Saudi Journal of Engineering and Technology (SJEAT)
Scholars Middle East Publishers
Dubai, United Arab Emirates
Website: http://scholarsmepub.com/

ISSN 2415-6272 (Print)
ISSN 2415-6264 (Online)

Performance Analysis of Distribution Transformer in Nigerian Power System

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Original Research Article

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Article History
Received: 02.06.2018
Accepted: 09.06.2018
Published: 30.06.2018

DOI:
10.21276/sjeat.2018.3.6.3

Abstract: Distribution transformers, being the most common equipment in a distribution system, are of very great importance and must be properly cared for so that they can perform optimally at all times and last long. One of the major challenges distribution transformers have is the amount of losses in the transformer. These losses are load and no-load losses, of which load losses constitute the most under full and medium capacity operations. Several methods have been proposed in the fight to improve the handling capacity of distribution transformers and reduce the load losses in the transformer. In this study, an analysis is carried out on the effects of linear and non-linear loads on an 11/0.415kV, 200kVA, three phase, two winding oil coiled distribution transformers and three of the methods of loss compensation. These system is modelled and simulated using Matlab Simulink 2015a. The simulation results are collected and using Microsoft Excel, graphs are used to compere the results from the different simulations.

Keywords: Distribution transformer, Linear and non –Linear Load, Harmonics.

INTRODUCTION

Distribution transformers, being the most common equipment in a distribution system, are of very great importance and must be properly cared for so that they can perform optimally at all times and last long. One of the major challenges distribution transformers have is the amount of losses in the transformer. These losses are load and no-load losses, of which load losses constitute the most under full and medium capacity operations. Several methods have been proposed in the fight to improve the handling capacity of distribution transformers and reduce the load losses in the transformer. In this study, an analysis is carried out on the effects of linear and non-linear loads on an 11/0.415kV, 200kVA, three phase, two winding oil coiled distribution transformers and two of the methods of loss compensation.

These systems are modelled and simulated using Matlab Simulink R 2015 [1]. The simulation results are collected and using Microsoft Excel, graphs are used to compere the results from the different simulations. The following methods are analysed in this study:

- Capacitor bank: this method provides the necessary reactive power for the reduction of losses caused by poor power factor loads.
- Passive Filter for Harmonic mitigation and Power Factor Correction (PFC): this method has both power factor correction and harmonic mitigation capabilities. It employs passive components (Capacitors, Inductors/Reactors and Resistors) arranged in different configurations to match the filtering ability.

TRANSFORMER

A transformer is an electrical machine without any mechanical or moving parts. It is used to transform electric signals from one level to another depending on the nature of application. Transformers are key equipment in a power transmission and distribution network. This piece of equipment is either of the step-up form (used to raise voltages from a lower level to a higher one), step-down form (used to drop voltages from a higher level to a lower one) or current transformer. The most common type found in the Nigerian power network is the 11/0.415kV oil cooled, distribution transformer. This type of transformer is the focus of this project. Fig-1 shows the equivalent circuit of a transformer.

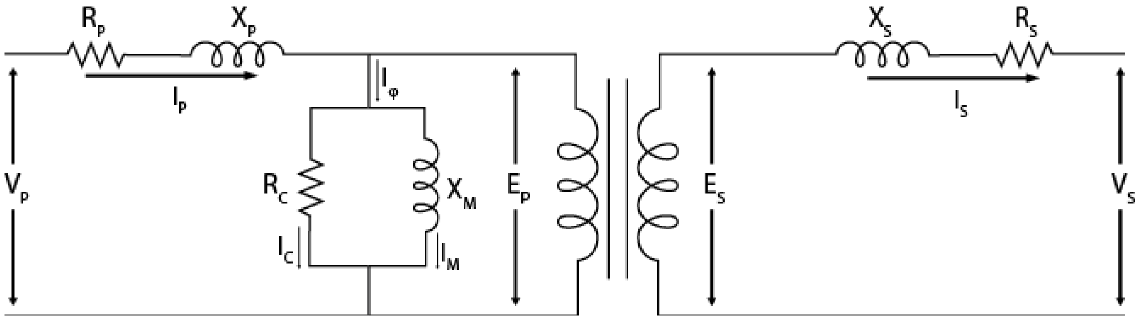

Fig-1: Equivalent Circuit of Transformer

Working Principle

The operation of a transformer is centred around electromagnetic induction. Electromagnetic induction is a phenomenon that occurs when an electromotive force is created within a conductor that is exposed to a magnetic field. In a transformer, a varying current in the transformer's primary winding creates a varying magnetic flux in the transformer core and a varying field imposing on the transformer's secondary winding. This varying magnetic field at the secondary winding induces a varying electromotive force (EMF) or voltage in the secondary winding due to electromagnetic induction. According to Faraday's law of electromagnetic induction, the same magnetic flux flows through both windings of an ideal transformer. Therefore, the following equations are used in describe the relationship between the winding EMF, the varying magnetic flux, and the number of winding turns, for both primary and secondary windings of the transformer.

$$V_S = N_S \cdot \frac{d\Phi}{dt} \quad (1)$$

$$V_P = N_P \cdot \frac{d\Phi}{dt} \quad (2)$$

Where,

V_s and V_p represents the Secondary and Primary Voltages
N_s and N_p represents the Number of winding turns of Secondary and Primary windings
$\frac{d\Phi}{dt}$ Represents the varying magnetic flux

By taking the ratio of equation 1 and 2 and introducing the law of Conservation of Energy, real, reactive and apparent power are conserver in both primary and secondary winding for any attached impedance. This gives rise to the ideal transformer identity equation as shown below.

$$\frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S} = \sqrt{\frac{L_P}{L_S}} = a \quad (3)$$

Where,

I_S and L_S are the Secondary Current and Inductance
I_P and L_P are the Primary Current and Inductance

The ideal transformer is a good approximation for the operation of any transformer. Nevertheless, in real life operation of a transformer there exists other factors that result in the reduction of the overall efficiency of the transformer, giving support to the saying that "no machine is and can ever be 100% efficient". These factors constitute the losses incurred during the operation of a transformer.

LOSSES IN A TRANSFORMER

The losses incurred by a transformer are grouped into two types, namely, No-load Losses (Core Losses) and Load Losses (Copper Losses).

No-Load Losses (Core Losses)

These losses are caused by magnetizing currents in the transformer core lamination and consist of mainly Hysteresis losses and eddy current losses. These losses are constant for different types of distribution transformers and are specified in the datasheet of the transformer. They are not dependent on varying load currents, hence giving it the name "No-Load Losses".

Load-Losses (Copper Losses)

These losses are dependent on the amount of current drawn by the load from the transformer, hence the name "Load Losses". Also referred to as I^2R losses, these losses constitute the most part of losses on a distribution transformer. Total Load loss is the sum of copper loss (P_{CL}), winding eddy current loss (P_{WEC}) and other stray losses (P_{OSL}) as shown in equation (2.4) below.

$$P_{LL} = P_{CL} + P_{WEC} + P_{OSL} \qquad (4)$$

The above equation only deals with load losses when a linear load is placed at the secondary winding of the transformer. In the case of having a non-linear load, which introduce harmonic components to the line signals, the above equation becomes;

$$P_{LLH} = P_{CL} \sum_{h=1}^{h=max} \left(\frac{I_h}{I_R}\right)^2 + P_{WEC} \sum_{h=1}^{h=max} \left(\frac{I_h}{I_R}\right)^2 h^2 + P_{OSL} \sum_{h=1}^{h=max} \left(\frac{I_h}{I_R}\right)^2 h^{0.8} \qquad (5)$$

Where,

I_h is the value of the current at the harmonic order h
I_R is the rated current
P_{LLH} is the Load Loss due to harmonics

Standards have been set by international bodies to regulate the level of harmonics devices introduce into the power system. The IEC/EN 61000-3-2 (2000 (A14)) sets limits for harmonic levels and current drawn by devices at different harmonic level. Different devices are grouped into classes in accordance to their harmonic effects on power systems. These devices are grouped from class A – D of which class A is the most harmful and must be controlled.

LOAD TYPES AND THEIR EFFECT ON TRANSFORMERS

In practice there are mainly two types of load, the Linear and Non-Linear loads.

Linear Loads

Linear loads are generally those that completely obey Ohm's law which is stated thus; the current flowing through a conductor is directly proportional to the voltage across it.

$$V = I.R \qquad (6)$$

This law allows for a linear relationship between the voltage across two points on a conductor and the current flowing through those points at a constant resistive value **R** (which is the proportionality constant). For a purely resistive load, there is no adverse effect on the transformer because the voltage and current waveforms are in phase. Nevertheless, when the load is linear but draws reactive power, either leading (Capacitive loads) or lagging (Inductive loads), the voltage and current wave forms go out of phase. The cosine value of this phase angle is what is called the Power Factor. At a power factor less than 1 (unity), the efficiency of the transformer reduces due to winding losses.

$$Power\ Factor_{Disp} = Cos\varphi = \frac{Active\ Power\ (P)}{Apparent\ Power\ (S)} \qquad (7)$$

The winding losses are due to increased values of current flowing through the windings of the transformer as the phase angle between the voltage and current signals increase.

Non-Linear Loads

Non-linear loads, unlike linear loads create what is known as harmonic distortions in the current and voltage waveforms. Harmonic distortions on current and voltage wave forms is simply the addition of higher order frequencies, which are whole number multiples of the fundamental frequency to the transmitted signal. Fig 2 shows an example of a wave form with fundamental, 2nd order harmonic and 3rd order harmonic frequencies alongside the resultant signal.

With added frequencies of the same signal flowing through or consumed by a load, comes additional current or voltage values i.e. the Root Mean Square of each frequency of the signal is summed up to form the total current drawn by the load as shown in equation (8).

$$I_{rms} = \sqrt{\sum_{n=1}^{n} I_n^2} \quad (8)$$

Where,

I_{rms} is the Root Mean Square of the Current Signal
I_n is the Value of the Current Signal at harmonic order n

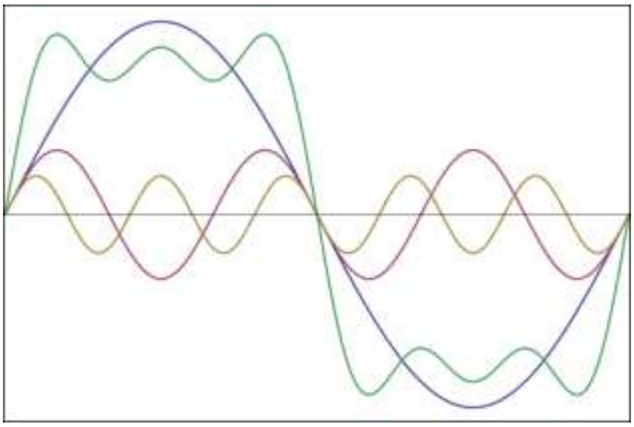

Fig-2: Signal with Harmonic Components

From equation (8) it can be seen that the total RMS value of the current signal is increased with the addition of harmonic distortions. A method of checking the amount of harmonic distortion of a signal is by calculating the total harmonic distortion of the signal. This is done by taking the ratio of the harmonic RMS current value and the value of the current signal at the fundamental frequency as given below.

$$THD_i\% = \frac{\sqrt{\sum_{n=2}^{n} I_n^2}}{I_f} \times 100 \quad (9)$$

Where,

THD_i is the Total Harmonic Distortion of the current signal
I_f is the value of the current signal at its fundamental frequency i.e. n = 1

Equations 8 and 9 are also used in the calculations for voltage distortion. The introduction of harmonic components to a signal has its own adverse effect on the power factor of the system. The mathematical relationship is as shown below.

$$P.F_{True} = P.F_{Disp} \times \frac{1}{\sqrt{1+THD_I{}^2}} \times \frac{1}{\sqrt{1+THD_V{}^2}} \quad (10)$$

According to Sanjay and Laxman [1], Fuchs [2] and Grady [3], the total voltage harmonic distortion in modern systems is very small in the range of 2% - 5% therefore it is neglected making equation 10 become

$$P.F_{True} = P.F_{Disp} \times \frac{1}{\sqrt{1+THD_I{}^2}} \quad (11)$$

$$P.F_{True} = P.F_{Disp} \times P.F_{Dist} \quad (12)$$

From the above equation it can be seen that the introduction of distortion power factor reduces the true power factor of the system, in a way that a THD_I of 30% (0.30) which gives a distortion power factor of 0.9578 will reduce the true power factor to 0.8620 at a displacement power factor of 0.9, thereby increasing the losses on the transformer.

LOAD-LOSSES REDUCTION METHODS

Several methods of loss reduction in transformers have been proposed by different individuals and groups. But the methods of concern to us in this study are the use of capacitor bank and the use of passive filters.

Capacitor Bank

The application of capacitor bank is the easiest means of loss reduction in distribution transformers. This works by supplying the required reactive power (VAr) to the system to correct/improve the power factor of the system. In this method, the capacitors are either placed at the load point (which is the common practice) or at the point of common connection as proposed by Sanjay and Laxman [1]. This method has been further improved by Ravendran and Krubakaran [4], Praveen *et al*., [5] and many others to include automatic switching system that switches between capacitors in order to deliver the exact reactive power required to improve the power factor and reduce losses. This improvement helps in tackling the effects of excessive reactive power delivered by a fixed value capacitor bank. Despite these improvements this method still has its limitations. This is the fact that in the presence of non-linear loads, instead of improving the power quality, it reduces it by increasing the total harmonic distortion of the signal thereby increasing the amount of lost power.

FILTERS

There are basically three categories of filters that are used in the reduction of losses on distribution transformers due to harmonic distortions on the voltage and current signal and reactive power compensation as well as power factor correction or improvement. These filters are Passive, Active and Hybrid filters

Passive Filters

A passive filter is one that makes use of passive devices (inductors, capacitors and resistors) to discriminate frequency levels i.e. it creates a low impedance path for certain frequency levels. Passive filters are of two main categories, the Series and Parallel passive filters.

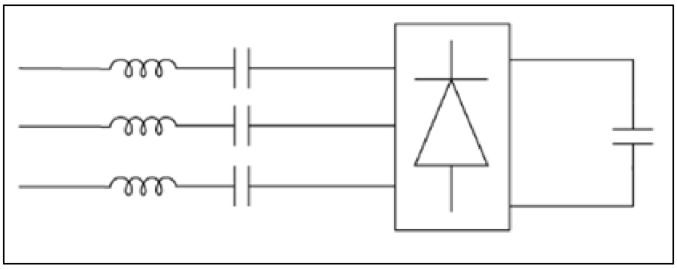

Fig-3a: Series Connected Passive Filter

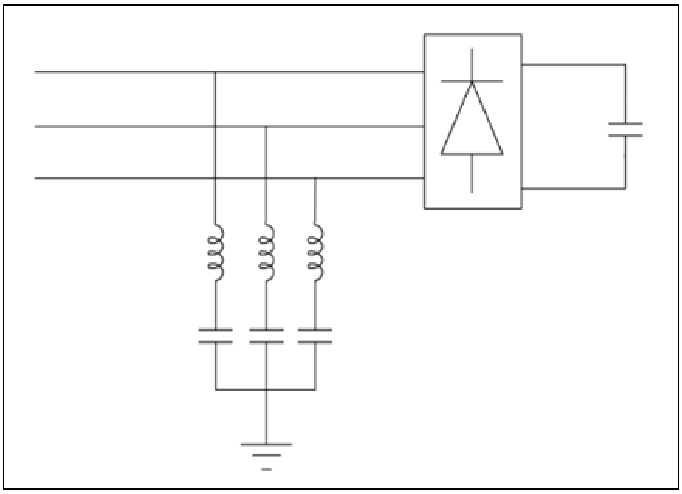

Fig-3b: Parallel Connected Passive Filter

These filters are tuned to filter specific harmonic components of a signal and deliver required reactive power to the system. Within the above mentioned categories of passive filters, there are three types or configurations, which are, single tuned, double tuned and High pass filters. Among these the most commonly used in the industry is the single tuned filter. Despite their effectiveness, they have limitations of design complexity, high cost of losses, inability to handle interharmonic and non-characteristic harmonic – Chauhan and Thakur [6], the introduction of resonance to the system and a bulky nature – Sahana [7].

METHODOLOGY

A software model of the system is developed using Matlab 2015a. The system model is divided into three sub-systems namely, Source-Load system, Measurement system and Compensation system.

SOURCE-LOAD SYSTEM

The source and load model comprises of the following block; AC supply, Transformer and Load blocks.

THE TRANSFORMER MODEL

The transformer model is based on a 200kVA, 11/0.415kV, distribution transformer, whose specifications were taken from the manufacturers datasheet which was gotten from Port Harcourt Electrical Distribution (PHED) Company's monitoring station, Moscow road, Port Harcourt. The transformer model used – which is a three phase two winding wye-delta transformer model – for the simulation is a Simscape Power Systems library model. This model is designed by using three single phase transformerss. It gives room for the user to select the operational characteristics of the transformer and input the necessary transformer parameters as shown in Fig-4a and b. Table-2 contains the parameters used for the transformer model. The transformer is modelled neglecting core saturation because the study is focused on load-losses. Fig-5a and b shows the model block and the internal structure of the block respectively.

Table-2: Transformer Specification

PARAMETERS	VALUE	UNIT
Power Rating	200	KVA
I_1	10.5	A
I_2	266.7	A
No-Load (Core) Loss	500	W
Full Load (Copper) Loss @ 75°C	3000	W
R_1	14.75	Ω
R_2	0.0062	Ω
L_1	0.003	H
L_2	0.067	H
R_C	728000	Ω
X_m	32105	H

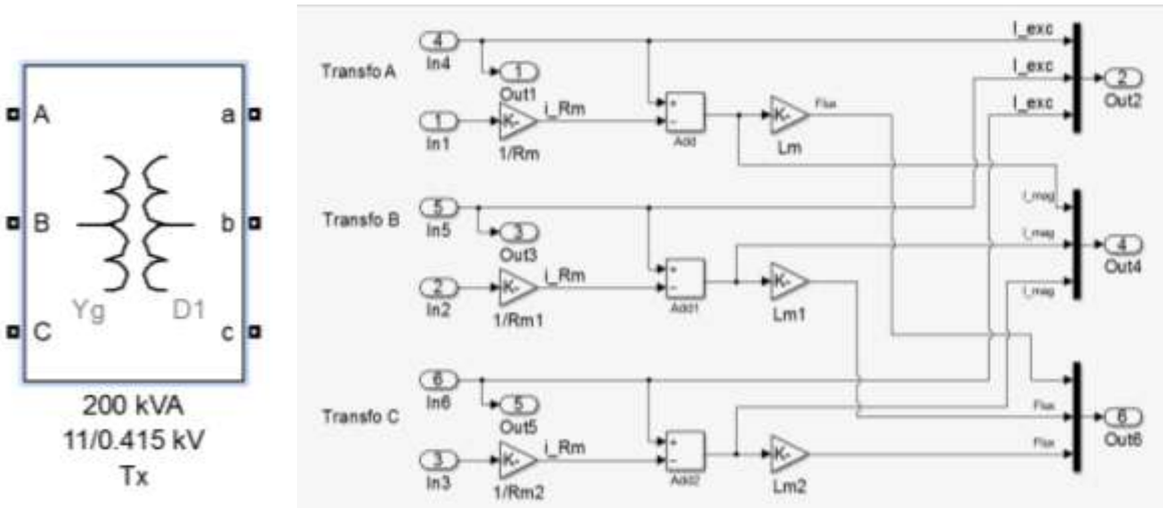

Fig-4 (a): Three-phase, Two winding Transformer Block (b) Internal structure of Transformer Block

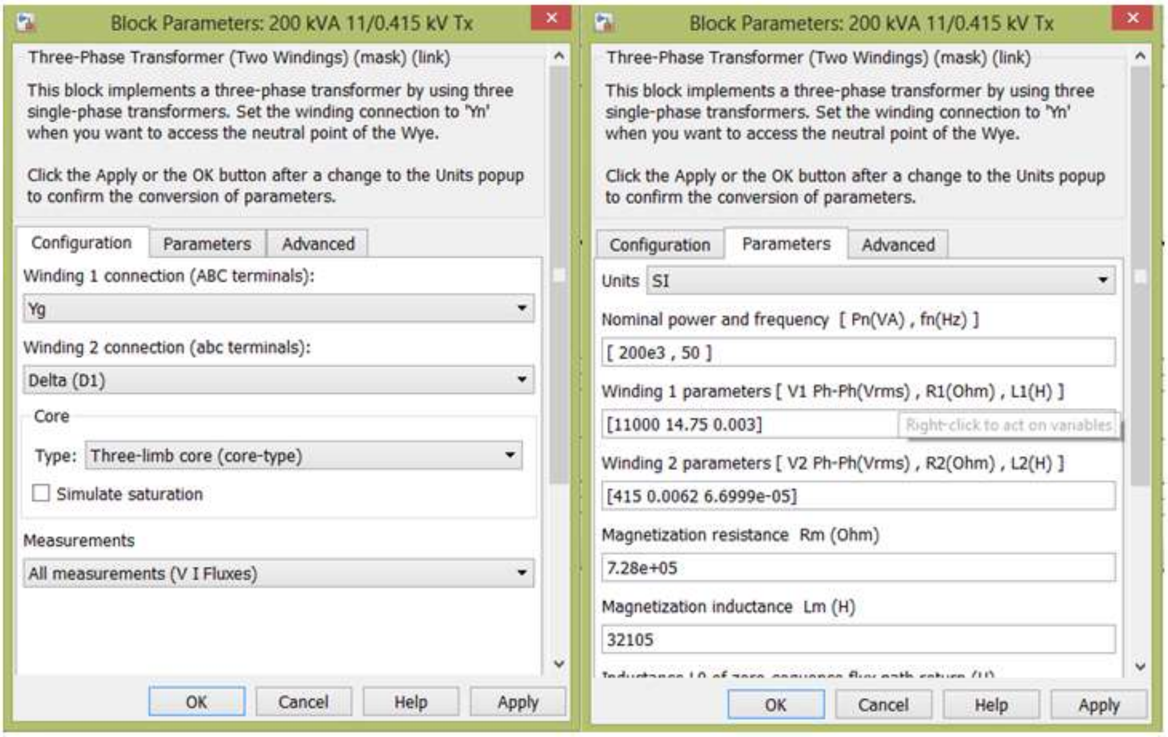

Fig-5 (a): Configuration section of Parameter Dialog box (b) Parameters Section of Parameter dialog box

LOAD MODEL

Two load types are modelled and adjusted to different capacities as required for the simulation. These loads are, linear and non-linear loads at full load and half load capacity of the transformer rating.

Linear Load

The linear load model is a three-phase series R-L-C load block gotten from the Simscape power systems library. This block makes use of the inputted parameters to simulate a linear load. At full load capacity i.e. 200kVA, and power factor of 0.8, the following calculations are made for the required parameters.

Given that Apparent Power is 200kVA, the Active power of the load can be calculated as follows:

$$Active\ Power\ (P) = Apparent\ Power\ (S)\ \times\ Power\ Factor \tag{13}$$

$$Reactive\ Power\ (Q) = Apparent\ Power\ (S)\ \times\ \sin\varphi \tag{14}$$

By selecting a value for Capacitive reactive power Q_C, the Inductive reactive power Q_L can be found by the following formula:

$$Reactive\ Power\ (Q)\ =\ Q_L - Q_C \tag{15}$$

$$\therefore\ Q_L = Q + Q_C \tag{16}$$

Fig-6a and b show the linear load block and the parameter dialog box of the block.

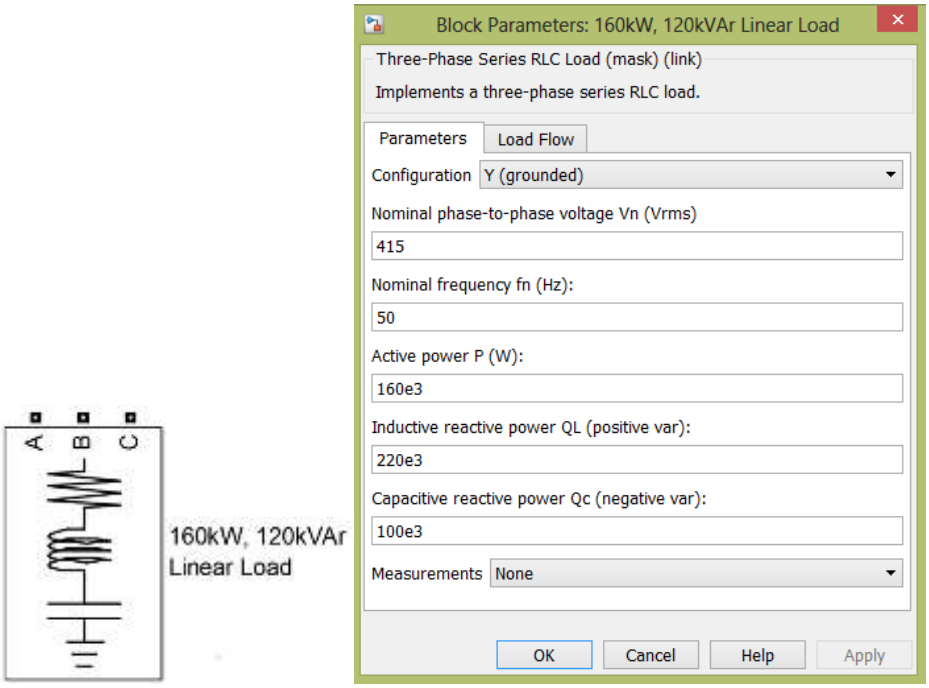

Fig-6 (a): Linear Load Model Block (b) Parameter Dialog Box for Linear Load Block

Non-Linear Load

The non-linear load model used is a basic non-linear model, which consists of a three-phase diode bridge rectifier block and a Resistor representing the load. The maximum permissible current and kVA rating of the transformer is used to calculate the value of resistor used as the Load. Therefore, at full load the parameters are calculated as follows:

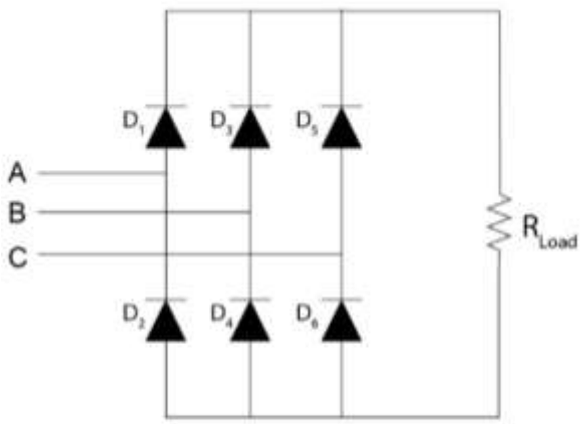

Fig-7: Circuit Diagram of Non-linear Load

Given that at full load the maximum permissible current and kVA rating of the transformer as given in table 3.1 is 266.7(A), the following calculations are valid:

$$S = \sqrt{6} \times V_{rms} \times I_{Dmax}$$
$$\therefore \; I_{Dmax} = \frac{S}{\sqrt{6} \times V_{rms}} \qquad (17)$$

$$R_{Load} = \frac{\sqrt{6} \times V_{rms}}{I_{Dmax}} \qquad (18)$$

$$V_{dc} = \frac{3\sqrt{6} \times V_{rms}}{\pi} \qquad (19)$$

$$P_{Load} = V_{dc} \times I_{Dmax} \qquad (20)$$

Since the load is non-linear, harmonic components will be present on the current waveform. Assuming a total harmonic distortion (THD_i) of 26% with 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th} and 19^{th} harmonics as the main harmonic components the current consumed by the load is calculated as;

$$I_f = \frac{I_{Dmax}}{\sqrt{2}} \tag{21}$$

$$I_{Total\ Harmonic} = \sqrt{\sum_{n=2}^{n} I_n^2} = \frac{THD_i\% \times I_f}{100} \tag{22}$$

Given the total harmonic current, the RMS value of the load current under harmonic conditions is calculated using equation 2.8;

$$I_{rms} = \sqrt{\sum_{n=1}^{n} I_n^2} = \sqrt{I_f^2 + \sum_{n=2}^{n} I_n^2} \tag{23}$$

$$\therefore I_{Peak} = I_{rms} \times \sqrt{2} = 248.56 \times \sqrt{2} \approx 351.51(A) \tag{24}$$

The displacement power factor of the non-linear load is calculated thus;

$$Power\ Factor_{Disp} = \frac{P}{S} \tag{25}$$

$$Power\ Factor_{Dist} = \frac{1}{\sqrt{1 + THD_i^2}} \tag{26}$$

$$Power\ Factor_{True} = P.F_{Disp} \times P.F_{Dist} \tag{27}$$

The above calculations are used to generate the parameters for the non-linear load at half load capacity with the same THD_i value. Fig-7 shows the model of non-linear load as done in Simulink.

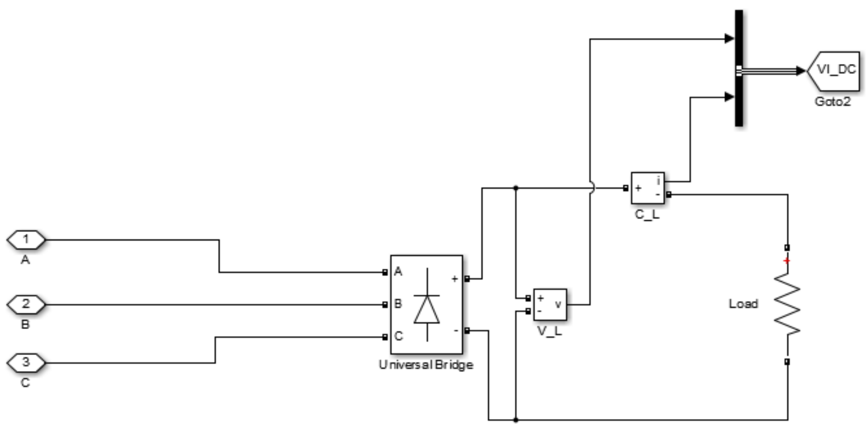

Fig-7: Model of Non-linear Load

COMPENSATION SYSTEM

This system comprises of the capacitor bank, passive filter and the active filter. These blocks are modelled as follows.

Capacitor Bank

Capacitor bank is used for power factor correction and power quality improvement. At full load (as calculated in section 3.0.3a) and power factor of 0.8, the required capacitor bank – connected in parallel to the load and in wye (star) configuration – to raise the power factor to 0.95 is calculated as follows;

Given that Active power, P = 160(kW), Reactive power, Q = 120(kVA_r), P. f, cos φ_1 = 0.8 and improved P. f, cos φ_2 = 0.95 the following applies;

$$kVA_r\ (Required) = kVA_{r1} - kVA_{r2} \tag{28}$$

$$kVA_r = P \tan\varphi \tag{29}$$

$$\therefore\ kVA_r\ (Required) = P(\tan\varphi_1 - \tan\varphi_2) \tag{30}$$

Using the following formula, the required capacitor value, C is calculated in micro-Farad (µF), based on the kVA_r value;

$$C = \frac{kVA_r\ (Required) \times 10^9}{2\pi f V_L^2} \tag{31}$$

A capacitor of the size calculated above is enormous in size. In other to reduce the size, an equivalent parallel connected capacitor bank is utilized. Taking new capacitor value to be 220(µF), the number of capacitors to be used is calculated as follows;

For Parallel connected capacitors, the equivalent capacitor value is;

$$C_{equiv} = \sum_{n=1}^{n} C_n \tag{32}$$

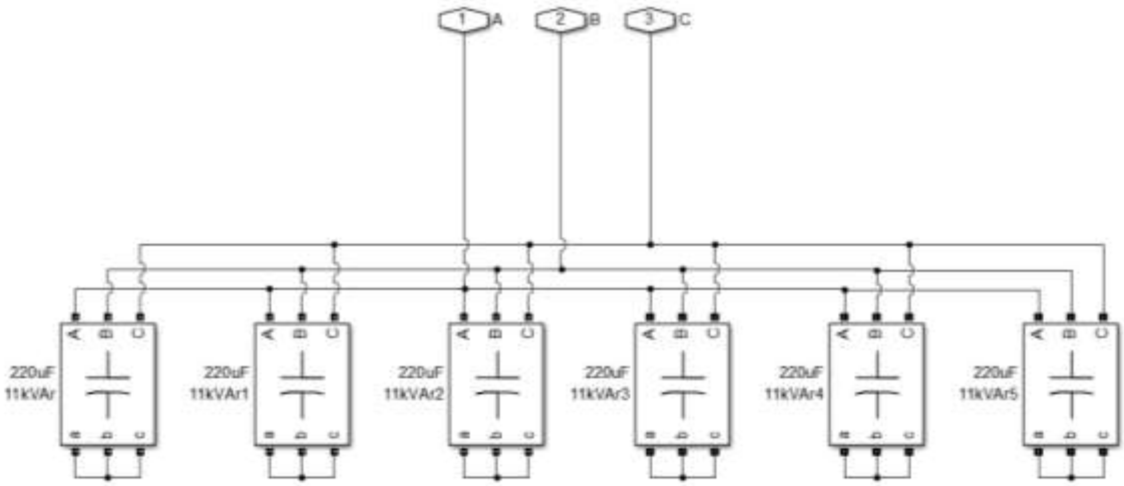

Fig-8: Simulink model of Capacitor Bank for full load capacity

The Simulink model is designed using the three phase series RLC branch block, from the SimPowerSystems library. This block can be configured to have a combination of all three components i.e. resistor, inductor and capacitor, only a combination of two or any single component. Since only the capacitor is required to develop a capacitor bank, the capacitor single element option is selected and the capacitor value is inputted. Fig-8 shows the Simulink model.

Passive Filter

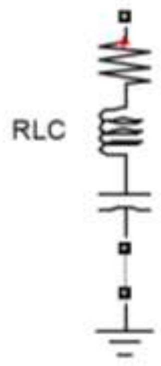

Fig-9: Single Tuned (low pass) Filter Configuration

There are a number of passive filter configurations, but the most commonly used is the single tuned (Low pass filter) configuration, which is used to filter specific harmonic components. The passive filter developed in this study eliminates the 5th, 7th, 11th, 13th, 17th and 19th harmonic components on the current wave form when a non-linear load is connected to the transformer and to raise the power factor from 0.95 to 1. The harmonics are filtered using a single tuned (low pass) filter. This filter comprises of a resistor, capacitor and inductor connected in series i.e. an R-L-C Series Filter (Fig. 9).

The single tuned passive filter depends on the reactance of the capacitor and inductor, X_C and X_L respectively, the harmonic frequency, f_n (where n is the harmonic order) and the quality factor, Q which is used to determine the resistors value. The value of quality factor for single tuned filter is of the range 50<Q<150. The following equations are used to generate the capacitor C, inductor L and resistor R values

The required reactive power is calculated using equation 3.23. This value is then used to calculate the required capacitor value as follows;

$$Capacitor\ Value, C = \frac{Required\ kVA_r}{2\pi f_1 V_{L-L}^2} \tag{33}$$

To calculate the capacitor value for individual branches of the filter, the relative percentage of each harmonic order is used;

$$C_n = \frac{Relative\ \%\ of\ harmonic\ order, h_{\%}}{100} \times C \tag{34}$$

$$L_n = \frac{1}{(2\pi f_n)^2 \times C_n} \tag{35}$$

$$R_n = \frac{\sqrt{\frac{L_n}{C_n}}}{Q_n} \tag{36}$$

Where,

Q_n is the quality factor for the branch and f_n is the frequency of the harmonic order n.

Fig-10 shows the Matlab model of the Passive Power Filter, comprising of six single tuned filters.

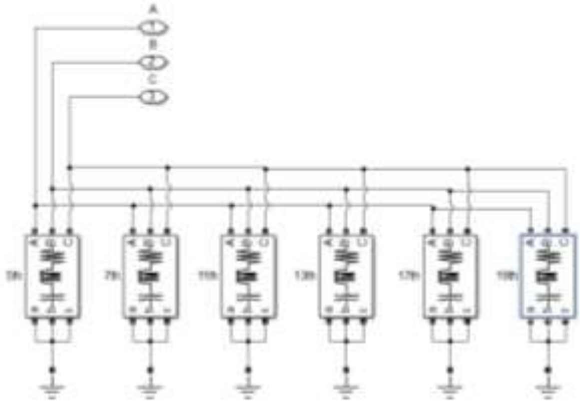

Fig-10: Internal Structure of 3-Phase Passive Filter.

In order to easily calculate the values of the capacitors, inductors and resistors used to design the passive filters a matlab program is written based on the above stated equations (see Appendix A for code). The generated values from the above program is stated in table 3.2

Table-3: Calculated Values for Filter Parameters

Harmonic Order	Resistor (Ω)	Inductor (H)	Capacitor (μF)
5	0.0329	0.0021	193.37
7	0.0392	0.0018	116.02
11	0.1559	0.0027	30.939
13	0.2638	0.0039	15.469
17	0.3228	0.0018	19.337
19	0.4813	0.0024	11.602

Putting together all the parts of the system model, the model is then simulated for different conditions as previously stated. A one-off simulation of the system is done using a signal builder to generate signals to control the switching on and off the circuit breakers attached to the different parts of the system at different times. This is done to enable the observer effectively compare the effects of the compensation methods applied to the system. Fig-11 shows the complete system model.

SIMULATION AND RESULTS

The simulation is done with the transformer under full load and half load conditions. The efficiency, Current Total Harmonic Distortion, Total Losses, Secondary Winding current, eddy current loss, other stray losses and the kVA saving capacity of the transformer under the different compensation methods at full load and half load capacity are calculated and the results are tabulated and compared using Microsoft Excel 2016. In Simulink, the THD_i is calculated using the powerGUI's Fast Fourier Transformation (FFT) Analysis tool. This tool uses Fourier transform to analyse the amount of harmonics in a signal.

At full load capacity the following simulation results were obtained. Fig-4.1 shows the FFT analysis chart of the current signal for linear load. It can be clearly seen that for a linear load the percentage magnitude of the current at fundamental frequency is 100%, while for other frequency levels, representing the harmonics, it is zero.

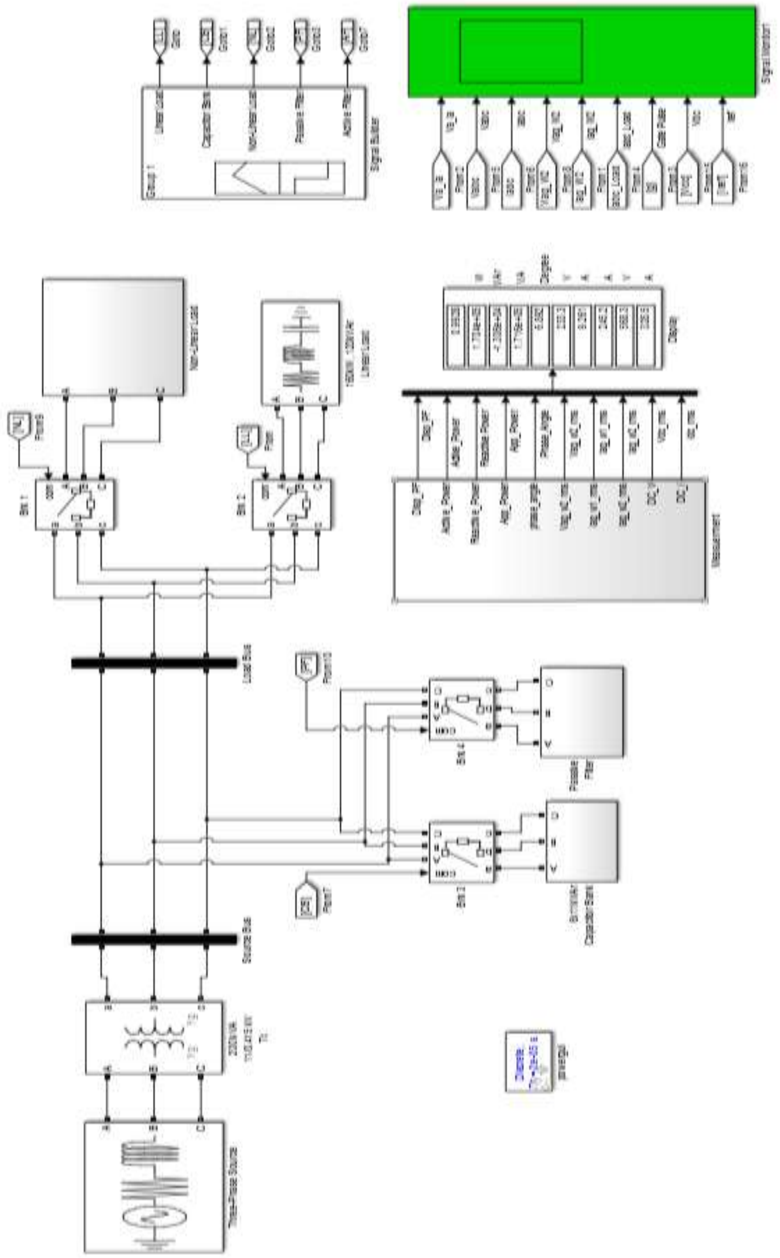

Fig-11: Simulink Model Of The Entire System

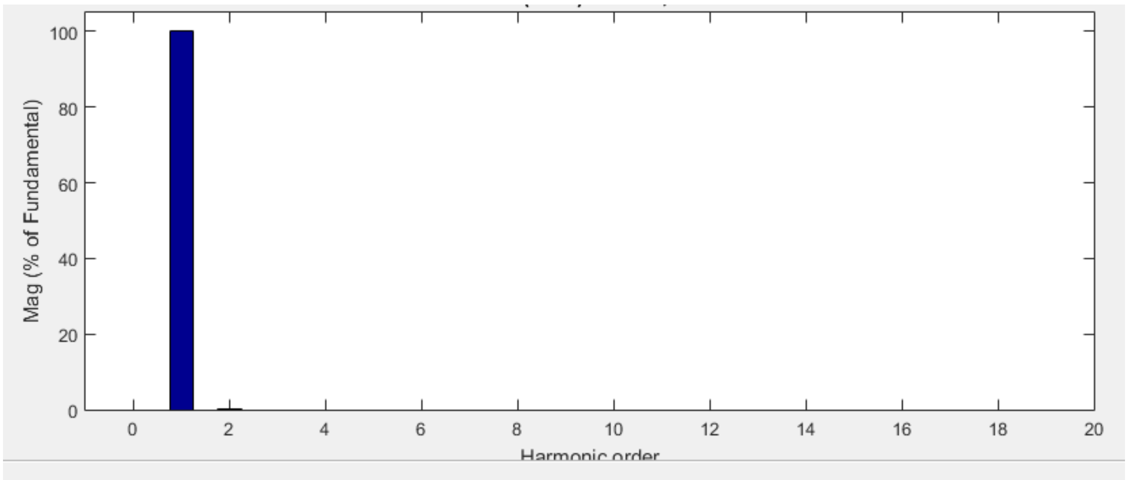

Fig-11: FFT Analysis for Linear Load

Fig-12 shows the voltage and current waveforms (yellow line is the voltage while the blue line is the current). From the figure it can be seen that the voltage and current wave form cross the zero line at different times, meaning they are not in phase. When a capacitor bank is attached to the system, from fig 13 it is observed that the amplitude of the current waveform is reduced and the phase angle is also reduced. The reduction shows an improvement in the power factor and the reduction of current losses in the system.

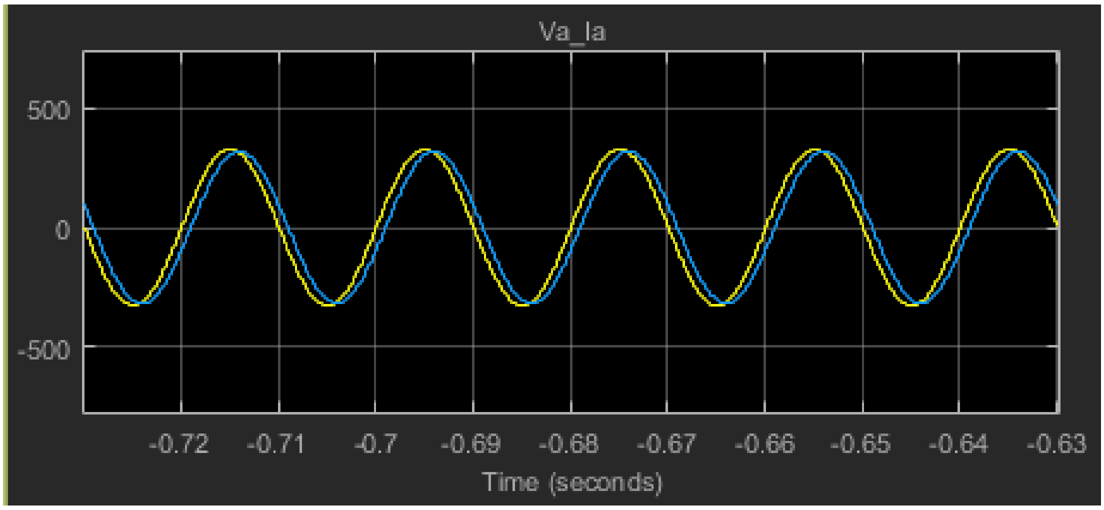

Fig-12: Waveform for Linear Load without Capacitor Bank

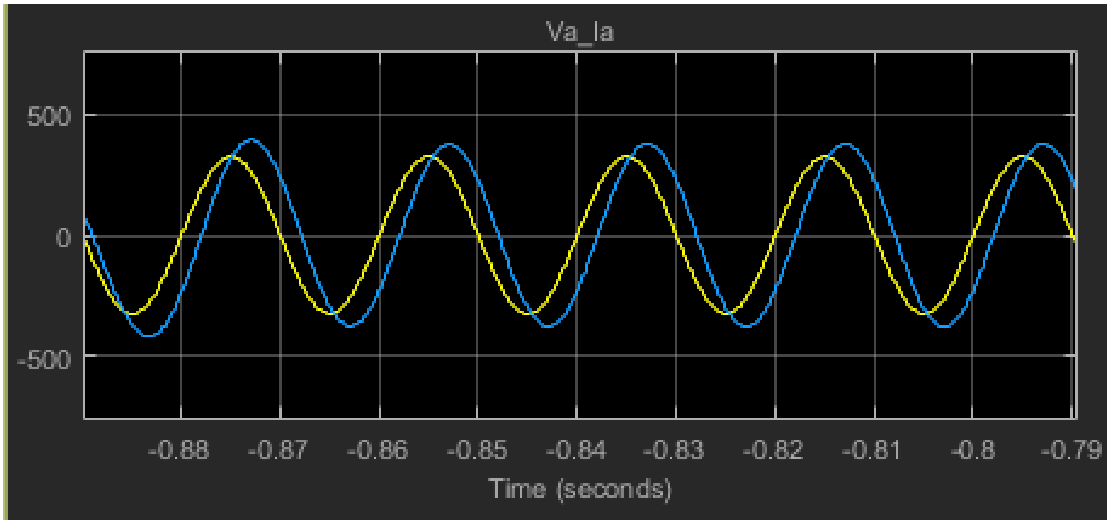

Fig-13: Waveform for Linear Load with Capacitor Bank

Under non-linear load, it can be seen in fig-14 that harmonic components are present in the waveform and in fig-14, the current signal is not sinusoidal. From the calculations done in excel using the data collected from the FFT analysis platform in Simulink, it can be seen that the total rms current seen by the transformer is high. Table-4 presents the harmonic currents measured as percentage of the fundamental current and table-5 shows the calculated values based on the harmonic components.

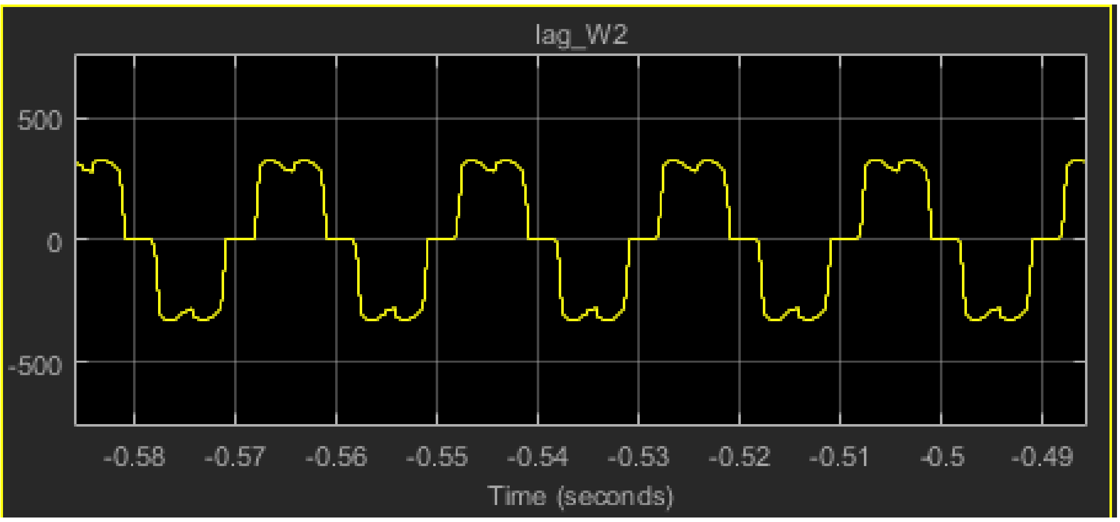

Fig-14: Current Waveform for Non-linear Load

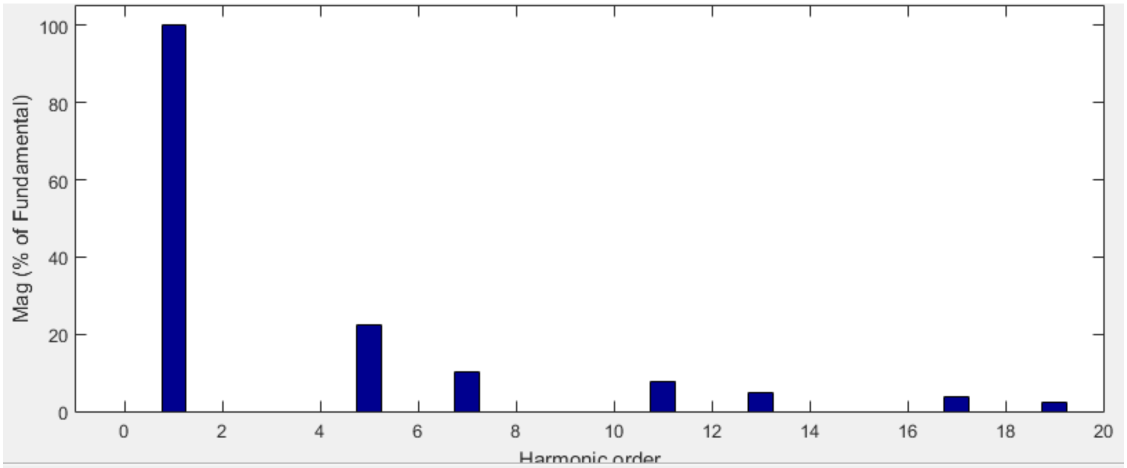

Fig-15: FFT Analysis for Non-linear Load

Table-4: Harmonic Currents of the Harmonic Orders Present in the Current Signal of Non-linear Load

h	% of I_f	I_h	h^2	$h^{0.8}$	I_h^2	$(I_h/I_R)^2$	$(I_h/I_R)^2$ * h^2	$(I_h/I_R)^2$*0.8^2
0	0	0	0	0	0	0	0	0
1	100	241.6	1	1	58370.56	1	1	1
2	0	0	4	1.7411011	0	0	0	0
3	0	0	9	2.408224	0	0	0	0
4	0	0	16	3.0314331	0	0	0	0
5	22.3	54.094	25	3.6238983	2926.1868	0.050131	1.253280	0.181670408
6	0	0	36	4.1929627	0	0	0	0
7	10.2	24.691	49	4.7432763	609.67115	0.010444	0.511797	0.049542763
8	0	0	64	5.2780316	0	0	0	0
9	0	0	81	5.7995461	0	0	0	0
10	0	0	100	6.3095734	0	0	0	0
11	7.83	18.917	121	6.8094831	357.86348	0.006130	0.741837	0.041748192
12	0	0	144	7.3003721	0	0	0	0
13	4.71	11.379	169	7.7831371	129.4898	0.002218	0.374911	0.017266189
14	0	0	196	8.2585238	0	0	0	0
15	0	0	225	8.7271613	0	0	0	0
16	0	0	256	9.189586	0	0	0	0
17	2.37	5.7259	289	9.6462638	32.786159	0.000561	0.162328	0.00541821
18	0	0	324	10.097596	0	0	0	0
19	2.37	5.7259	361	10.54393	32.786159	0.000561	0.202770	0.005922425
					4088.7835	**1.070048**	**4.246924**	**1.301568187**

Table-5: Calculated Values Based on the Harmonic Order Values in Table 4

Harmonic Current	63.943597
Fundamental Current	241.6
Total Current	249.92
THD	0.26467
kW	166.9
kVAr	19.42
kVA	173.9
Displacement P.F	0.9597
Distortion P.F	0.9667
Power Factor	0.9278
Rated Cu Loss (kW)	3.00
Rated Core Loss (kW)	0.50
Rated Total Stray Losses (kW)	0.2149
Rated Eddy Current Loss (kW)	0.070917
Rated Other Stray Loss (kW)	0.143983
Copper Losses	3.210146
Eddy Losses	0.301179172
Other stray	0.187403692
Total Loss (kW)	4.20
Efficiency (%)	97.55

When a capacitor bank is applied to the system, in view of curbing the effects of the non-linear load on the transformer, it is observed that the it worsens the condition of the transformer. It is observed that the THD_i is increased to 39.43% and the total current seen by the transformer is raised by 6.81% above the rated current. Thereby increasing the losses in the transformer and reducing the efficiency of the transformer. Table-6 shows the calculated current and THD_i based on the data collected from Simulink's FFT analysis tool. Fig 16 shows the analysis done using the FFT analysis tool in Simulink.

Table-6: Calculated Current and THD_i Under the influence of Non-linear Load and Capacitor Bank

Harmonic Current	104.53
Fundamental Current	265.1
Total Current	284.97
THD (%)	0.39432

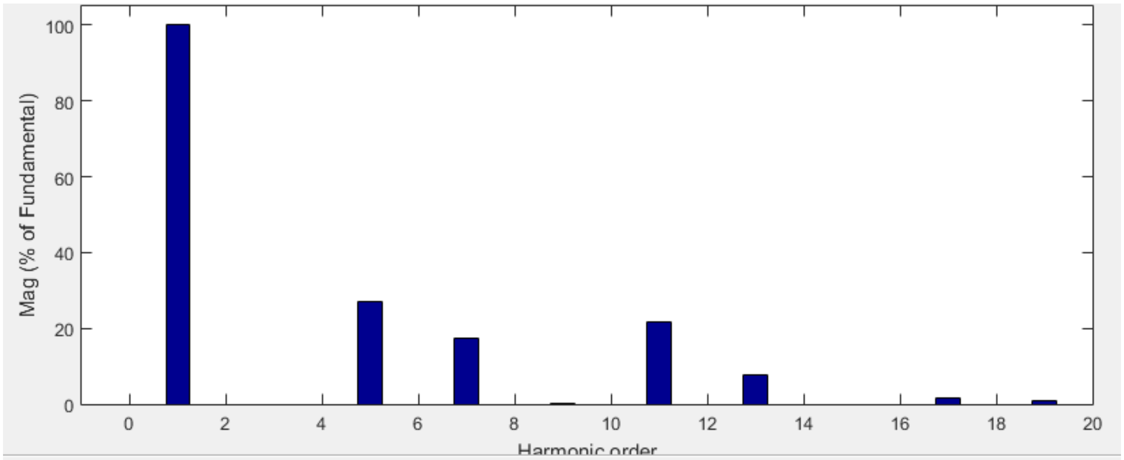

Fig-16: FFT Analysis of Non-linear Load with Capacitor Bank

Fig-17: Current Waveform for Non-linear Load with Capacitor Bank

When the Passive filter is connected to the system, the power factor is raised to 0.989, THD_i is dropped to 8.46%, total current reduced by 8.14% below the rated current and the efficiency is raised to 97.82%.

Table-7 compares the effects of the different conditions at full load capacity on the total current, THD_I, Power factor, total losses and efficiency of the transformer as calculate using the data generated by the FFT analysis tool in Simulink.

Table-7: Simulation Results for Transformer at Full Load Condition

	Linear Load without Improvement	Linear Load with Capacitor Bank	Non-linear Load without improvement	Non-linear Load with Capacitor Bank	Non-linear Load with Passive Filter
Secondary Winding Current (A)	266.80	225.20	249.92	284.97	245.07
Total Harmonic Distortion (%)	0.01	0.03	26.47	39.43	8.46
Power Factor	0.80	0.957	0.928	0.809	0.989
Total Losses (kW)	3.71	3.715	4.199	5.003	3.795
Efficiency (%)	97.52	97.583	97.546	97.171	97.820

The graphical representation that compares the effects of the five conditions at full load as stated in the table above is shown below.

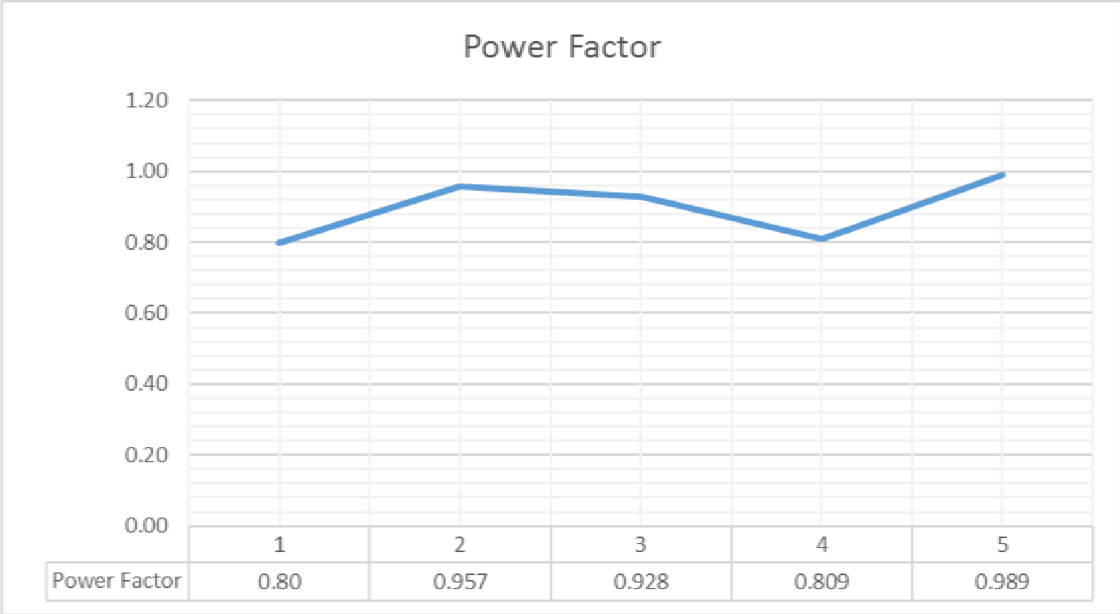

Fig-18: Power Factor

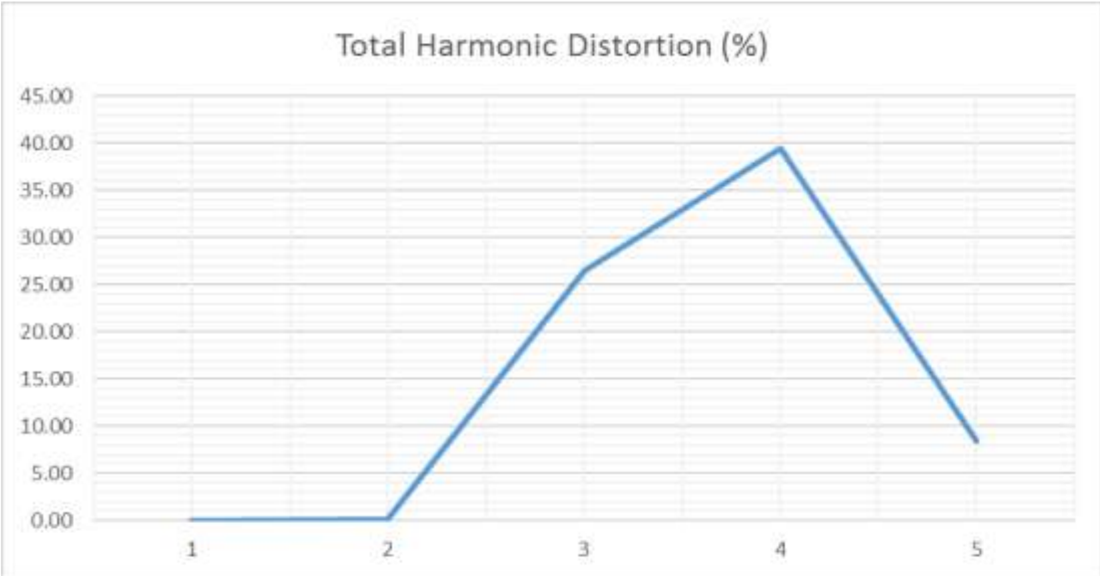

Fig-19: Total Harmonic Distortion (%)

Fig-20: Efficiency (%)

Fig-21: Total Losses (kW)

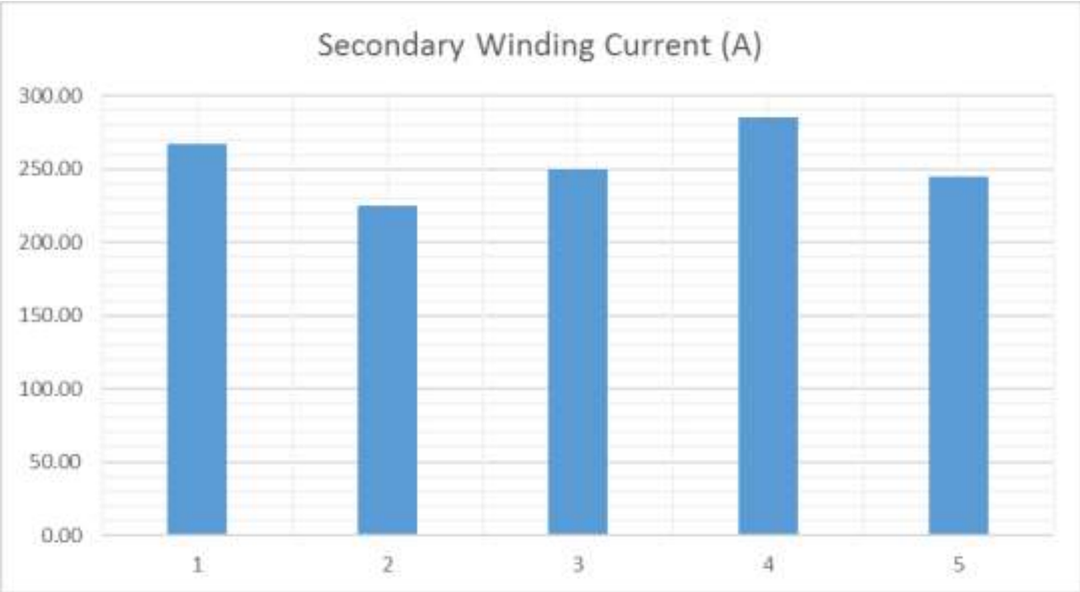

Fig-22: Secondary Winding Current (A)

CONCLUSION AND RECOMMENDATION

CONCLUSION

The major problem affecting the performance of distribution transformer is the effect of harmonics on them due to non-linear loads. Linear loads can also have low power factor and can also affect the distribution transformer performance.

From the simulation and results, the power factor of linear loads can be improved by the use of capacitor banks though with a little reduction in current. Applying same capacitor banks to non-linear loads increase the harmonics in the system thereby increasing the current seen by the transformer and causes increase in load-losses.

Therefore, harmonics due to non-linear loads can be reduced by the use of passive filters. The passive filter gradually takes care of the harmonics in the system, though not perfectly. It is the more efficient of the two methods when dealing with harmonics in the power system.

RECOMMENDATION

Although the passive filter is more effective in terms of reducing current harmonics and increasing the power factor of the system and it observed that the passive filter more effective than the capacitor banks but its response time its poor as compared to active filters, therefore we recommend that this filters be built in the distribution transformers. For more effective reduction of harmonic distortion in distribution transformer we recommend active filter to be used.

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APPENDIX A: Matlab Program to Calculate Passive Filter Parameters

```
prompt1 = 'Initial Power factor = '; %Request initial power factor
prompt2 = 'Improved Power factor = '; %Request improved power factor
prompt3 = 'Load Active Power = '; %Request Load Active power
prompt4 = 'Line-to-Line Voltage = '; %Request line-to-line voltage
prompt6 = 'Fundamental Frequency = '; %Request fundamental frequency
prompt7 = 'Number of LPF = '; %Request number of low pass filter
p.f1 = input(prompt1);
p.f2 = input(prompt2);
P_Load = input(prompt3);
VL = input(prompt4);
f1 = input(prompt6);
LPF = input(prompt7);
%HPF = input(prompt8);
Qf = P_Load*(tan(acos(p.f1))-tan(acos(p.f2))) %Calculate reactive power
Cf = Qf/(2*pi*f1*VL.^2) %Calculate filter capacitor value
j=1;
if j<LPF||j>0
  for j=1:1:LPF
    prompt9 = 'Harmonic Order = '; %Request for harmonic order
    prompt5 = 'Relative % of harmonic order = ';
    prompt10 = 'Quality Factor ='; %Request for quality factor
    h = input(prompt5);
    n = input(prompt9);
    Q = input(prompt10);
    Cn = ((h/100)*Cf)/3  %calculate branch capacitor value
    fn = n*f1;  %Calculate value of harmonic frequency
    Ln = 1/((2*pi*fn).^2*Cn)  %Calculate branch inductor value
    Rn = sqrt(Ln/Cn)/Q %Calculate branch resistor value
  end
end
```