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Design and Simulation of an Automatic Hysteresis Transformer For Power Losses Reduction In Transmission System

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Abstract
Low power quality has been an issue with most power been supplied as a results of faults in transformers undergoing power losses such as iron, copper, eddy current and hysteresis losses, The project has presented a way to reduce hysteresis losses in transformers by the application of multiple winding auto transformers. The study has proposed the design of auto transformers with multiple windings so that the transformer can select a winding free from magnetic losses.The project has implemented hysteresis losses together with eddy and copper losses as a way to help analyze transformer losses. The result presented has shown that current free from hysteresis can be produced at transformers output by the application of auto transformers to reduce hysteresis losses.

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I. Introduction

As part of a study of the distribution and use of power on spacecraft, the Lewis Research Center has been evaluating power system components in unusual configurations and at temperatures and frequencies outside the ordinary ranges. Early in this study it became evident that neither classical nor modern approaches to magnetism could completely predict transformer properties and their variations with frequency.

The classical approach to the study of losses in ferromagnetic materials is the conventional engineering analysis which assumes the magnetic material to be isotropic and homogeneous and defines the losses in terms of the hysteresis loop and classical electro- dynamics. The modern theory of magnetism utilizes crystal energies and magnetic do- main configurations to provide an understanding of losses. The classically derived losses are characterized by measurements that are relatively easy to make while the modern theory relies on crystal anisotropy energies and domain wall velocities that are very difficult to evaluate and measure in polycrystalline materials.

Traditionally, transformer core losses have been divided into two groups, hysteresis and eddy-current loss. Hysteresis loss is thought to be associated with the energy required to rotate or move the walls of the magnetic domains over a full cycle. The hysteresis loss is proportional to the area of the familiar hysteresis loop. The eddy-current loss is due to the currents generated within a real conductor subjected to a varying magnetic field.

The purpose of this report is (1) to provide a better understanding of classical theory for the readers already familiar with the basic engineering approach and (2) to derive expressions useful in predicting the dependence of core losses on frequency and easily measured properties. Hysteresis and eddy -current losses are usually treated separately with no common underlying basis. A more unified viewpoint will be provided starting with Maxwell's equations and will show that considerations of the Poynting theorem yield the classical core loss formulations. The separation of core losses into their two traditional components results as a natural consequence of the analysis.

A transformer can be referred to as a power transmission device system that basically converts one voltage level into another voltage level without altering the frequency of the system. During this conversion process, losses occur in the core and windings of the said system. These losses are generally termed heat losses. As a result of these losses in the transformer. The output power of the transformer drops and returns a bit less than its input power. The increase in the rating and capacity of a transformer directly results to an increase in its generated heat. There are different mediums of cooling system conversant with this power system device, they basically include: air, water, oil mediums of cooling systems. The oil and water-cooling mediums of cooling systems in the past years has been done manually. Due to its manual operation characteristic, it is faced with the disadvantage and challenge of not recognizing over heating (Bharathidasan, et al., 2019). Transformer design most takes into consideration the thermal behavioral aspect. Therefore, precise and proper temperature calculations to a reasonable extent guarantees good quality, performance and long-life expectancy of transformers. The temperature gradient between conductor and oil consists of a gradient inside the solid winding insulation and a gradient inside the boundary layer at the winding surface must be optimal. The gradient inside the solid insulation depends on the thickness of the enamel, paper insulation and oil pockets between conductor and paper wrapping. The heat transfer at the winding surface of a transformer is determined by the cooling conditions approach. The two basic approaches mostly in use are: The Natural Convective Cooling (ON) and The Forced Convective Cooling (OD). During the operation of the transformers, heat losses occur and the windings temperature get heated up. Heat losses in the transformer include the losses in iron core, due to the magnetic induction and the copper losses that occur as a result of the flow of electrical current through the windings of the transformer. It is paramount to set up a medium of external cooling system to reduce the heating up of the transformer winding temperature. While the standard average temperatures for the standard-class dry transformers are 80ºC, 115 ºC and 150 ºC, the temperatures of the hottest point reach 150 ºC, 185 ºC and 220 ºC respectively. The expected life of transformers at various operating temperatures is not exactly known. (Buyukbicakci et al., 2014).

An auto transformer is the one which consists of a single winding, part of which acts as the primary winding of the transformer, and some part of which acts the secondary winding, which can be varied by switching between the contacts of the transformer. By varying the contact of the switch we can change the number of turns which are accommodated in the secondary winding. Since the output voltage depends upon the number of turns of the secondary winding, so in this way the voltage output can also be varied. For this reason, an auto transformer is also known as a “Variac” because it is mostly used to vary (step up or step down) the output voltage which has to be supplied to the circuit.

Construction and working of an Auto Transformer

In general transformers, there are two windings which are magnetically linked to each other, but re physically separated from each other. But in an auto transformer, both the primary and secondary windings are connected to each other, both physically and magnetically. The internal construction of an auto transformer is shown in the figure 1.1:

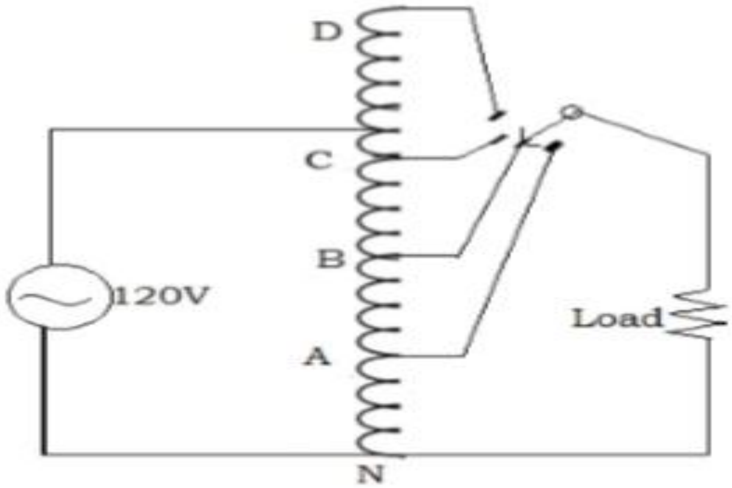

Figure 1.1: schematic diagram of an auto transformer

II. LITERATURE REVIEW

Auto transformer employs only single winding per phase as against two distinctly separate windings in a conventional transformer.

2.2 Origin of Hysteresis Loss

The VSM output indicates the average response of all magnetic phases in the sample volume to the highly homogeneous applied field. The sample may have structural defects that can be located in the sample volume or generated at the surface during the machining (or cutting) of the magnet. Ferrite magnets produced by the hydro thermal synthesis method can have unwanted phases of iron oxide α-Fe_2O_3 and orthorhombic barium iron oxide $BaFe_2O_4$ (Losses, 2023) as impurities in addition to the major phase of the hexagonal barium M-type ferrite $BaFe_{12}O_{19}$. The coercivities of both these undesirable phases at ambient temperature can be in the range of the anomaly, which supports the assumption about the volumetric origin of the hysteresis loss in ferrite PMs. The studies of Nd-based magnets mostly assume that the hysteresis loss originates from the reduced coercivity of the damaged grains on the sample surface. The results in (Olivares et al., 2002) show that the heat treatment of a thin NdFeB PM sample with the surface -to-volume ratio S/V = 21.9mm–1 in temperatures exceeding the melting point of the Nd-rich phase results in a considerable reduction in the unexpected slope change near the J-axis, but does not fully eliminate it. The JH curve of the sample in [29] still indicates an unexpected decrease in polarization at magnetic field strength values below the intrinsic coercivity |HcJ|. The NdFeB sample with a relatively small S/V = 1.82mm−1 (3.1×2.9×4.1(M↑↑)mm3) in [16] demonstrates a considerable slope change near the Jaxis while the ferrite sample of the BM9 grade in (Olivares et al., 2002)with S/V = 1.72mm−1 (3×3.6×4(M↑↑)mm3) does not exhibit a similar behavior of the recoil curves. The pulse field magnetometer measurement results in [30] show the possibility of hysteresis loss in Nd- and SmCo-based PM samples even with values of S/V = 0.4–0.6mm−1. The recent research (Olivares et al., 2002) provides convincing evidence that the hysteresis loss can partly be an intrinsic property of the Nd-based magnet material, generated in the PM manufacturing as a negative consequence of enhanced coercivity. Based on the observations available about the possible origin of the hysteresis loss in PMs, it was concluded that both volume- and surface-caused defects can be present in ferrite PMs simultaneously. Thin REPMs used in electrical machinery obviously contain a considerable proportion of damaged grains on the magnet surface. This damage is caused by the machining phase in the production process if no other surface treatment is applied. However, the relatively weak magnetic properties of the ferrite PMs facilitate the designs of PMSMs with thick magnets to avoid possible irreversible demagnetization of ferrite magnet material [4]. Therefore, the hysteresis loss in ferrite magnets with dimensions relevant to the actual machine design will mostly be associated with volumetric defects. This study assumes that the behavior of the recoil curves is caused by the presence of unwanted magnetic phases, which are equally distributed in the PM volume.

In an attempt to measure hysteresis, (Dworakowski et al., 2017)describes a feedback Preisach hysteresis model equivalent circuit implementation of a medium frequency single-phase transformer being a part of a high power and high efficiency DC-DC converter. The macroscopic models of magnetic hysteresis are introduced and the feedback Preisach model is selected for further analysis. The hysteresis model is developed for a prototype transformer and the hysteresis loops are compared against a measurement. The equivalent circuit implementation of the hysteresis model is proposed and analysed. The equivalent circuit model is validated in no load operation and compared with a measurement.

(Chwastek, 2022) in his study, focused on modeling the rate dependence of hysteresis loops in conductive magnetic materials. The concept, which was advanced about fifty years ago by Chua, is discussed. It is shown that the viscous-type equation considered by Zirka and co-workers belongs to the class of Chua-type models. The dynamic effects are described with a simple fractional power law. The value of the exponent in the above-mentioned power law may be assessed on the basis of measurements of coercive field strength at different excitation frequencies. To verify the usefulness of the approach, the measurements of hysteresis loops were carried out at several excitation frequencies under standardized conditions for two grades of non-oriented electrical steel. The modeled curves are in a good correspondence with the measured ones. The considered model uses fewer parameters than approaches based on three-term loss separation schemes.

In (Du et al., 2018), the authors asserts that the hysteresis characteristics of a transformer core are determined from limited on-line measured voltages and currents under certain excitations. A method for calculating the magnetization curve and hysteresis loops of the transformer core under various excitation is developed based on limited excitation conditions, and using the deep neural network, support vector regressor and the Wlodarski model. The coercivity and the amplitude of magnetic field strength of hysteresis loops can be captured with high accuracy based on this method. Then, a finite element model of the transformer core is constructed to predict the distributed magnetic flux density and the excitation current using the calculated hysteresis loops. The currents from various excitation voltages on two different transformer structures are also measured to compared with simulated currents. The outcome indicates that the overall hysteresis loops and magnetization curve of the transformer core may be useful for modeling the magnetic field and excitation current under any voltage excitation.

(Mgunda, 2017)presents the design approach used in designing transformers mostly used in power supplies and power systems. The paper will cover theoretical principles applied in analyzing magnetic circuits to better understand the operation of the transformer. Since well-designed transformer is supposed to meet the specifications of the environment that it is going to be used, there is a need to confirm after the transformer is built to make sure that it is going to operate efficiently and without a failure. Therefore, this paper will also present the traditional methods used to test transformers in the industries to make sure that it will operate within the prescribed loading limits and voltages. This paper covers the transformer losses in detail including the test methods used to calculate nameplate parameters for power transformers used in power systems.

III. MATERIAL AND METHODS

3.1 Material

There is need to properly model the transformer loses to take a closer view on how to reduces hysteresis loses in transformer core, this chapter will look to mathematically describe the hysteresis losses in transformer and also implement them in Matlab/simulink simulation environment, this chapter will also develop technique for reduction of hysteresis loses using auto-transformers model. For design and simulation purpose, the following materials were used Matlab/Simulink, Transformer data, Laptop/ windows 11

3.2 Methods

Figure 3.1 shows the block diagram for the design of the auto transformer for core switching in the system, the auto transformer function by switching its winding. In Auto Transformers, one single winding is used as primary winding as well as secondary winding. the auto winding transformer switches amongst several winding to reduce hysteresis effects when detected in any particular winding

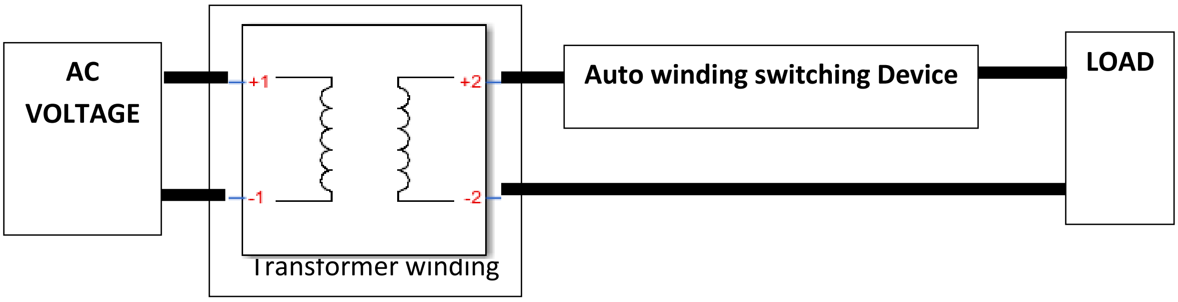

Figure 3.1: system block diagram of the auto transformer for reduction of hysteresis losses in transformers

3.3 Mathematical description of the transformer loses

The main causes of the transformer core losses are eddy current and Hysteresis losses. The other losses in a transformer are stray losses which are difficult to calculate precisely due to their complexity.

8.1. Hysteresis Loss

For the core to be magnetized there is a continuous alignment and reversal of magnetic dipoles in the core material. This process requires energy hence contributes to the core loss called hysteresis loss. The hysteresis loss is frequency dependent loss. Energy lost per cycle is;

$$W_{CYCLE} = f A_c I_c \int_0^{2\pi} H dB \qquad 3.1$$

Where A_c is cross-sectional area of the core and I_c is the length of the core. Empirical equation (Steinmetz equation)

$$W_h = K_h f A_c I_c (B_m)^{1.6} \qquad 3.2$$

Where W_h is hysteresis loss in watts, K_h (K_h = 4.44 for a sine voltage) is a Hysteresis constant, f is frequency in Hertz and m B is maximum flux density.

Eddy Current losses

Based on Faraday's Law, changing magnetic flux induces voltage in a conducting material which in return causes current flow in that material

$$e_{ind} = \frac{d\phi}{dt} \qquad 3.3$$

Since the core is within the vicinity of magnetic flux, there will be an induced voltage in the core which will cause current circulation in the core. This circulating current will cause power loss in the core in form of heat due to the resistance of the core. The formula for calculating Eddy current is;

$$P_E = \frac{A_c B_{max}^2 f^2}{\rho_e} \qquad 3.4$$

Where $A_c$the cross-sectional area of the core is, ρ_e is the resistivity of the core, B_{max} and f is the frequency. There are other transformer losses called stray losses. Some of the stray losses may be caused by some of the magnetic flux inked to the transformer tank. Stray losses in a transformer are difficult to estimate, hence this paper will only cover hysteresis and eddy current losses for the core. Estimated total core losses will the sum of hysteresis and eddy current losses, thus.

Inductive Reactance

Power when ac voltage is applied to the windings, the magnetic fields built up in the windings. Some of the input power to the transformer is used up for this magnetic field built-up. The magnetic field on the primary are supposed to link the secondary winding so the secondary voltage is induced in the coil. Not all the primary magnetic flux is linked to the secondary. Therefore, this also contributes to energy losses in the transformer.

$$P_L = \frac{L_{leakage} I_{pk}^2}{2} \; [watt - seconds] \qquad 3.5$$

Estimated Total Core Losses

$$P_{TC} = P_h + P_E = K_h f A_c l_c (B_m)^{1.6} + \frac{A_c B_{max}^2 f^2}{\rho_e} \qquad 3.6$$

That is,

$$P_{TC} = A_c l_c k f^a B_m^b \qquad 3.7$$

Implementation of system model

The implementation of the system model was done using Matlab/simulink, the model will consist of the system with and without the auto transformer, figure 3.3 describes the Simulink implementation of the system

Figure 3.3 and 3.4 shows the transformer models with and without the auto transformer, in each case, there is a hysteresis and eddy current attached to the transformer windings, the implementation of the auto transformer model in figure 3.4 is seen to contain 3 primary winding and 4 secondary winding for step with each containing a total of 90 and 120 windings for the primary side and secondary side, this is done for step up purpose.

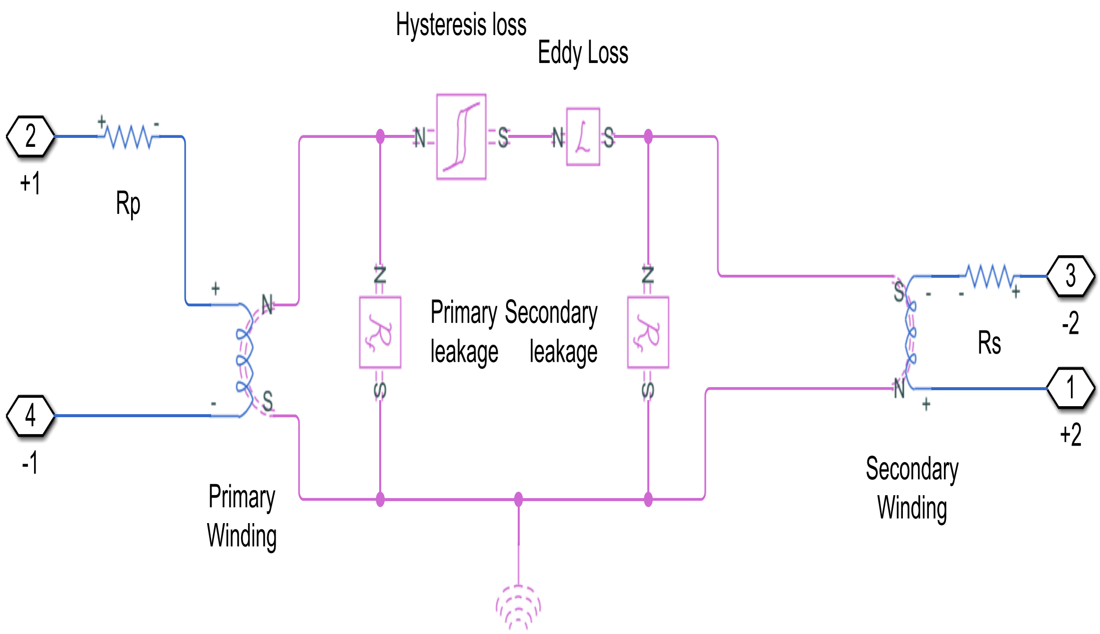

Figure 3.3: hysteresis system without auto transformer

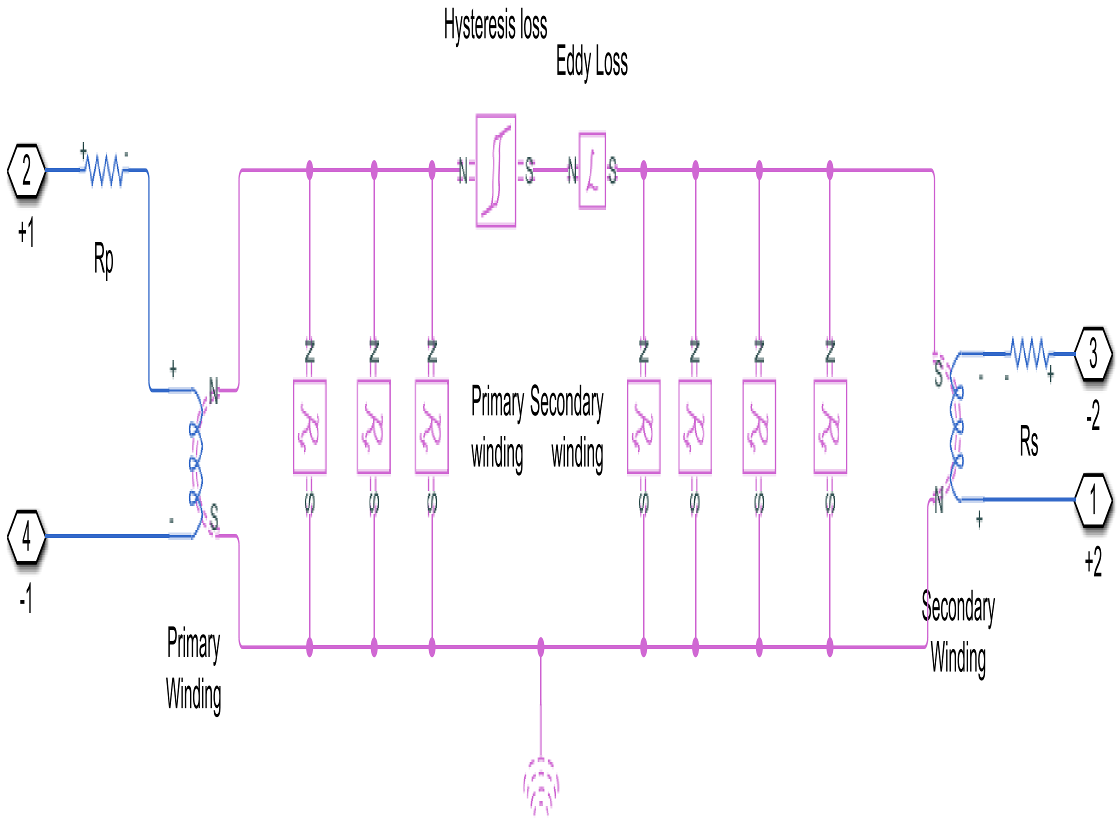

Figure 3.4: hysteresis system with auto transformer

IV. RESULTS AND DISCUSSIONS

4.1 Results

Here presents the implementation of the auto transformer model for hysteresis reduction, the parameter used for the simulation are presented in table 4.1. The parameters presented show the overall design of the transformer system for hysteresis loses.

Table 4.1: simulation parameters

Parameters	Value
Ns 1	30
Ns 2	30
Ns 3	30
Ns 4	30
Ns (Total)	120
Np 1	30
Np 2	30
Np 3	30
Np (Total)	90
Vp	200V
Vs	270V
Core length	12cm
Core area	120cm
Frequency	60 Hz
Resistivity of core	120 Ohm/m
Core inductance	2.6 H

4.2 Transformer Voltages And Currents

Figure 4.1 presents the transformer voltages for the primary and secondary sides, the primary voltage is seen to have a max of 200 V, while the secondary voltage a max of 270 V.

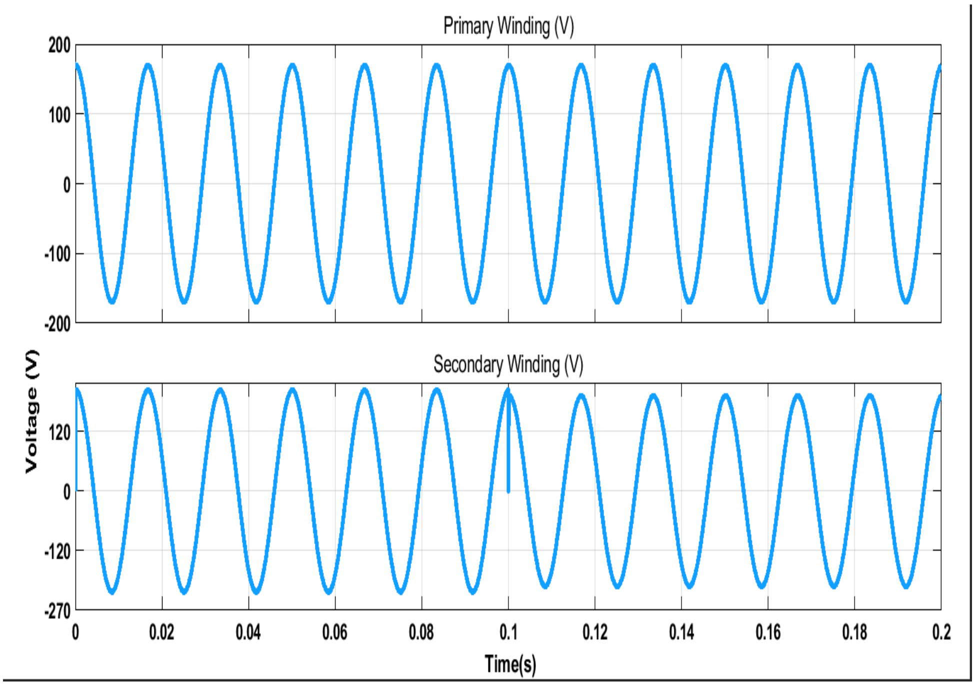

Figure 4.1: transformer voltage

Figure 4.2 shows the transformer currents with and without hysteresis, the plots shows that on application of the auto transformer, a winding with less hysteresis effect is selected to reduce currents due to hysteresis. The secondary current shows a current free from hysteresis is been produced at the transformer output.

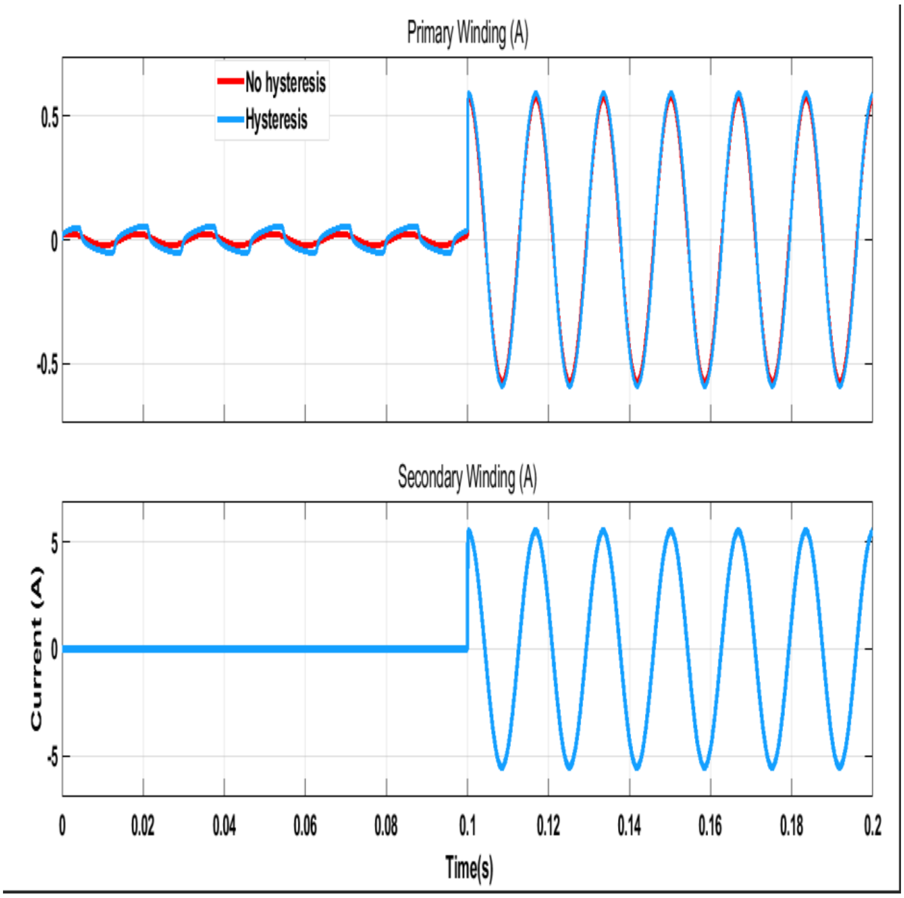

Figure 4.2: transformer currents with and without hysteresis

Analysis Transformer Hysteresis Loss

Figure 4.3 presents the losses due to hysteresis in the transformer for cases of with and without the hysteresis losses, the losses combination are the copper loss, eddy current loss and magnetic power generated in the core.

For transformer with hysteresis losses, the magnetic and eddy losses are seen to maintain a steady value of 5 W until about 0.1 s of the simulation and even continue to about 0.2 seconds of simulation after which the auto transformer was not implemented in this case. For transformer without hysteresis losses, the magnetic and eddy current losses are seen to maintain a value below 5W (low losses) even till the point of application of the auto transformer, after 0.1 seconds of simulation, the hysteresis loss is seen to drop to 0 watt enabling the production of current free from hysteresis at the transformer output.

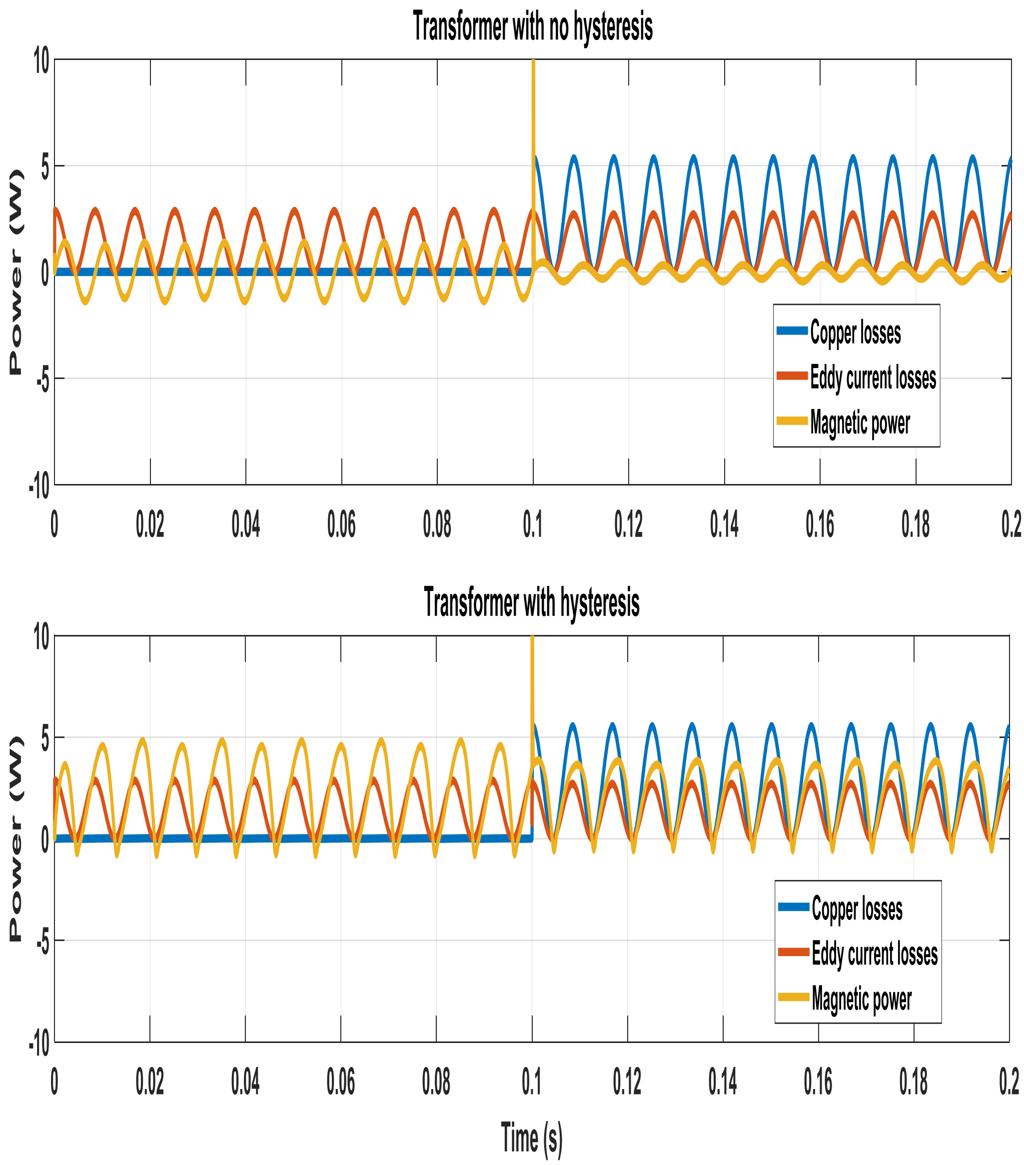

Figure 4.3: analysis of transformer losses with and without the auto transformer

V. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The project has presented a way to reduce hysteresis losses in transformers. The study has proposed the design of auto transformers with multiple windings so that the transformer can select a winding free from magnetic losses.

The project has implemented hysteresis losses together with eddy and copper losses as a way to help analyze transformer losses. The result presented has shown that current free from hysteresis can be produced at transformers output by the application of auto transformers to reduce hysteresis losses.

5.2 Recommendations

This project has proposed the auto transformer as a means of reducing most transformer loses like hysteresis and copper losses, for better reduction of transformer losses, it is recommended that the application of fuzzy logic decision makers embedded in logical system be used to detect faulty winding and help switch to windings without faults.

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