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Modeling and Analysis of Transformer

Divyapradeepa .T
Department of Electrical and Electronics,
Rajalakshmi Engineering College, Chennai
divyapradeepa@gmail.com

Abstract: The transformers are an integral part of the power system. In transformers, the main consequence of harmonic currents is an increase in losses, mainly in windings, because of the deformation of the leakage fields. Higher losses mean that more heat is generated in the transformer so that the operating temperature increases, leading to deterioration of the insulation and a potential reduction in lifetime. Due to the non-linear loads, the transformers are much affected by the distorted currents and supply voltages which largely reduce its efficiency due to overheating. Nonlinear loads cause harmonics to flow in the power lines which can overload wiring and many desktops, personal computers present nonlinear loads to the AC supply because of their power supplies design (capacitor input power supply). In power transformers, the main consequence of harmonic currents is an increase in losses, mainly in windings, because of the deformation of the leakage fields. Higher losses mean that more heat is generated in the transformer so that the operating temperature increases, leading to deterioration of the insulation and a potential reduction in lifetime. As a result, it is necessary to reduce the maximum power load on the transformer, a practice referred to as de-rating, or to take extra care in the design of the transformer to reduce these losses. To estimate the de-rating of the transformer, the load's K Factor may be used. Thus analysing this problem and reducing the losses of the transformer has become a major area of research in today's scenario. This report includes the effects of non-sinusoidal supply voltage on the transformer excitation current and the core losses which includes eddy current and hysteresis losses.

Keywords: Saturation, Current, Voltage, Linear Load, Non-Linear Load.

INTRODUCTION

Events over the last several years have focused attention on certain types of loads on the electrical system that results in power quality problems for the user and utility alike. Equipment which has become common place in most facilities including computer power supplies, solid state lighting ballasts, adjustable speed drives (ASDs), and uninterruptible power supplies (UPSs) are examples of non-linear loads. It is forecast that before the end of the century, half of all electrical devices will operate with a nonlinear current draw. These nonlinear loads are the cause of current harmonics. Non-linear loads are loads in which the current waveform does not have a linear relationship with the voltage waveform. Non-linear loads generate voltage and current harmonics which can have adverse effects on equipment that are used to deliver electrical energy such as transformers, feeders, circuit breakers, which are subjected to higher heating losses due to harmonic currents consumed by non-linear loads. The discontinuous, Harmonic currents cause overheating of electrical distribution system wiring, transformer overheating and shortened transformer service life. Electrical fires resulting from distribution system wiring and transformer overheating were rare occurrences until harmonic currents became a problem. Transformers which provide power into an industrial environment are subject to higher heating losses due to harmonic generating sources (non-linear loads) to which they are connected. The major source of harmonic currents is the switch mode power supply found in most desktop computers, terminals, data processors and other office equipment is a good example of a non-linear load. The switching action of the computer power supply results in distortion of the current waveform [2]. Harmonics are produced by the diode-capacitor input section of power supplies. The diode-capacitor section rectifies the AC input power into the DC voltage used by the internal circuits. The personal computer uses DC voltage internally to power the various circuits and boards that make up the computer. The circuit of the power supply only draws current from the AC line during the peaks of the voltage waveform, thereby charging a capacitor to the Peak of the line voltage. The DC equipment requirements are fed from this capacitor and, as a result, the current waveform becomes distorted. The increasing usage of non-linear loads on electrical power systems is causing greater concern for the possible loss of transformer life. So, Manufacturers of distribution transformers have developed a rating system called K Factor, a design which is capable of withstanding the effects of harmonic load currents. The amount of harmonics produced by a given load is represented by the term "K" factor. The larger the "K" factor, the more harmonics are present [3].

From previous studies on losses, 10% of the losses occur in the 10kV high voltage cable, 60% occur in 10/0.4 kV distribution transformer and 30% in 400V low voltage cable [3].

Transformer

In power transformers, the main consequence of harmonic currents is an increase in losses, mainly in windings, because of the deformation of the leakage fields. Higher losses mean that more heat is generated in the transformer so that the operating temperature increases, leading to deterioration of the insulation and a potential reduction in lifetime. As a result, it is necessary to reduce the maximum power load on the transformer, a practice referred to as de-rating, or to take extra care in the design of the transformer to reduce these losses.

To estimate the de-rating of the transformer, the load's K-factor may be used. This factor is calculated according to the harmonic spectrum of the load current and is an indication of the additional eddy current load losses. It reflects the excess losses experienced in a traditional wire wound transformer.

Modern transformers use alternative winding designs such as foil windings or mixed wire/foil windings. For these transformers, the standardized K-factor – derived for the load current - does not reflect the additional load losses and the actual increase in losses proves to be very dependent on the construction method. It is, therefore, necessary to minimize the additional losses at the design stage of the transformer for the given load data using field simulation methods or measuring techniques [5].

Direct switching of the transformer to a network gives rise to a transition phenomenon with the associated current surge. The flux starting from remnant flux changes so as to make its derivative vary in accordance with imposed network voltage which results in drawing heavy exciting current. This large transient current called magnetic inrush current also causes flux saturation.

Transformers De-rating and Power system Harmonics Analysis: A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors. A varying current in the primary winding creates a varying magnetic flux in the core of the transformer and thus a varying magnetic field created through the secondary winding. This varying magnetic field induces a varying electromagnetic force (EMF) or voltage in the secondary winding. This effect is called inductive coupling.

If the secondary winding is connected to a load, then the EMF induced in the secondary winding causes a current to flow through it which creates an MMF which opposes its cause. This reduces the magnetic flux of the core, thus the supply provides extra current to neutralize the opposing MMF. Thus the net MMF in the magnetic core is the difference of the MMF of the primary current and that produced by the attachment of load. This MMF corresponds to the no load current magnitude and is constant in the core while in operation.

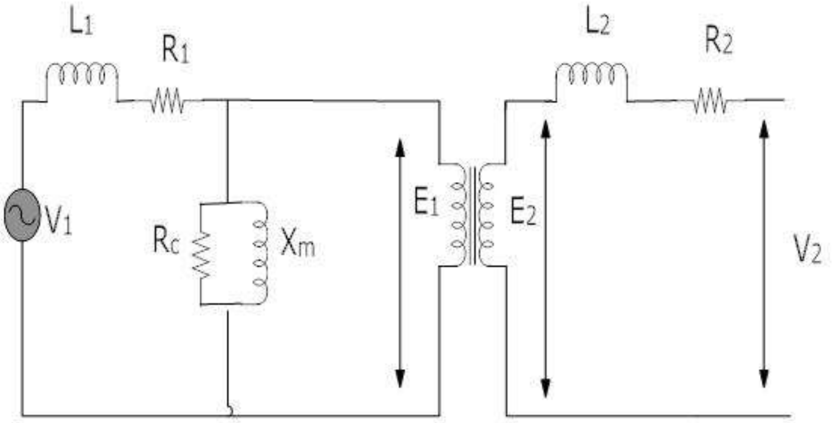

Fig 1: Equivalent Transformer

The equivalent circuit drawn above is called the exact equivalent circuit of the transformer. The resistances of the windings are given by R_1 and R_2 of primary and secondary respectively. The leakage inductances are given by L_1 and L_2 of primary and secondary respectively. The core loss component is given by R_c. This is a virtual resistance which represents the iron losses of the transformer and X_m represents the magnetizing branch. It decides the amount of current required to magnetize the core. The current flowing through it is I_m and the current flowing through the core loss component is I_c. These two components are orthogonal to each other. The combination of these two currents provides the no load component. The supply of the transformer provides the no load component as well as the load current when it is connected to any load.

The equivalent circuit model above is a bit complicated while solving for various quantities unknown in the transformer. The secondary side has to be solved and then its value is reflected the primary side and hence the unknown parameters are solved. Thus it would be easier if, in the model, the secondary side parameters are reflected the primary side by the transformation ratio. Thus the secondary side just behaves as if an ideal transformer with no resistance and leakage reactance. The secondary side resistance is reflected the primary side by multiplying the secondary side resistance with the square of the turn's ratio. Similarly, the leakage reactance is reflected the primary side by the same technique.

The resulting model is sometimes termed the exact equivalent circuit, though it retains a number of approximations. The analysis is again simplified by moving the magnetizing branch to the left of the primary impedance, an implicit assumption that the magnetizing current is low, and then summing primary and referred secondary impedances, resulting in so-called equivalent impedance. This assumption is based on the fact that the no load current is 2 to 5 per cent of the full load current. The shunt branch is moved across the primary impedance and kept in parallel with the voltage supply. Thus the final exact equivalent circuit model is given below:

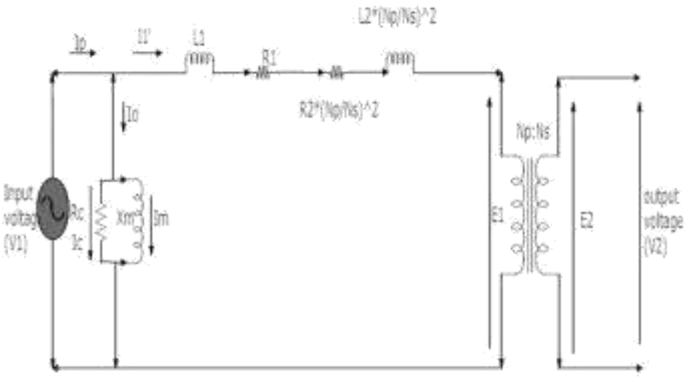

Fig.2: Exact Equivalent Circuit

Saturation of Transformer

Saturation of transformer may occur due to many reasons, some of which are listed as below [9]:

a) Normal excitation: Even under normal excitation condition, transformer core may have entered, slightly, the saturation region and begin to generate some harmonics in the excitation current. The degree of the saturation depends on the transformer design.

b) Over excitation: Over excitation is basically caused by over voltages. This problem is particularly subjected in the case of transformers connected to large rectifier plant following load rejection. Over voltage shifts the peak operation point of the transformer excitation characteristics up to saturation region so that different harmonics are generated. The magnetizing current of over excitation is often symmetrical.

c) Converter load: Converter loads may draw DC and low frequency currents from supplying transformers. The transformer cores are biased by these load currents and driven to saturation by these harmonics components. Ex, a cyclo convertor connected to a single phase load will draw dc currents from the transformer as well as harmonic components which are integral multiples of two times the supply frequency.

d) Geomagnetically induced currents: Geomagnetically Induced Currents (GIC) flow on the earth surface due to Geomagnetic Disturbance (GMD). They are typically 0.001 to 0.1 Hz and could reach peak values as high as 200A. They enter transformer windings by way of grounded wye connections and bias the transformer cores to cause half cycle saturation.

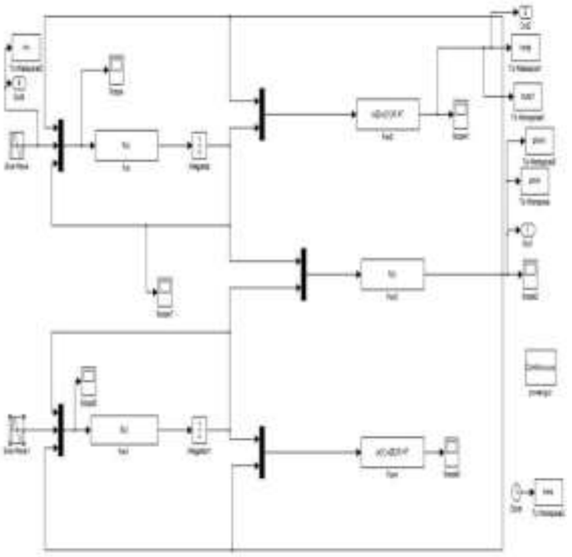

Fig.3: Simulink model of transformer

The transformer is designed to deliver the required power to the connected loads with minimum losses at the fundamental frequency. Any periodic, distorted waveforms can be expressed as a sum of sinusoids. When a transformer is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a harmonic of the fundamental. Usually, the higher order harmonics are negligible for power system analysis. While they may cause interference with low-power electronic devices, they are usually not damaging to the power system [1].

If the power system is depicted as series and shunt elements, the vast majority of the nonlinearities in the system are found in shunt elements i.e. loads. The series impedance of the power delivery system (i.e. the short circuit impedance between the source and the load) is remarkably linear. In transformers, also, the source of harmonics is the shunt branch (magnetizing impedance) of the common “T” model, the leakage impedance is linear. Thus the main sources of harmonic distortion will ultimately be end-user loads.

In addition to the operation of transformers on the sinusoidal supplies, the harmonic behavior becomes important as the size and rating of the transformer increases [9].

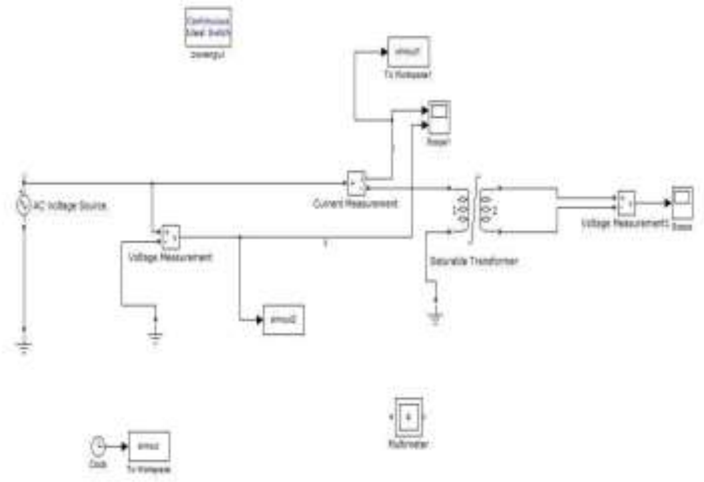

Fig.:4 Representation of Simulink Model of Transformer Under sinusoidal Excitation

Effect of Saturation with Non-Sinusoidal Supply Voltage

To analyses the excitation current the equivalent circuit of an unloaded single phase transformer was used. A non-sinusoidal supply voltage was given to the single phase saturable transformer. The non-sinusoidal supply voltage is created by summing up different voltage sources with different magnitude and frequency of each voltage source is an integral multiple of the fundamental

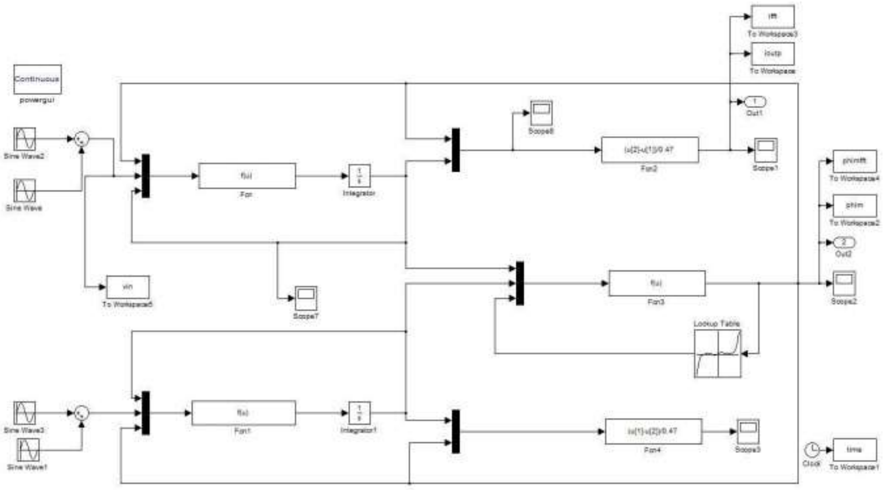

Fig.5: Simulink Model Representing Transformer with Core Saturation

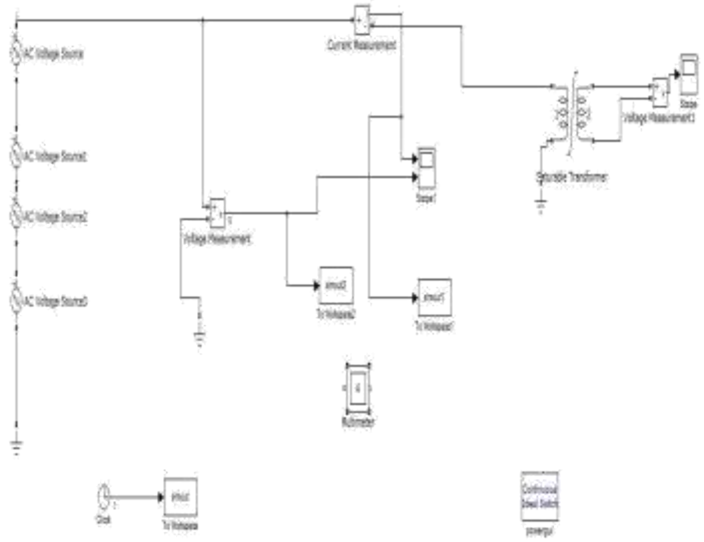

Fig.6: Representation of Simulink Model Transformer under Non Sinusoidal Excitation

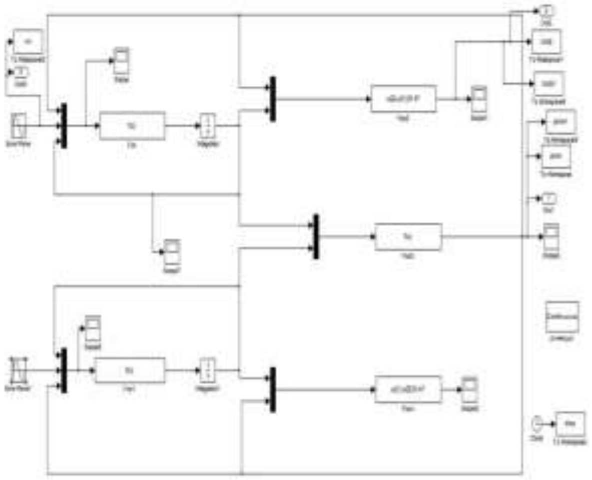

Fig.7: Representation of Simulink Model Transformer without Core Saturation

The transformer used in the experiment is a single phase 3 KVA, 230 V/230 V Transformer.

The open circuit test was per formed on the transformer to find the open circuit magnetization curve of the transformer. The secondary of the transformer was left open circuited. The primary side is connected to a voltage source, an ammeter in series with the voltage source and a wattmeter to measure the no load power loss. A low PF wattmeter of 0.2 is used as the no load current has very low PF because it is mainly the magnetizing component which is quadratic in nature. The voltages are gradually increased from zero to more than rated value. The open circuit results are as follows:

The effects of the harmonic currents are:

1. Additional copper losses due to harmonic currents
2. Increased core losses
3. Increased electromagnetic interference with communication circuits.

On the other hand the harmonic voltages of the transformer cause:

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Table 1: Open Circuit Test Results

SI.NO	INPUT VOLTAGE V1(V)	OUTPUT VOLTAGE V2(V)	CURRENT(mA)	LOSSES(w)
1	0	0	0	0
2	50	59	48.8	1.5
3	70	75	69	2
4	110	106	106	3.8
5	180	170	169	9.6
6	220	237	219	13.8
7	260	362	259	18
8	280	489	389	28

The short circuit test was done on the primary side of the transformer. The secondary was short circuited and the reduced voltage was applied to the primary side to flow rated current in the primary winding.

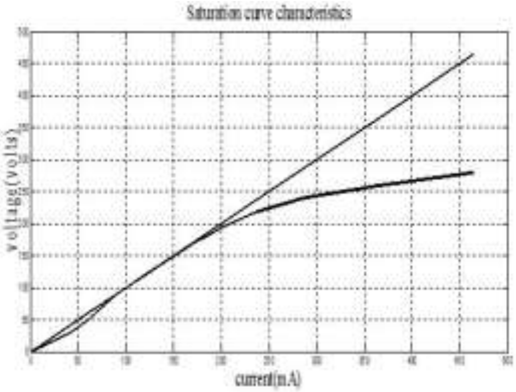

Fig.8: Open Circuit Characteristics

Experimental Results of Open Circuit Test

The variation in excitation current was observed for different values of supply voltage:

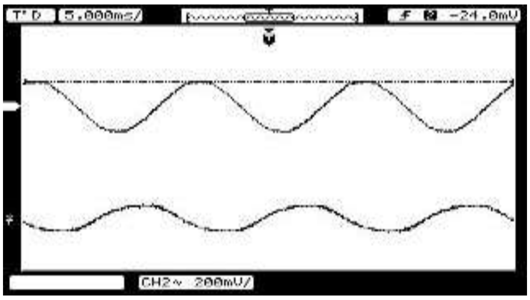

Fig.9: Excitation Current Waveform for Input Sinusoidal Voltage 40v.

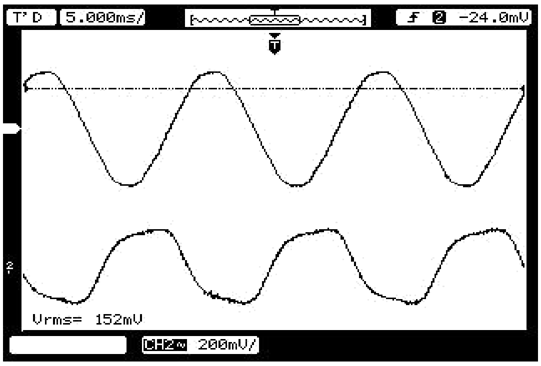

Fig.10: Excitation Current Waveform for Sinusoidal Input Voltage 70v.

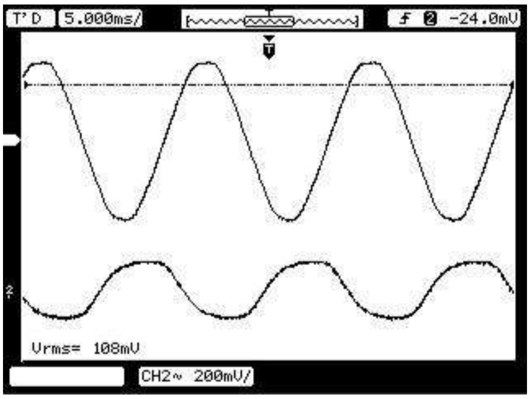

Fig 11: Excitation Current Waveform for Sinusoidal 140v

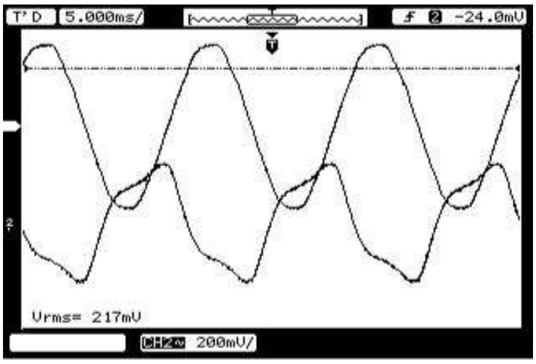

Fig.12: Excitation Current Waveform for Sinusoidal Input Voltage 160v

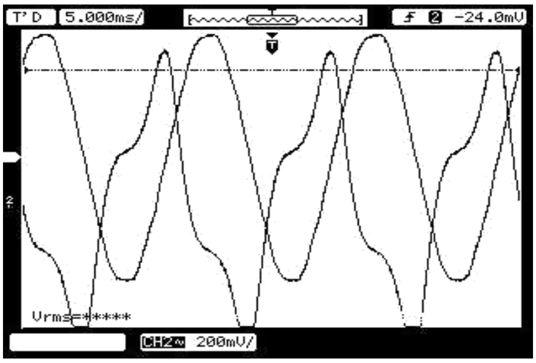

Fig.13: Excitation Current Waveform for Sinusoidal Input Voltage 200v

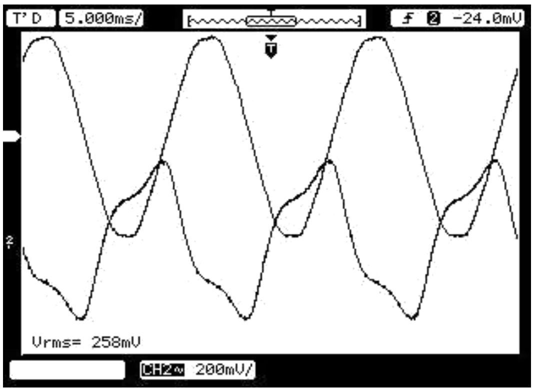

Fig.14: Excitation Current Waveform for Sinusoidal Input Voltage 220v

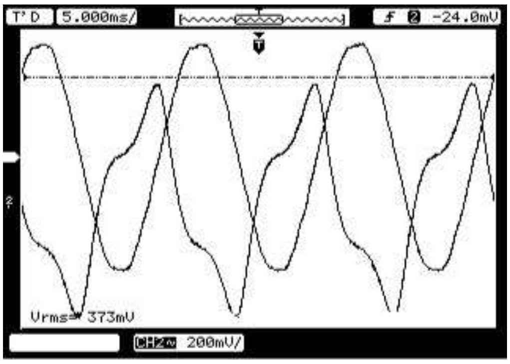

Fig 15: Excitation Current Waveform for Sinusoidal Input Voltage 240v

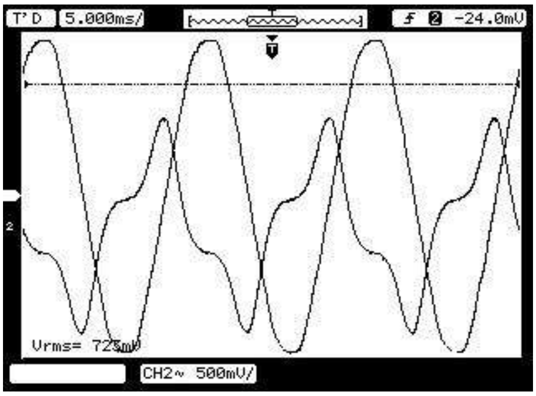

Fig.16: Excitation Current Waveform for Sinusoidal Input Voltage 280v

Increased dielectric stress on insulation
1. Electro static interference with communication circuits.
2. Resonance between winding reactance and feeder capacitance.

In the present times, a greater awareness is generated by the problems of harmonic voltages and currents produced by non-linear loads like the power electronic converters. These combine with non-linear nature of transformer core and produce severe distortions in voltages and currents and increase the power loss. Thus the study of harmonics is of great practical significance in the operation of transformers.

The primary effect of harmonic currents on transformers is the additional heat generated by the losses caused by the harmonic contents generated by the nonlinear loads [3].

There are three effects that result in increased transformer heating when the load current includes harmonic components:

1. RMS current: If the transformer is sized only for the kVA requirements of the load, harmonic currents may result in the transformer r.m.s current being higher than its capacity.
2. Eddy-current losses: These are induced currents in a transformer caused by the magnetic fluxes.
3. Core losses: The increase in nonlinear core losses in the presence of harmonics will be dependent under the effect of the harmonics on the applied voltage and design of the transformer core.

HARMONIC EFFECT ON NO LOAD LOSSES EFFECT OF HARMONIC CURRENT ON OHMIC LOSSES

The I^2R losses occur due to distorted primary and secondary current flowing through the primary and secondary winding of the transformer. The I^2R loss occurring in the winding transformer under the effect of the harmonic condition is given by.

$P_{DC}=R_{DC}*I^2=R_{DC}*(\sum_{h=1}^{h=max} I^2_{h.rms})$ watt

Table 2: Voltage, Current, Resistance and Inductance Values

V_1(V)	V_2(V)	I_1(A)	I_2(A)	P_O(W)	P_{SC}(W)
11KV	433	10.5	266.7	500	3000

R_1	R_2	L_1	L_2	R_C	X_m
3.27 Ω	.0041 Ω	.003 H	.067m H	728K Ω	32105 H

To calculate P_{TSL} is calculated below:
$P_{TSL}=P_{SC}-P_{DC}=3000-3(10.5^2*3.27+266.7*.00413)=1043.57$Watt
$P_{EC}=.33*1043.57=3443.7$watt
$P_{OSL}=P_{TSL}-P_{EC}=699.2$watt

Table 3: Harmonic Load Specification Is Given Below

1	5	7	11	13	17	19
0.966	0.208	0.09	0.06	0.04	0.3	0.02

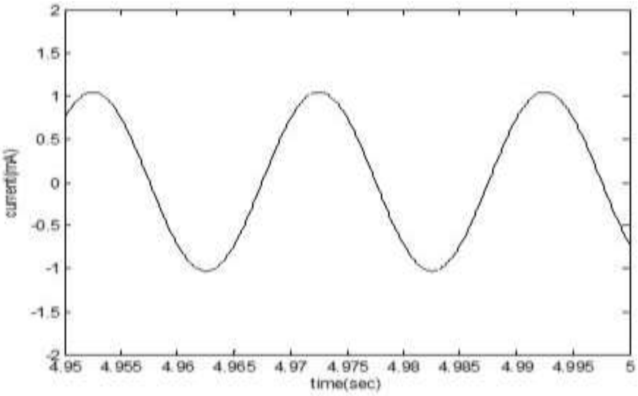

Fig.17: Current Waveform Due to Harmonic Load

Table 4: Comparison of Losses under Rated Current by Analytical Method and Simulation Method

RATED LOSSES(Watt)	ANALYTICAL METHOD	SIMULATION METHOD
NO LOAD	500	498.6
D.C	1956.43	727.36
WINDING EDDY CURRENT	344.37	309.02
OTHER STRAY LOSSES	699.2	627.42
TOTAL	3500	2162.64

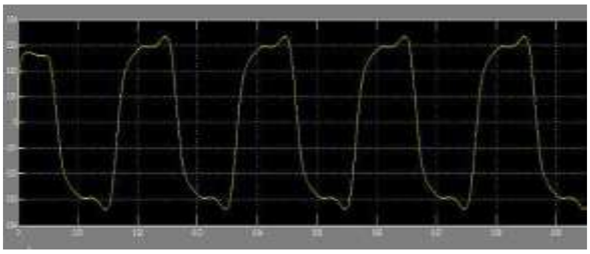

Fig.18: Excitation Current without Core Saturation

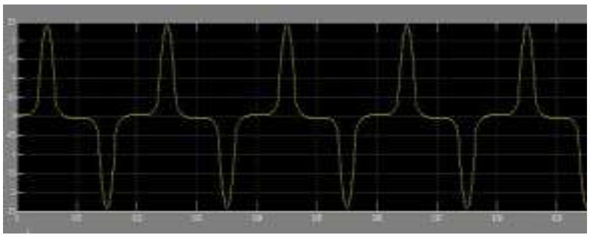

Fig19: Excitation Current with Core Saturation

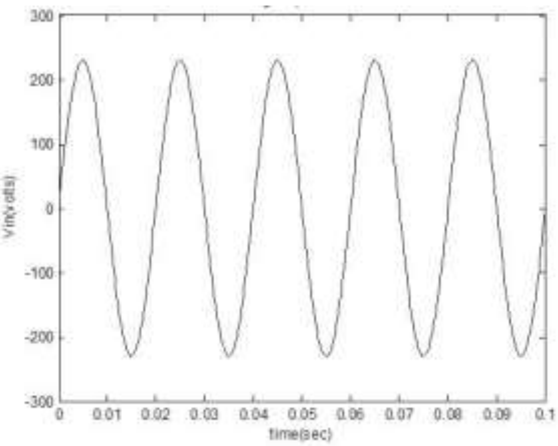

Fig.20: Sinusoidal Input to Transformer

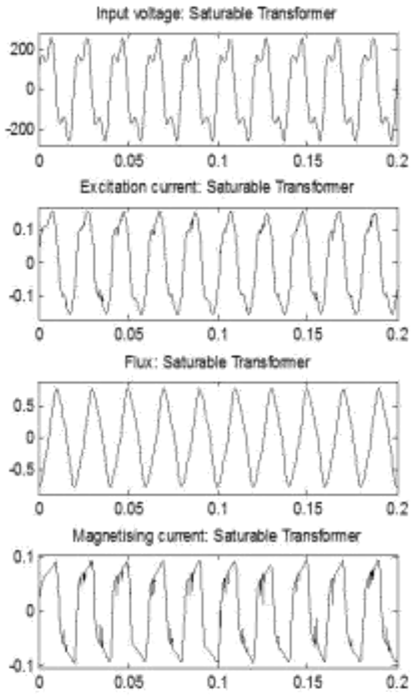

Fig. 21: Waveform of the Sinusoidal Input Voltage to Saturable Transformer

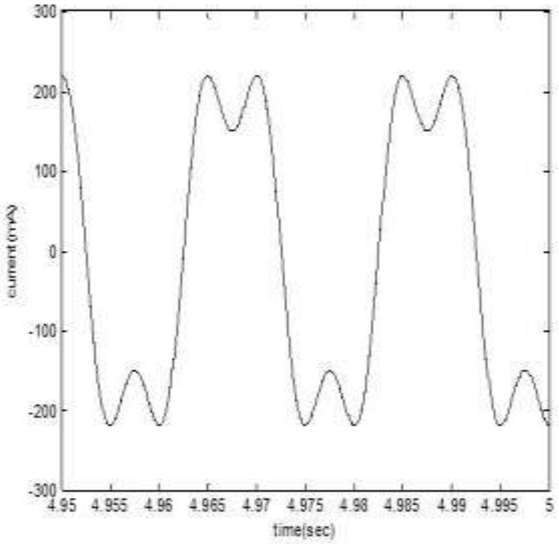

Fig.22: Non Sinusoidal Input Transformer

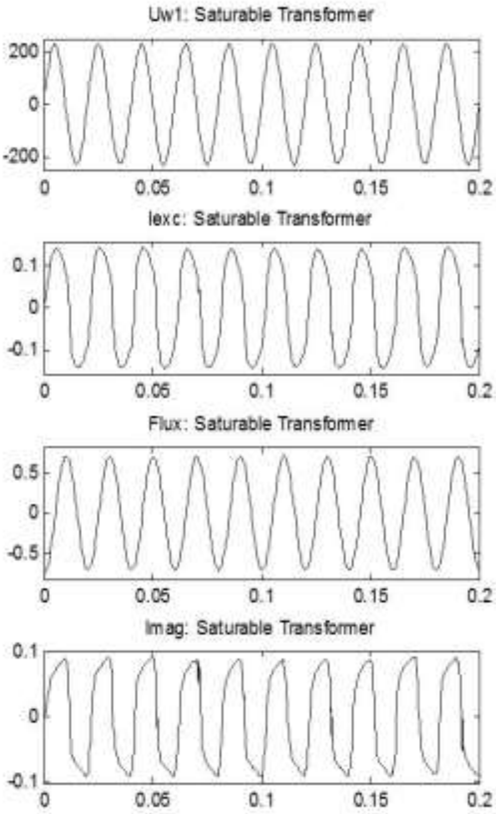

Fig. 23: Waveform of the Non Sinusoidal Input Voltage to the Saturable Transformer (Simulink Model)

CONCLUSION

Non-sinusoidal currents cause excessive heating in transformers due to the increase in the losses, especially the eddy current losses. K-Factor transformers differ from standard transformers. The most common type of distribution transformer coupling for low voltage distribution 10/0.4 kV is the Delta-wye. Distribution transformers are designed to operate at frequencies of 50 Hz, but there are loads which also produce currents and voltages with a frequency that are integer multiples of the 50 Hz fundamental frequency; this type of distortion effect on transformers leads to increased losses and heating as well as affecting the lifetime of the transformers. Where existing or standard transformers are used to supply non-linear loads, they should be de-rated in a manner appropriate to their construction. On applying the transformer with sinusoidal supply voltage the flux is sinusoidal while the excitation current waveform is sinusoidal or non-sinusoidal depending upon the region of operation.

If the region of operation is below knee point then the current waveform follows the voltage waveform. If the region of operation is above knee point the saturation is automatically incorporated into the core which then distorts the excitation current. In case of non-sinusoidal supply voltage, the flux gets saturated due to the saturation in the core leading to the excitation current with a total harmonic distortion. The eddy current losses increase quadratically as the RMS value of supply voltage increases. The modeling of the transformer is done without core saturation and with core saturation. And the results were observed. From the waveforms, it is observed that with an increase in non-linearity in the supply voltage the excitation waveform becomes more and peakier thus increasing the third harmonic component. With the deviation of the supply voltage from perfect sinusoid the flux also becomes non-sinusoidal. As of now, the three phase transformers are an integral part of our power system, modelling of three phase transformers are to be performed. The modelling of different connections of transformer delta-wye, wye-wye is to be performed. The autotransformer has to be simulated by using its winding its winding connections. The single phase transformer model has to be modelled with a non-linear load.

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