filter is on the other side a single filter where the L and R element are in parallel connection rather than series. This results to the wide band filter with an impedance of high frequency with reduced resistance R. The Q factor of the C-type filter is presented as Q = R / L*2*3.142*Fn. The figures in 3.11 presents the RLC parameters and impedance frequency ratio curved for the four type of filter at 60Hz network. The ratings of the three filters are 315KV, 49M Var. the table 3 was sued to configure the filter while the Simulink equivalent is presented in figure 3;

Table 3: The three phase harmonic filter parameters

Parameters	Model	Description
Tuned harmonic filter	$n = \frac{f_n}{f_1} = \frac{GX_C}{X_L}$	F1 = fundamental frequency ; ω=$2\pi f1 = angluar\ frequency$; fn = tuning frequency, n = harmonic order V =nominal line voltage Xl = capacitor reactance at fundamental frequency
Quality factor	$Q = \frac{nX_L}{R} = \frac{X_C}{n_R}$	
Bandwidth	$B = \frac{f_n}{Q}$	

Reactive power at f1	$Q_c = \left(\frac{V^2}{X_c}\right) * \frac{n^2}{n^2-1}$	
Active power at f1 (Losses)	$P = \left(\frac{Q_c}{Q}\right) * \frac{n^2}{n^2-1}$	

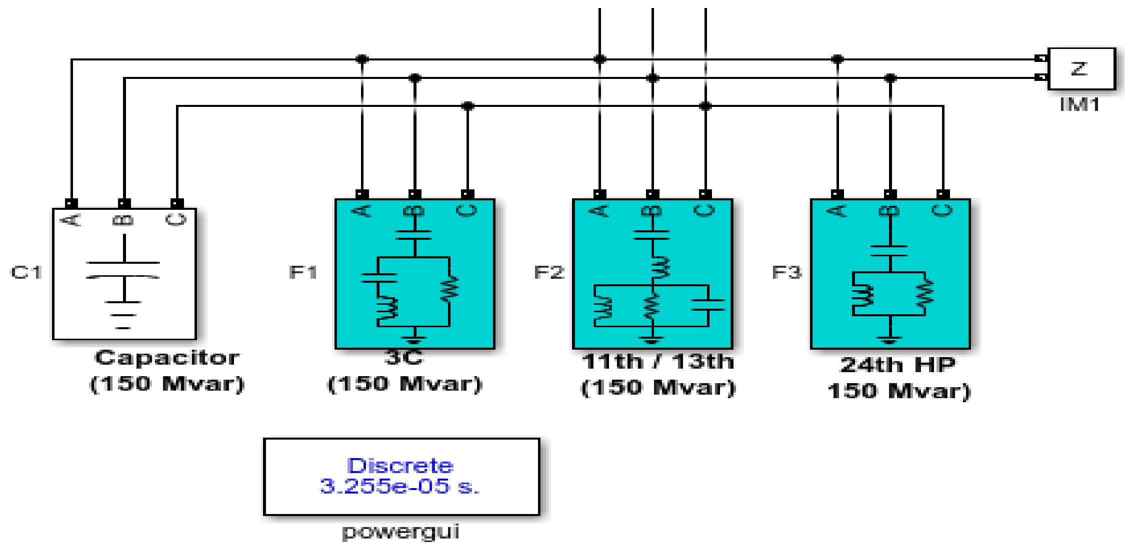

Figure 3: The electrical circuit of the filter

2.4 Development of the HVDC Link

The HVDC was used in this study for the control of the active and reactive power flow from the distribution system. The HVDC was developed using 12 pulse thyristor converter and rectifier system configured with bi-universal bridge which is connected in series through the distribution line and 0.5 H smoothing reactors. The Rectifier Pole Control (Current) and the Inverter Pole Control (Current/Voltage/Gamma) subsystems generate the current reference for both converters and initiate the starting and stopping of the DC power transmission. At the inverter, the Gamma measurement subsystem measures the extinction angle Gamma of the 6-pulse thyristor converters. The figure 4 presented the block model of the HVDC.

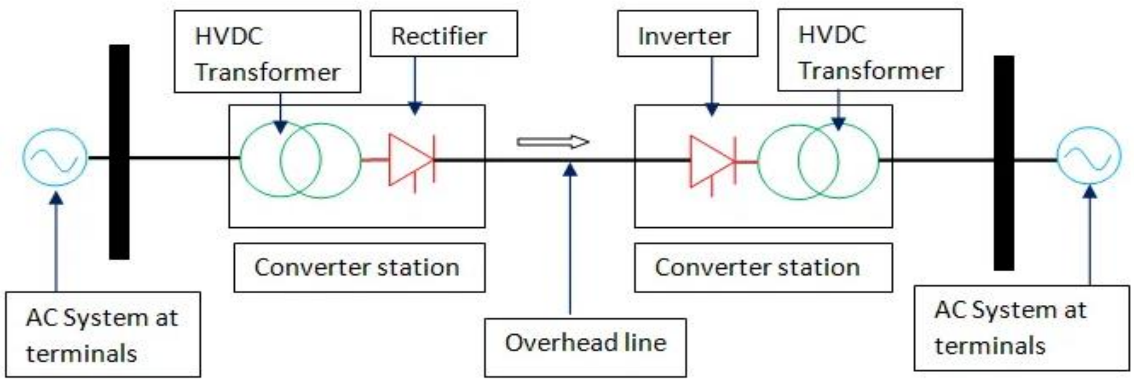

Figure 4: HVDC block diagram,

2.5 The improved power distribution system

The improved power distribution system used the harmonic filter developed and the HVDC to optimize the performance of load flow while mitigating harmonic content during distribution. The HVDC was used to control the stability margin of the active and reactive power for steady state load flow while the harmonic filer was used to mitigate the harmonic distortion attributed with the power system network. The flow chart o the improved power system network was presented in figure 5;

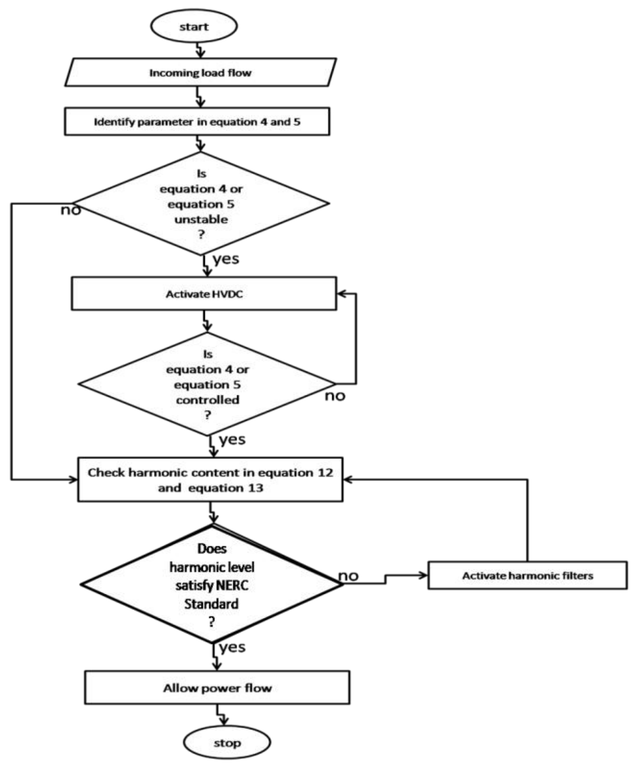

Figure 5: system flow chart

3. IMPLEMENTATION

This was achieved using the mathematical models of the load flow and harmonics on the distribution network and then system using tool such as power system toolbox, optimization toolbox and Simulink. The 11/0.45KV distribution network was connected to the three phase harmonic filter from the bus 1 and bus 2. Then the HVDC was also connected to the secondary side of the transformer for power flow output control. The Simulink model of the network was presented in figure 5

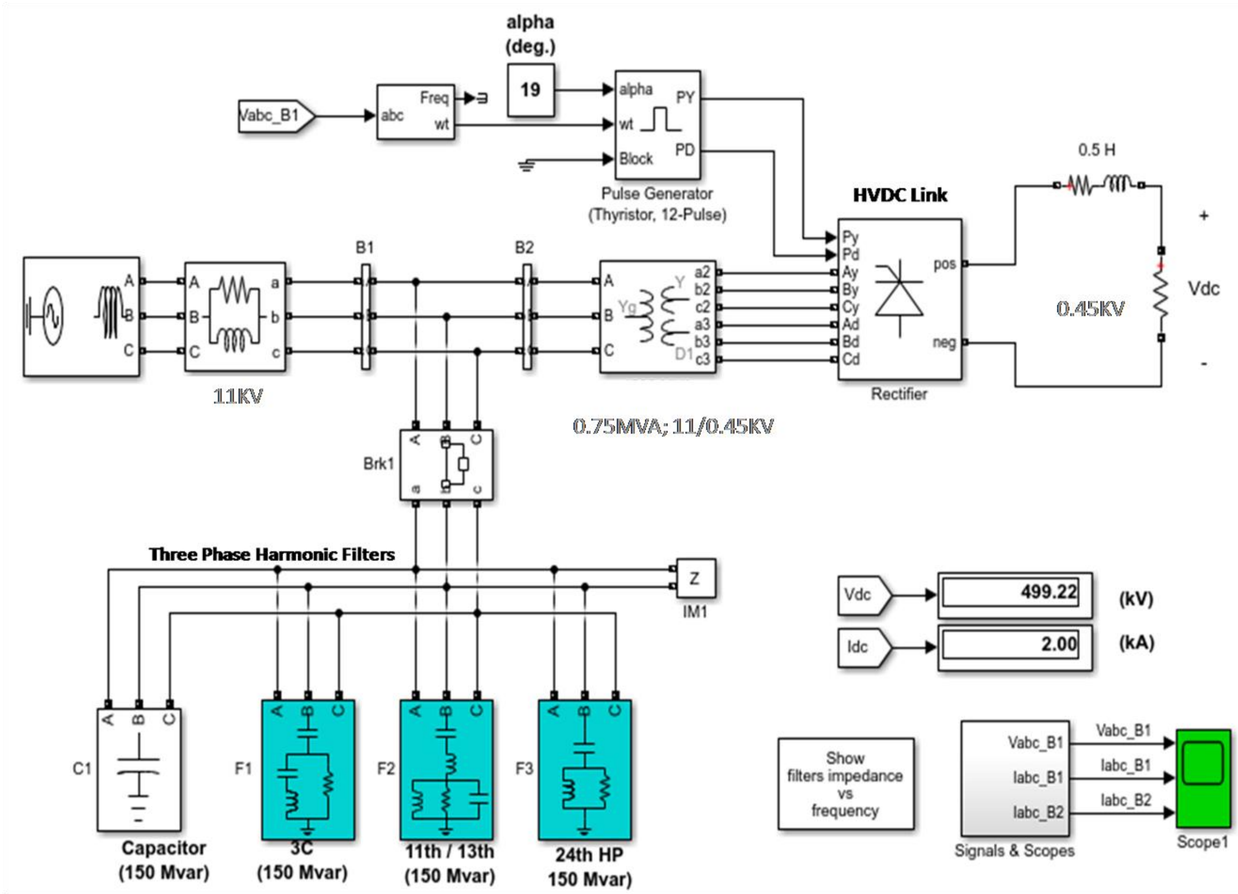

Figure 6: Simulink model of the system

The figure 6 presented the Simulink model of the 0.75MVA, 11/0.45KV Emene distribution transformer improved with the HVDC and harmonic filter. In the HDVC the 6 pulse thyristor-based converter device is connected in series to the feeder transformer for active and reactive power flow control. When harmonic is induced on the load flow due to the operational limitation of HVDC, the filters are activated to mitigate the harmonic content in various phases. To simulate the system, the filter was disconnected from bus 2 and then simulated with the parameters in table 3; the reason is to compare the quality of power in bus 1 with filter and in us 2 without filter.

TABLE 4: Simulation Parameters

Parameters	Values
Power system capacity	11kV
Number of Buses	2
Transformer type	Three phase power

	transformer
Capacitance	20 X 10^6uf
Load capacity	15MVA
Inductance	0.5H
Total reactive power	600Mvar
Frequency	50Hz
Start time	0.06Ss
Base value	1.0
Signal number	1,2 or 3
Frequency axis	Harmonic order or Hertz
Window style	FFT window or

	signal
DC components	4.849e + 04
Samples per cycle	614
Sampling time	3.25521e-05s

4. RESULT AND DISCUSSION

The result of the power distribution system was presented showing the load flow performance of the network with the current and voltage flow in the bus as modeled in equation 3.0 and the result presented in figure 7;

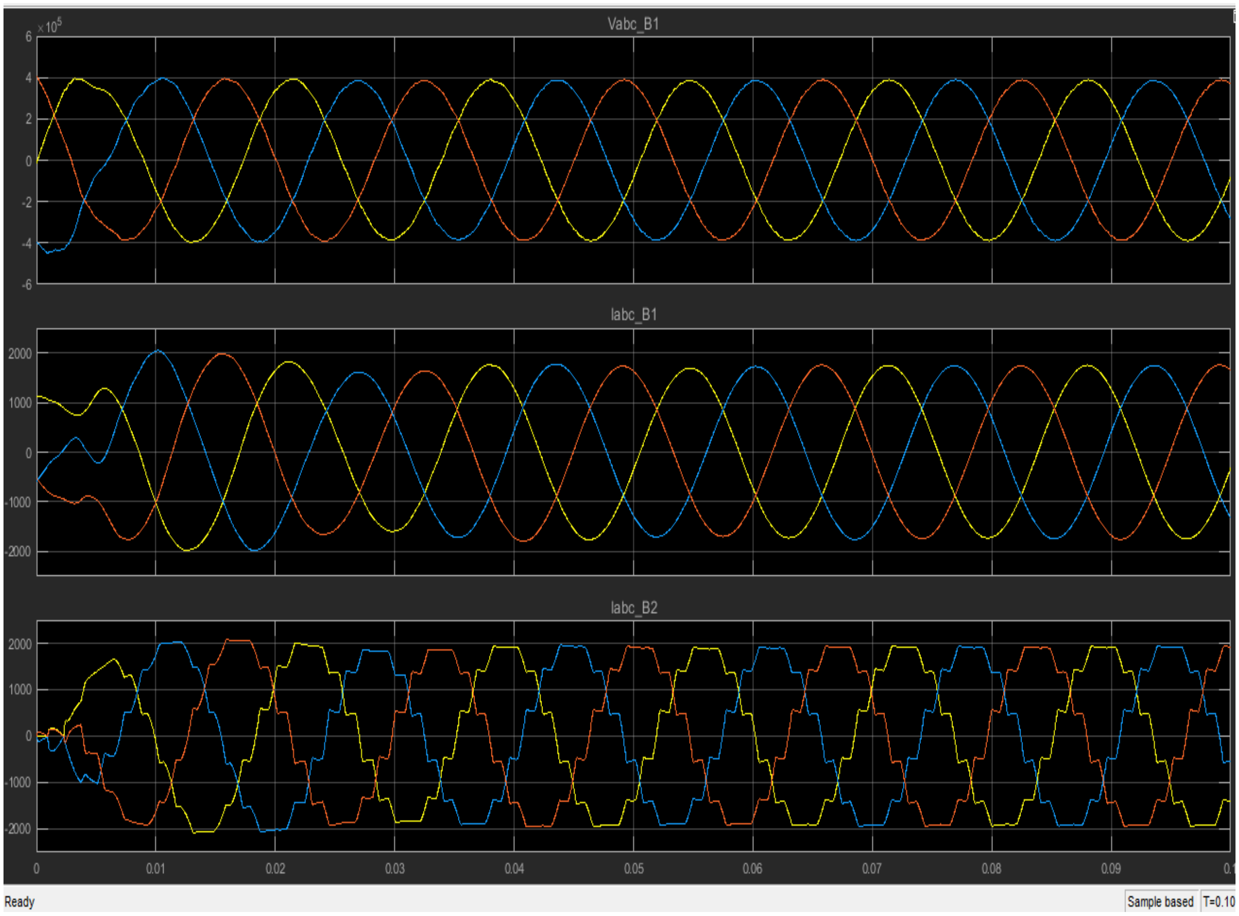

Figure 7: Result of the load flow

The figure 7 presented the performance of the load flow with the HVDC. From the result it was observed that at 0.01s when there was nonlinear power flow, the HVDC was able to control the load flow and ensure balance in the three phase of the network. It was observed that the three phase harmonic filter installed in bus 1 was able to mitigate harmonics and allow smooth flow of power as against bus 2 where the filter was not active. To measure the percentage of the current harmonics, the harmonic analyzer in figure 8 was used as;

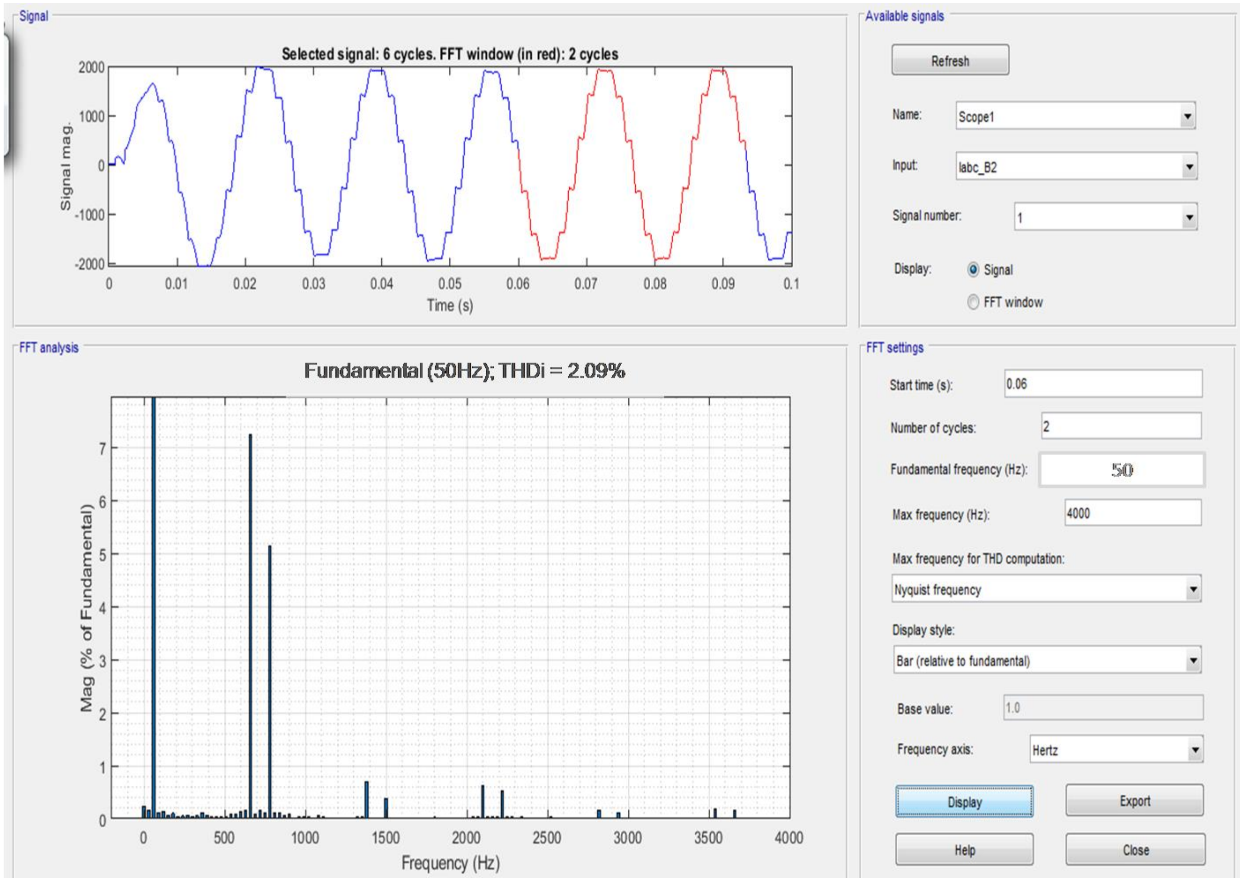

Figure 8: Result of current harmonics

From the result it was observed that the percentage of current harmonics in the load flow is 2.09% which is good as it satisfied the NERC standard for harmonic content in load flow. The performance of the filter on the mitigation of voltage harmonic is also reported in figure 9;

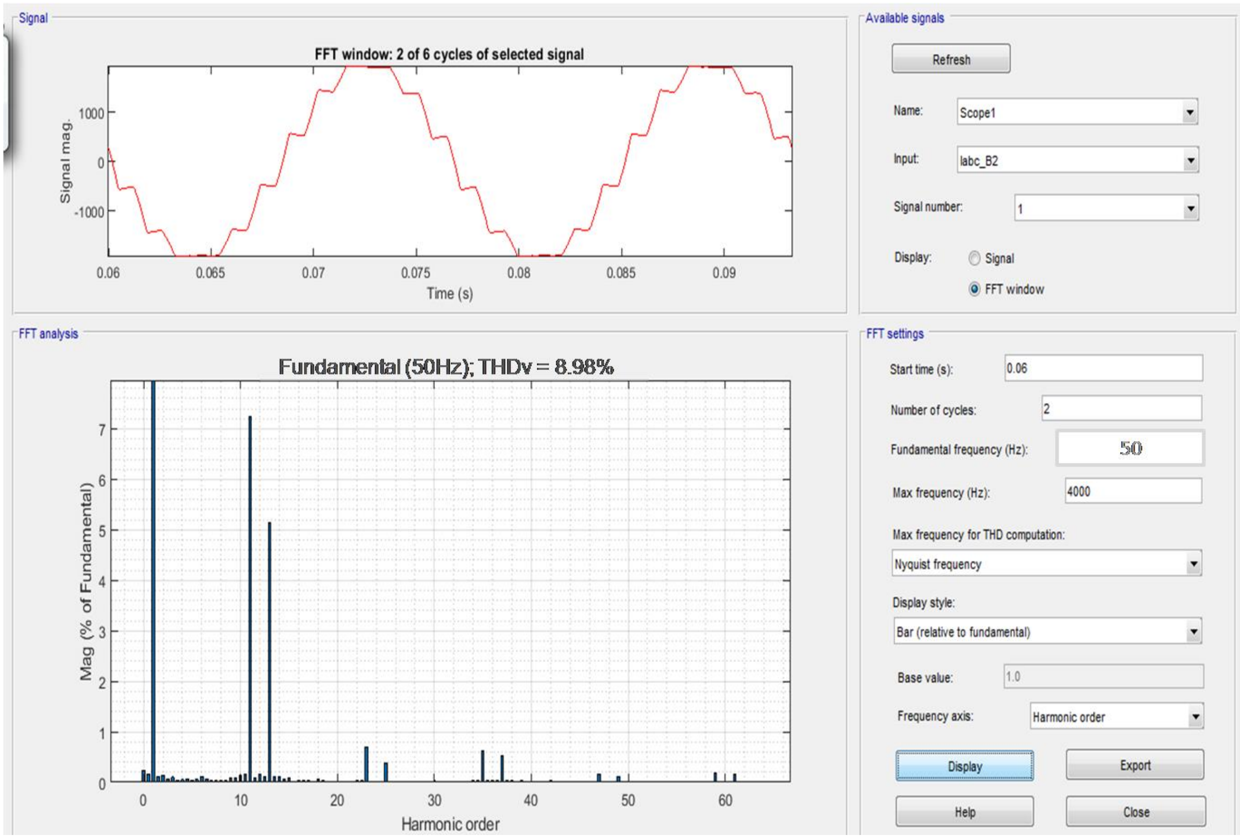

Figure 9: Result of the voltage harmonics

From the figure 9 it was observed that the performance of the three phase filter on the harmonic voltage was very effective as it was reduced to 8.98% which satisfied the requirement of the NERC regulations

5. CONCLUSION

This paper has successfully developed a HVDC system for control of power system instability and also counter the system limitation which is harmonics using a three phase harmonic filter. The result when tested showed that the HVDC was able to control the flow of active and reactive power via the 6 pulse thyristor components, while the harmonics was reduced to the satisfaction of the NERC standard for power quality in distribution network.

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