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Investigating Ferroresonance Phenomenon in a Single-Phase Transformer with the Effect of Magnetic Hysteresis

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Abstract

Ferroresonance is a non-linear phenomenon and very dynamic in the power quality problems. This phenomenon should be carefully analyzed so that preventive measures could be taken before its appearance and prevent injury and damage to electrical power appliances. Ferroresonance is seen more in the middle-voltage networks with supplying unloaded or slightly loaded transformers by cables. The materials used in the manufacture of transformer cores are creates a major role in their dynamic behavior. In this article are used from two types magnetic material GOES and NGOES in the transformer core of single phase. The physical behavior of these materials is considered during the core hysteresis. For modeling the hysteresis loop has been used from Jiles-Atherton method. By using the finite element method and with help COMSOL Multiphysics Software, transformer is simulated in two space dimensions. Laboratory test the transformer core hysteresis loop is described and shows which the Jiles-Atherton model is one of the best known models of hysteresis. The results shows which use of GOES materials in the transformer core is cause Significant reduction the core losses in comparison with the NGOES materials. Also change of ferroresonance mode and the severity its occurrence are the results of changing the material used in the transformer core.

Keywords: *Ferroresonance, Finite Element Method (FEM), Hysteresis loss, Single Phase Transformer*

1. Introduction

A transformer is a device used to transfer electrical energy from one circuit to another. In other words, transformers are devices used in electrical circuits to change the voltage of electricity flowing in the circuit. Therefore, transformers are one of the most important electrical equipment. Ferroresonance is a nonlinear phenomenon, which occurs between the network capacitor and nonlinear inductance the equipment such as transformers reactor. In conditions unloaded or slightly loaded, with the incidence of disturbances, transformer winding through the capacitor of lines and transformer windings constitute the resonant circuit and with the transformer core saturation, ferroresonance is created [1]. Although resonant is also includes a capacitor and an inductor, but certainly does not exist resonant frequency where in the ferroresonance occurs. So that in the ferroresonance phenomenon, there are more than one response for a set of identical parameters [2]. In ferroresonance mode, relationship between voltage and current in addition to the frequency is related to other factors such as voltage, initial conditions and circuit losses [3]. Nowadays, from soft magnetic materials are used strongly in the structure of electrical equipment. Silicon steel is used as a soft magnetic material in the manufacture of transformers, motors and generators [6-4]. This type of materials is considered as the best combination for transmission and distribution of electrical energy and using them is more economical. Silicon steel used in core of electrical machines has a significant impact on the magnetic field [7]. In the event that these materials have placed under an alternating current, are causes losses and heat in the circuit. Silicon used in this material has range of 0.5 to 5%. By increasing the amount of silicon decreases the amount of losses. In terms of Electrical processing, these materials can be divided into two categories:
1) Grain Oriented Electrical Steel (GOES)
2) NON-Grain Oriented Electrical Steel (NGOES).

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Silicon range used in NGOES materials is between 0-3% and in the GOES materials is between 3-3.8% [8]. The basic difference between these two types of steel is differences in the direction of magnetization. Studies of magnetic behavior are shows optimal state GOES only one direction. So magnetic dipoles are converges in one direction. While NGOES is shows magnetic properties as an isotropic feature. Based on the standards applied in the manufacture of products, type of steel used in manufacturing equipment is different. At the core of transformers are used usually of GOES categories and for the production of motors and generators from NGOES category. From properties of these materials can be mentioned the high Permeability and induction and low magnetic losses. Permeability and high inductance reduces the size and weight of the equipment. Also low magnetic losses reduces generate heat and increases its efficiency. In general, the properties of magnetic materials are evaluated according to the magnetic field strength and magnetic flux density. Although the need to accurate descriptions magnetic processes has been increased in these materials with their development, but is continues careful analysis of magnetic behavior. Physical behavior these materials are reflected as magnetic hysteresis. One of the important factors is the effect of hysteresis losses which creates an important role in the behavior of ferroresonance [9-10]. The conducted researches about ferroresonance have shown that the simulation results are very sensitive to magnetic saturation characteristic method and core losses [11]. The core hysteresis losses are dependent to frequency and enclosed level in the hysteresis curve and therefore dependent to the hysteresis model. Therefore for modeling magnetic characteristic and the core hysteresis are used from more accurate models.

Nowadays calculation the hysteresis losses with finite element method has been noticed increasingly by computer science [12]. Reference [13] ferroresonance phenomenon is examined on a transformer to the finite element method, but does not provide exact model of hysteresis. Various methods is provided for modeling of hysteresis, which in this between the Jiles-Atherton model [17-14] and preisach model [18] are provides accurate models of hysteresis losses. In reference [19] ferroresonance damping control is studied with regard to the effect of the non-linear losses. In reference [20] a new model of hysteresis is provided based on the preisach theory with the new formulation in the ATP software which the nonlinear characterizes of materials is not modeled well. In this paper, a new approach is presented of the ferroresonance phenomenon. By simulating the transformers core made of soft magnetic material in the two-dimensional space by finite element method, the effect of use these material in ferroresonance problem has been studied. For modeling the magnetic hysteresis is used from Jiles-Atherton method. Modeling of Transformer is done in the comsol software which simulates Non-linear elements with very high precision.

In Section 2, the basics of Ferroresonance phenomenon has been studied in order to understand better of these phenomenon. In Section 3, a brief explanation is provided of how taking into account the hysteresis model and calculation method of the core losses. In Section 4 the simulation results are presented.

2. The Basics of Ferroresonance Phenomenon

When the ferromagnetic cores of high pressure equipment saturated and are placed in circuit as series with capacitive property, the conditions are provided for ferroresonance phenomenon. In power systems, transformers are fed mainly by cables. The cables have the higher capacitive properties and as series are placed with the transformers coil equipped with ferromagnetic core [21]. Ferroresonance is a kind of temporary overvoltage and has different types. This phenomenon is reviews aspects of the domain and duration and its harmonics. If a wave with high amplitude and the more harmonics exists in the long duration on the equipment, lead to damage and even destruction of it. For example, the existence of harmonic voltage on the transformer causes overheating and damage to the transformer windings. So should be avoided from the existence of this factor that is under impact the ferroresonance phenomenon on the transformer. Figure 1 shows the equivalent circuit the ferroresonance phenomenon where inductors have nonlinear characteristics. With current passing through the circuit, the capacitor is charged. The voltage stored in a capacitor could be assumed DC voltage which is located in two ends of the magnetization reactance of transformer, and causes the core to be saturated. The magnetization reactance reduced and ferroresonance occurs. Therefore

Ferroresonance is a non-linear phenomenon which is function of parameters including the induced voltage, magnetization characteristic, losses and the circuit capacitor.

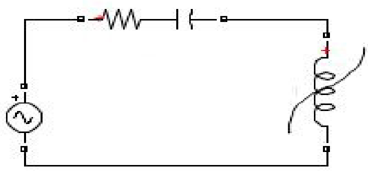

Figure 1. The equivalent circuit ferroresonance

3. The Hysteresis Model

With the advancement of technology has been created the possibility of to consider more complete model of the ferromagnetic material. The most prominent behavior which shows ferromagnetic materials from themselves is the hysteresis behavior, which in the simplest case causes the direction without the magnetization is different from direction with its magnetization. The Jiles-Atherton method is used due to high accuracy in estimating the hysteresis loop and also easy implement in the software. This model is based on the energy balance in ferromagnetic materials. So that the total energy during a period is saved as the magnetic energy (Wm) and/or is wasted as the hysteresis losses (W_h).

When the network is protected with distance relays, each line is protected by the main and backup relay of its line. By placing overcurrent relays along with distance relays, protective territory of the transmission network will expand. If a disturbance occurred, initially main distance relay will operates and if it fails to clear fault, overcurrent relay will operates. If main relay fails to operate, the backup distance relay will operate and if it fails to operate ultimately backup overcurrent relay must isolate the faulted section. As shown in Figure 2 in order to establish the mentioned sequence protection, two other constraint should be added to the constraints of coordination problems:

$$W = W_m + W_h \tag{1}$$

Based on this assumption and reference [16] obtained the following equation for all ferromagnetic materials:

$$M = M_{rev} + M_{irr} \tag{2}$$

Where M is the materials magnetization, M_{rev} is the materials reversible magnetization and M_{irr} is the materials irreversible magnetization.

$$M_{an}(H_e) = M_s(\coth(\frac{H_e}{a} - \frac{a}{H_e})) \tag{3}$$

According to the modified langevin function that is expressed to describe behavior of ferromagnetic materials, for the ideal magnetization curve, M_s is the magnetic saturation, a is a coefficient to describe the temperature and H_e is the effect of the magnetic field which is achieved as the following equation:

$$H_e = H + \alpha M \tag{4}$$

By changing the magnetic field the equation derived from renewable field is as follows:

$$\frac{dM_{irr}}{dH} = \frac{M_{an}(H_e) - M_{irr}}{k\delta - \alpha(M_{an}(H_e) - M_{irr})} \tag{5}$$

In the equation (5) k is the material hardness coefficient, α is coefficient to describe connection of the magnetic fields and δ indicates the direction of the magnetic field change. δ is a directional parameter which has the value of +1 if $dH/dt > 0$ and has the value of -1 if $dH/dt < 0$.

$$M_{an} = \begin{cases} M_s \frac{H_e}{3a} & |H_e| < 0.1 \\ M_s(\coth \frac{|H_e|}{a} - \frac{a}{|H_e|}) \frac{H_e}{|H_e|} & |H_e| \geq 0.1 \end{cases} \tag{6}$$

The reversible equation of the magnetic fields as follows:

$$M_{rev}(H_e) = c(M_{an}(H_e) - M_{irr}) \tag{7}$$

Where c is the material reversible coefficient. Using of equations (2), (3) and (7), equation the magnetization material is obtained as follows:

$$\frac{dM}{dH} = (1-c)\frac{(M_{an}(H_e) - M_{irr})}{k\delta - \alpha(M_{an}(H_e) - M_{irr})} - c\frac{dM_{an}(H_e)}{dH} \tag{8}$$

The parameters of this method could be observed summarized In the Table 1.

Table 1. Describes of the parameters J-A method

parameter	Description	the unit
M_s	the magnetic saturation	[Am^{-1}]
a	Temperature coefficient	[Am^{-1}]
k	the material hardness	[Am^{-1}]
α	Connection magnetic field	-
c	The reversible coefficient	-

3.1. Calculating Hysteresis Losses

As was mentioned many methods have been proposed in the literature and books for calculating hysteresis losses. In this article, for calculating hysteresis losses are used the following equation:

$$P_{Loss} = \frac{1}{T}\int_0^T HdB \tag{9}$$

3.2. Calculation of Eddy Current Losses

Most ferromagnetic materials are conductors of electrical current. This causes which with placed in a time-varying magnetic field, the phenomenon of eddy currents are created in the opposite direction of the external field. Incidence of eddy current phenomena is caused the creation of a losses component at the core of electromagnetic systems. For laminate ferromagnetic materials, which its sheet thickness is smaller in comparison to its other dimensions, power Losses caused by eddy currents can be expressed as follows [22]:

$$P_{edd} = \frac{\sigma\, d^2}{12}\int_0^T \left(\frac{\partial B}{\partial t}\right)^2 \quad (10)$$

Where σ is the sheet electrical conductivity, d is sheet thickness and B is the flux density passing through the sheet. The thickness of a sheet of in the international standards is between 0.35 to 0.5 mm. Also calculation of eddy current losses is done in accordance to the state before.

4. Laboratory Sample Specification

For investigate the electromagnetic behavior these materials is used from a single-phase transformer. The transformer used with voltage 220 volt and frequency 60 Hz has been located in the circuit. The transformer specification is presented in the table 2. Also the transformer geometrical dimensions are shown in figure 2. The J-A model parameters is presented for the iron core of transformer with magnetic materials GOES in the table 3.

Table 2. specification of the studied transformer

Parameter	the amount of
Nominal power	20 W
The initial voltage	220 V
Secondary voltage	12 V
Frequency	50 Hz
Number of primary windings	1600
Number of Secondary windings	90

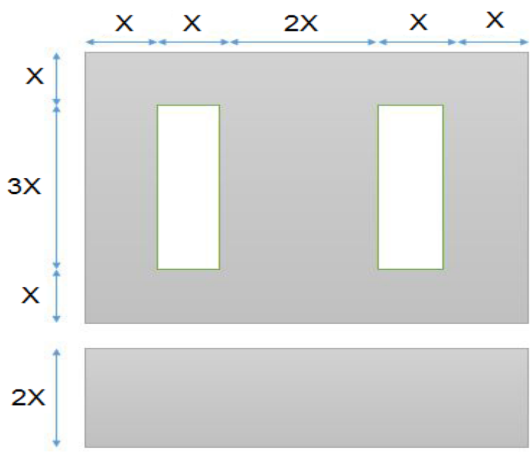

Figure 2. Transformer Geometrical Dimensions (x=11mm)

Table 3. The J-A model parameters for transformer core with GOES materials

parameter	the amount of
M_s	1350000
a	62.15
k	94.52
α	0.05
c	0.000108

4.1. Modeling of by Finite Element Method

In mathematics finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems. This method is similar to the idea that connecting many tiny straight lines can approximate a larger circle. FEM encompasses all the methods for connecting many simple element equations over many small Subdomain, named finite elements, to approximate a more complex equation over a larger domain [24-23]. By applying relations the J-A model to the finite element method could be achieved the hysteresis curve for different parts of the transformer core. From the Finite element method and to help COMSOL Multiphysics software is used for computer simulation [25]. This software solves the nonlinear systems equations by the partial differential equation and in the presence of an electromagnetic field and so on. Also, it there is possible to define electrical circuits such as load, resistance, inductance, capacitance and so on with the magnetic field. Figure 3 shows a two-dimensional model of transformer. Considering the hysteresis curve by the J-A method could be achieved the magnetic path each point of transformer core. Figure 4 shows magnetic flux path to a desired point from the transformer core. Figure 5 shows the flux density distribution the transformer core. The Primary and secondary transformer current curves is presented in the normal operating mode in figure 6.

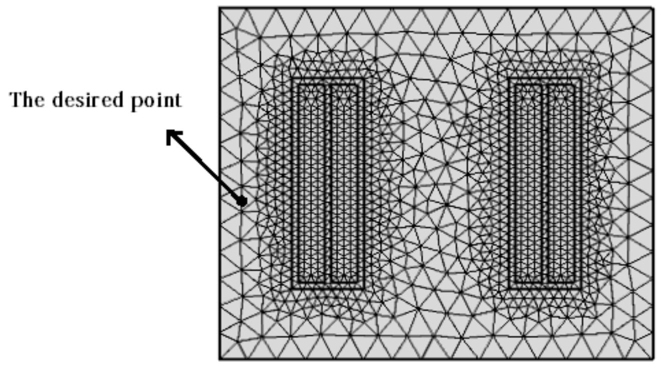

Figure 3. Two-dimensional model of transformer

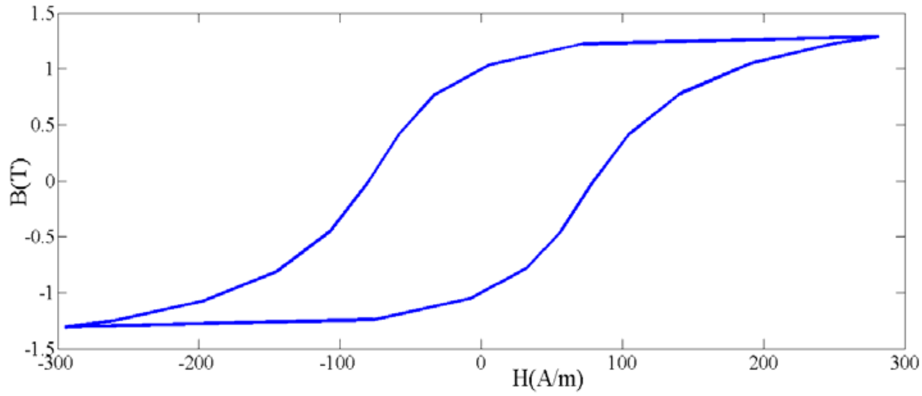

Figure 4. Hysteresis curve for desired point

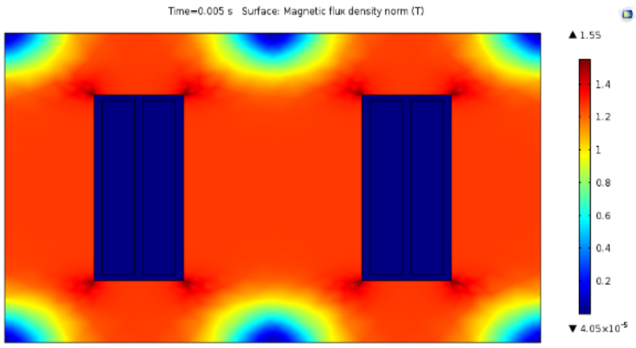

Figure 5. The flux density distribution the transformer core with GOES core

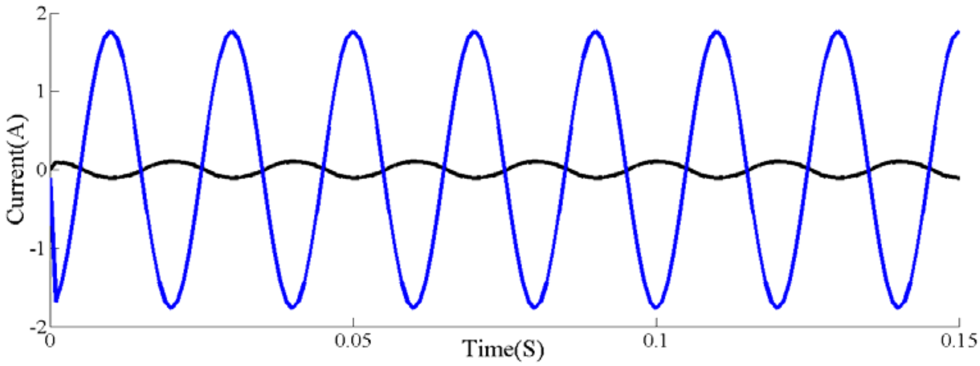

Figure 6. Current curves in the normal operating mode

In Figure 7 the hysteresis loop obtained from these state is shown with the hysteresis loop by experimental results. As is expected, considering the dynamic phenomena has led to the correct results from the hysteresis loop. Therefore, taking into account the hysteresis in a transformer model cause where it model more accurate physically. It is noteworthy that outputs analysis was carried are related to no-load state of transformer.

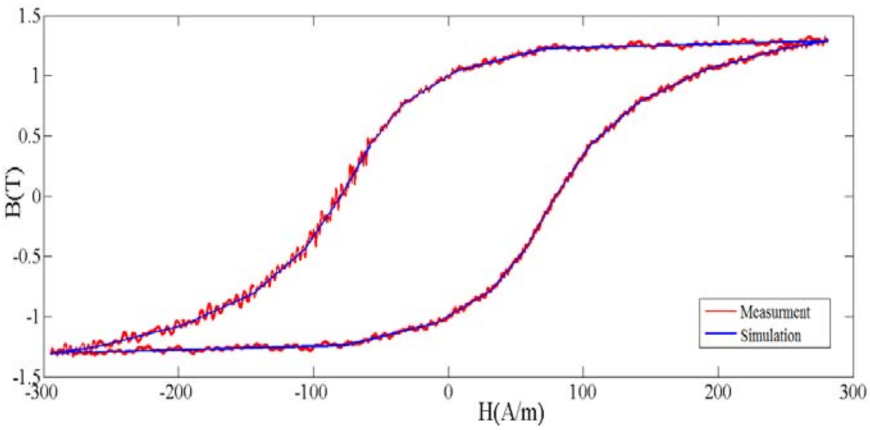

Figure 7. The hysteresis curve

By using the mentioned method the value of core losses calculated at normal operating point of transformer is shown in the Table 4.

Table 4. Transformer core losses with GOES materials

losses	value of losses (w)
hysteresis losses	0.4552 W
Eddy current losses	0.1298 W

Therefore the Jiles-Atherton method with good accuracy models the hysteresis loop. Correctness of results is expressed based on the correct choice of parameters the Jiles-Atherton method, so that changing any parameter will create a great impact on hysteresis loop. Therefore from this model could be used to simulate transformer with core from NGOES materials. In the event that the lines capacitance, transformer windings and/or Or load connected to the transformer is neutralizes The effect of inductive of transformer windings, ferroresonance occurred and causes the creation of unbalanced currents and large voltages in the transformer. When occurrence of ferroresonance the transformer core is entered magnetic saturation. This issue is shown in figure 8. Figures 9 and 10 shows transformer primary current curve and capacitor voltage during the occurrence of ferroresonance in transformer with iron core made of the material GOES, respectively. In this state, current and voltage curves get out from sinusoidal mode. Amplitude of the voltage and current is greatly increased. Voltage and current harmonics are causing warming and transformer insulation damage.

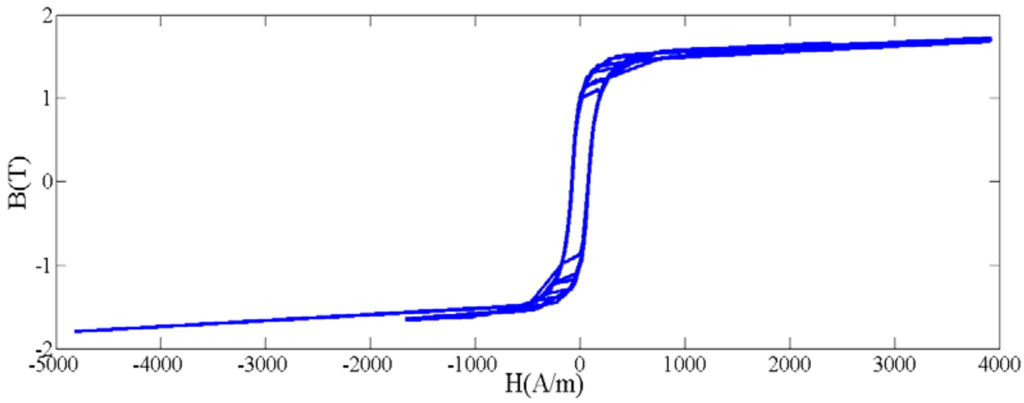

Figure 8. The hysteresis loop curve during the occurrence of Ferroresonance

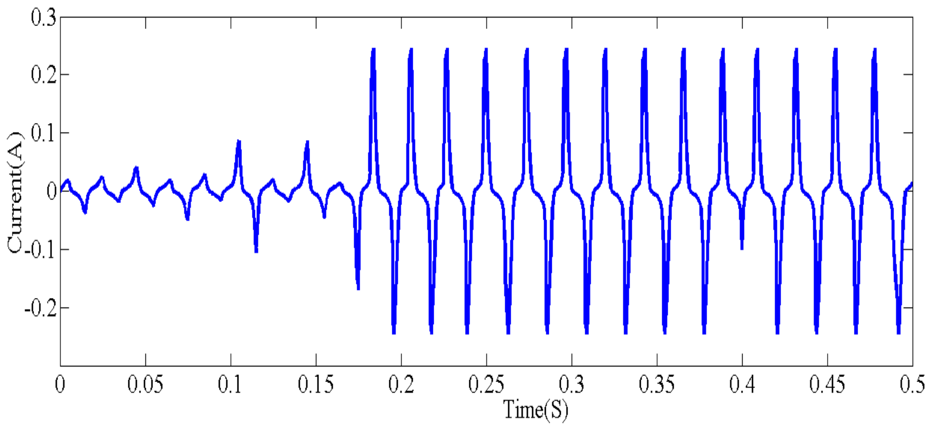

Figure 9. Transformer current waveform during the occurrence of Ferroresonance at the transformer core of GOES

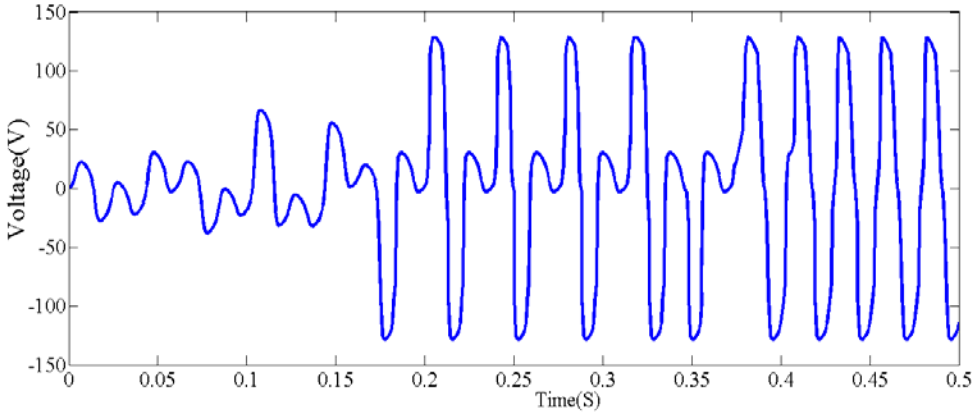

Figure 10. Transformer voltage waveform during the occurrence of ferroresonance at the transformer core of GOES

By obtaining the hysteresis loop when the occurrence of ferroresonance and by using of mentioned method, the values of hysteresis and eddy current losses generated are calculated in the transformer core. Losses calculated are shown in the table 5.

Table 5. The core losses during the occurrence of Ferroresonance

The type of losses	value of losses (w)
hysteresis losses	15.7229 W
Eddy current losses	0.1666 W

The results of the simulation show that during the occurrence of ferroresonance increases the core losses. In the event that ferroresonance not stop, with continuing ferroresonance also increases the core losses.

In the next phase, transformer was tested Similar to the transformer previous. With this difference that only the magnetic core these transformer is made up of NGOES. Table 6 shows J-A procedure parameters for core these type of transformer. The voltage and current curves are shown in the ferroresonance mode in Figures 11 and 12, respectively. As can be seen, ferroresonance occurred in the milder mode. Also, ferroresonance mode change is due to the change the iron core. Compare the results shows that the materials used in the transformer core have creat an essential role in the occurrence of the ferroresonance.

Table 6. The J-A method parameters for the transformer core with NGOES materials

parameters	value
M_s	1159000
a	177.69
k	359.99
α	0.1396
c	0.00035

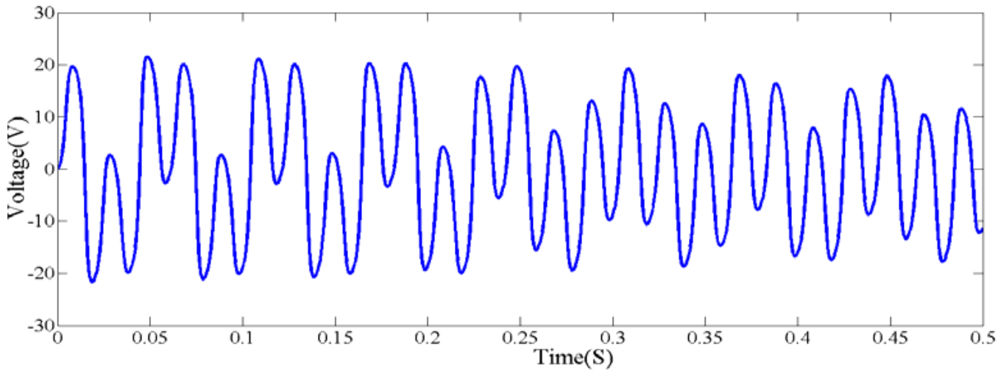

Figure 11. Transformer voltage waveform during the occurrence of ferroresonance at the transformer core of NGOES

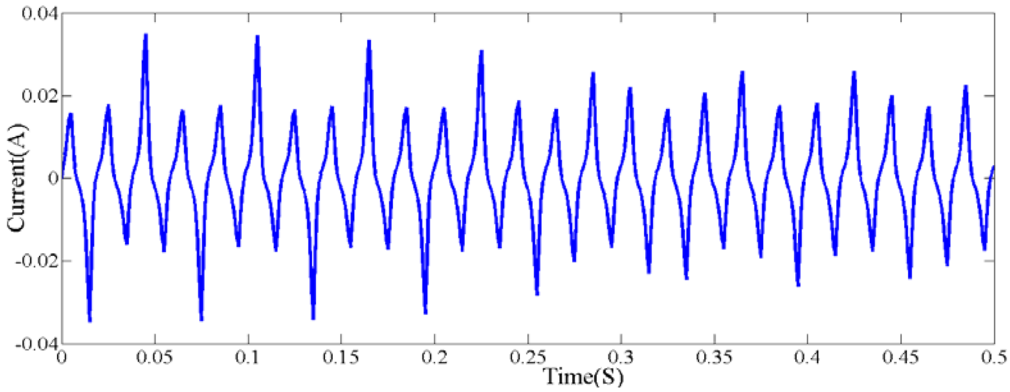

Figure 12. Transformer current waveform during the occurrence of ferroresonance at the transformer core of NGOES

5. Conclusion

In this paper, using the finite element method is been investigated ferroresonance phenomenon in transformers. Contrary to previous research, a new approach is provided from review ferromagnetic materials used in the manufacture of transformer cores. From two types of magnetic materials GOES and NGOES is used in the single-phase transformer core. The following results were obtained by analyzing the ferroresonance phenomenon:

1. During occurrence of Ferroresonance the transformer core entered to the intensity magnetic saturation. Current and voltage get out of their normal operating mode and increases theirs amplitude. This increasing amplitude in the power transformers are causes creating the insulation failure and getting warmer of transformers.
2. Considering the magnetic hysteresis in the simulations is very necessary and important. Because the behavior of ferromagnetic materials used at the equipment core is reflected in magnetic hysteresis current.
3. The use of GOES material in the transformers core, unlike the lower core losses compared to NGOS material, the more deleterious effects show during occurrence of Ferroresonance. Ferroresonance in the transformers made of GOES material occurs with more intensity.

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