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Characterization of Electromagnetic Force of the Transformer during the Occurrence of a Ferroresonance Phenomenon by FEM

Alireza Shams[1], Ahmad Zare[2], Iman Rostami[3], Saeid Saberi Firoozi[4]

[1,4] Department of Electrical Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran, alirezashams.un@gmail.com
[2,3] Department of Electrical Engineering, islamic azad University, marvdasht, Iran

Abstract

Ferroresonance is a non-linear resonance which occurs between the capacitors of the cables, lines, and breakers and nonlinear inductance of the reactors and transformers when their core is saturated. Due to ferroresonance, it has been proved that large pulse currents pass through the transformer winding which seems to cause severe electromagnetic forces on the transformer windings. This research work is aimed at characterizing the transformer behavior at ferroresonance mode and calculation of the electromagnetic forces applied on the windings. To this end, a 2D FEM model of a 25KVA distribution transformer is developed. The accuracy of the FEM model is validated by comparing the FEM results and those obtained from the analytical methods. The results of this study are of great importance in the electrical and mechanical design of transformers and their windings.

Keywords: Ferroresonance phenomenon, Electromagnetic force, Finite element method (FEM), Distribution transformers
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1. Introduction

Transformers are one of the most expensive equipment on the network and their loss can be damaging to the network. Therefore, their protection and maintenance are important. Transformers experience different stresses during the operation period, including electrical, mechanical and thermal faults, some of which can increase the current and thereby increase the electromagnetic force on the winding. This increase in electromagnetic force causes damage such as bending of the winding, displacement and tearing of the winding. Therefore, the prediction of electromagnetic force in the design process of transmissions is necessary [1,2]. When the ferroresonance occurs, pulsed currents with the multi-amplitudes pass through the transformer's winding that can increase the electromagnetic force on the windings [3].

An overview of the investigations carried out in the field of the ferroresonance phenomenon, reveals that, in the case of the ferroresonance phenomenon, many of the past work is related to the investigation of the states of occurrence of ferroresonance in different network structures. In ref [4], to study ferroresonance occurred on a power autotransformer 13/275/400KV is presented and the practical results of the simulations were compared with the results. The reference [5] has analyzed the ferroresonac of the lightning strike and switching on a capacitor voltage transformer. In [6], the impact on the occurrence of capacitors opens circuit breaker Ferroresonance a voltage transformer is studied.

Different parameters of the network and transformer have a different effect on the ferroresonance phenomenon, which has been investigated in Ref. [7,8] and how these parameters are affected. Also, the effect of different components of the power system, initial conditions on the occurrence of ferroresonance and the impact of the residual on the stability of ferroresonance in references [9-11] have been studied. Different solutions have been proposed in order to prevent and reduce the ferroresonance in various systems. In [6], a detailed presentation of these methods is presented, as well as a method of protecting transformers against overvoltages due to ferroresonance using The active load is shown in reference [12]. In the references [13,14], the methods of decreasing the ferroresonance of the posts in the posts using the controller (UPFC) and the use of an inverters gas desorption reactor have been investigated. Reference [15,16] uses a two-dimensional transformer model to analyze the voltages caused by ferroresonance in the frequency domain and to analyze sub-harmonic volatility.

The study of past work shows that the major work is done in most areas of studying the occurrence of ferroresonance in different systems, the effect of different parameters and initial conditions, methods for reducing and eliminating ferroresonance and analyzing the signals of ferroresonance. The description and calculation of the forces involved in the transformer winding as a result of the ferroresonance phenomenon, in spite of the importance of discussing the electrical and mechanical design of the transformers, is a subject that has not been studied so far. This paper, by considering a two-dimensional model of a 20/0.4 kV transformer, 25 KVA, has investigated the amount of electromagnetic force applied to the transformer's winding under normal operating conditions and the occurrence of ferroresonance.

2. Ferroresonance

Ferroresonance or iron resonance is a nonlinear phenomenon that occurs between a network capacitor such as a cable capacitor, lines, a power key capacitor, and a nonlinear inductance of equipment such as transformers [17]. According to Fig. 1, this phenomenon occurs in a distribution network when the transformer is blunt or low, while in a point away from the single-phase cut-off or two-phase due to the burning of one of the Augmented Cut fuses.

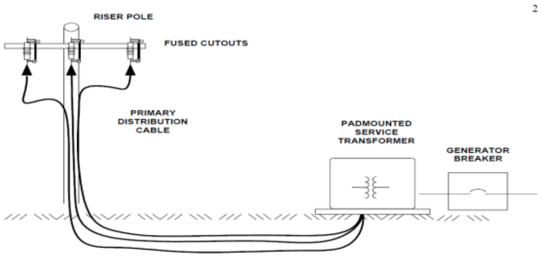

Fig. 1. The occurrence of ferroresonance in the distribution network

This phenomenon has several destructive effects on the network, including over voltage and current, distortion in voltage and current waveforms, noise generation, destruction of transformer insulation, and so on. The ferroresonance circuit consists of a serial connection of an alternating source V_s, a capacitor C, and a nonlinear inductance L, as shown in Fig. 2, which shows that the relations between the circuit elements are:

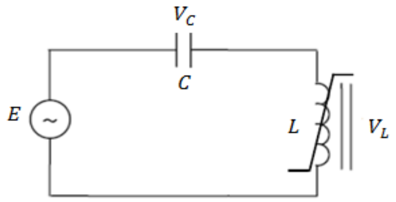

Fig. 2. The occurrence of ferroresonance in the distribution network

$$|E| = |L_m \omega I| - \left|\frac{I}{C\,\omega}\right| = \left(L_m \omega - \frac{1}{C\,\omega}\right)|I| \tag{1}$$

To determine the point of nonlinear circuit operation, we can deduce the curve of the voltage difference $E = V_L$-V_C, which is considered to be the magnetization curve of the kernel core $V_L = f(I)$. The capacitor voltage is plotted as V_C on the V-I coordinate with a coefficient of 1/ ω_c.

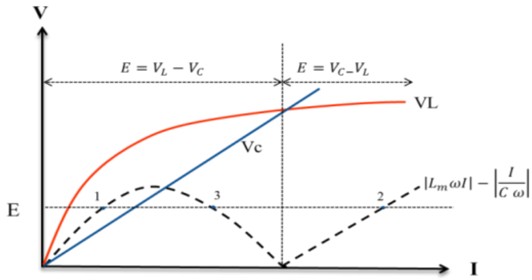

Fig. 3. The operation point of ferroresonance

The linear curve in Fig. 3 shows the difference between two self-acting and capacitive characteristics, which, according to the shape, yields three cross points as the working point (1, 2 and 3) for the circuit. Working Point 1 is a stable, non-ferromagnetic state point where the circuit is in self-ignition mode, and the working point 2 is a stable ferroresonance point where the circuit is in capacitive state and the operating point 3 is an unstable circuit operating the circuit. In three-phase networks, the ferroresonance events occur more in the 10-35 KV distribution networks with transducers fed through the cable [18]. In this case, as shown in Fig. 4, when the three-phase keys do not function correctly, the current may pass through the primary winding and the capacitor between the circuit lines, which results in the formation of a fog-viscosity circuit.

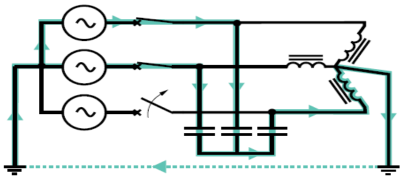

Fig. 4. The occurrence of ferroresonance in a three-phase network

3. Electromagnetic Forces

The electromagnetic force is produced by the interaction between the current and magnetic field in a winding. As shown in Fig. 5, the magnetic flux density vector has two radial and axial components, which the radial components are only stronger at the top and bottom ends of the windings. These radial and axial fluxes distribution, lead the resultant electromagnetic force to have two components. Based on the Ampère's force low, if two wires carry current in the same direction, the force between them is attractive and for the opposite direction currents, the force is repulsive. So, the forces between each winding loops are attractive but the force between the two HV and LV windings which are carrying current in the opposite direction is repulsive. Hence, the acting radial forces on the outer winding of the transformer are tensional and trying to rupture the winding conductors, but the inner winding of the transformer experiences the radially compressive forces.

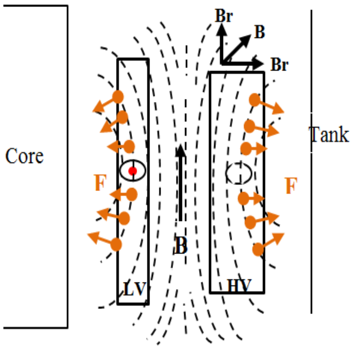

Fig. 5. Electromagnetic forces produced by the interaction between the windings current and leakage flux

A) Radial Forces

When a transformer exposes to a short circuit fault, axial leakage flux increases and produces radial forces which act outwards on the outer winding and leads the winding conductors to endure stretch stress [18] and also, cause the inner winding to experience a compressive stress [21], as shown in Fig.6. Different types of the deformations such as free buckling and forced buckling on the inner winding and hoop stress on the outer winding can be occurred due to the radial forces. Fig. 6 illustrates radial forces in a cylindrical winding and various types of radial deformations.

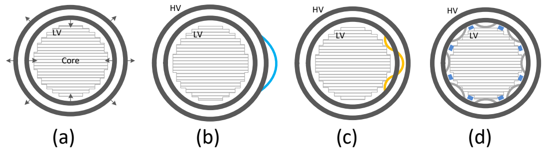

Fig. 6. Electromagnetic radial forces and windings radial deformation, a) Radial forces acting on LV and HV windings, b) HV winding deformation, c) LV winding free buckling, d) LV winding forced buckling

B) Axial Forces

The resultant axial forces due to the radial stray flux density, act on all windings and impose an axial displacement or lead the conductors to tilt or bend. The axial forces will be strengthened by Ampere-turn mismatch between the *LV* and *HV* windings if the windings are not situated symmetrically or the *HV* and *LV* windings height is not equal. Titling and bending of the conductors between the spacers are one of the most common deformations due to the axial forces [22]. Fig. 7 shows the winding axial forces and the resultant deformations.

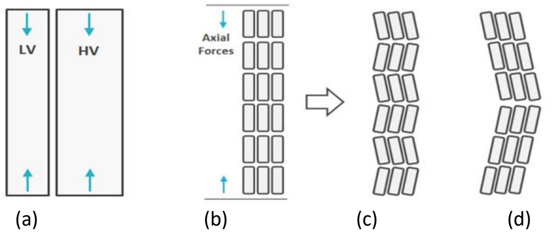

Fig. 7. Electromagnetic axial forces and windings axial deformations, a) Axial forces acting on the windings, b) Winding healthy state, c) Stand-wise tilting, d) Cable-wise tilting

4. Calculation of the Electromagnetic Forces

In this section, two methods are presented for the calculation of the electromagnetic forces: numerical method (FEM) and analytical method.

A) Numerical Method

The electromagnetic forces are calculated from the local magnetic flux density in the power transformers. When current flows into the windings of the transformer, the governing equation of the magnetic field is expressed as [5, 18]:

$$\nabla \times \frac{1}{\mu}(\nabla \times A) = J_s - \sigma \frac{\partial A}{\partial t} \qquad (2)$$
$$B = \nabla \times A$$

In equation (1), μ is magnetic permeability, A is magnetic vector potential, Js is the current density, σ is the conductivity and B is the flux density. According to Lorentz law, the electromagnetic force becomes [5]:

$$df = idl \times B \tag{3}$$

The radial and axial components of the magnetic flux density are as follows [18]:

$$\begin{aligned} B_r &= -\sigma \frac{\partial A_\phi}{\partial z} \\ B_\phi &= 0 \\ B_z &= \frac{1}{r}\sigma \frac{\partial A_\phi}{\partial r} \end{aligned} \tag{4}$$

Where B_r, B_ϕ, and B_z are directional components of the flux density in the cylindrical coordinate. So, the electromagnetic forces for the radial and axial directions can be computed by using [5]:

$$\begin{aligned} F &= \int_V J_\phi \times \left(B_r \hat{r} + B_z \hat{z} \right) dv = F_r \hat{r} + F_z \hat{z} \\ F_r &= B_z \times J_\phi \\ F_z &= B_r \times J_\phi \end{aligned} \tag{5}$$

As regard to the equation (5), the axial leakage flux density Bz, interacts with the current passing from the windings and generates a radial force Fr. As well, the interaction between the winding current and radial component of the leakage flux Br, generates the axial forces Fz.

B) Analytical Method

The analytical method for electromagnetic force calculation is completely linear and follows the ideal condition. In the normal condition of the transformer, the maximum value of the axial field density (Ba) occurs in the region between the windings and the minimum one is on the internal and external surfaces of the LV and HV windings. So, the radial force F_r (per unit of length) remains practically constant along the length of the windings and can be accurately calculated. The radial component of the force which is produced by the interaction between the instantaneous ampere-turns in each winding (NI) and the leakage field density, can be calculated as equations (6) and (7):

$$B_a = \frac{4\pi(NI)}{10^4}[T] \tag{6}$$

$$F_r = \frac{2\pi(NI)^2 D_m}{h \times 10^7}[N] \tag{7}$$

Where N is the number of turns, h is the length of the winding, D_m is the mean diameter of the winding and I is the current flowing in the transformer winding.

The analytical calculation of the axial force is not as simple as the radial force calculations. Therefore, there is a well-accepted approach for the above calculation that is the residual Ampere-turns method. According to this method, the calculation of axial force can be performed as follow [7]:

$$B_r = \frac{4\pi}{10^4} \times \frac{a(NI)}{2h_{eff}}[T] \tag{8}$$

$$F_a = \frac{2\pi a(NI)^2}{10^7} \times \frac{\pi D_m}{h_{eff}}[N] \tag{9}$$

Where a is the fractional difference in winding heights and h_{eff} is the effective length of the path of the radial fluxes that it differs for each arrangement of tapings [30, 32].

5. Case Study

Figures 8 and 9 illustrate a two-dimensional model of a 25KVA transformer with a Yz connection with its meshed structure, which is neglected for ease of simulation of protectors and insulators. In order to simulate the transformer using finite element software and obtaining results, the geometry and structure of the transformer including core and winding are first drawn. Then, to structure the structure, determine the initial conditions and conditions of loading. The software used in this paper is Flux 10.3 software to investigate the occurrence of ferroresonance.

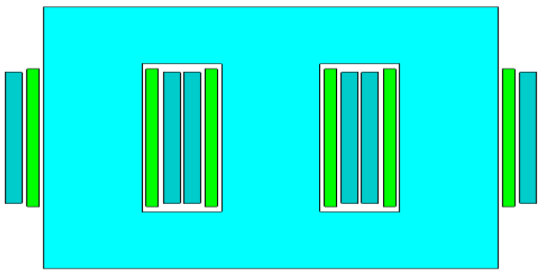

Fig. 8. Two-Dimensional Transformer Model

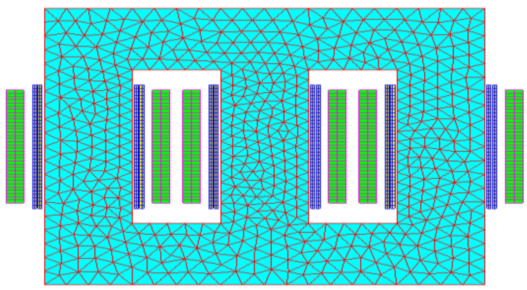

Fig. 9. Transformer Mesh Model

The characteristics of the transformer studied are shown in Table 1. The network used in this paper is derived from a distribution network with its medium-voltage maintainer cable, comprising three

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cable strings as shown in Fig. 4, where the cable information is shown in Table 2. Fig. In order to create annealing condition by placing a key on one of the high voltage winding phases and disconnecting it within 0.3 seconds, conditions for the occurrence of the ferroresonance phenomenon according to Fig. 4 are provided. In this case, the transformer is in No load mode. In Table 3, a comparison between the analytical results and the finite element is presented to verify the force in the normal conditions of normal operation, which indicates the correctness and accuracy of the model.

Table.1.
Transformer specifications

Item	*HV side*	*LV side*
Number of turns	5023	116
Rated phase voltage	20kv	400v
connection	Y	Z
The height of windings (mm)	178	195
The inner/outer diameter (mm)	142/181	102/123
Rated power	25 KVA	
frequency	50 Hz	
Core size (mm)	487/436	
Window size	98/242	
depth	97.5 mm	

Table.2.
Specifies the cable

Source voltage	***20 KV***
Reactance	0.148 Ω/km
Inductance	0.438 mH/km
Capacitance	0.207 µF/km

Table.3.
Comparison between the analytical results and the finite element

	Axial force HV (N)	*Radial force HV (N)*
Analytical method	0.0059	14
FEM method	0.0005	12.7

A) Distribution of force in normal conditions

When the transformer is in normal conditions, the flow of the windings is low compared to the ferroresonance mode. As a result, the electromagnetic force of the winding is less than that of the ferroresonance state. In this section, considering the two-dimensional transformer model, and by dividing the HV winding, one of the phases into several regions, investigates the distribution of force in normal conditions and during the winding. The magnetic flux density, the radial, and axial force distribution, respectively, are shown in Figures 10, 11 and 12 in the pre- ferroresonance state in normal and stable transformer working conditions, as shown below. Figs. 13 and 14 show the amount of force applied to the transformer's winding in normal operating conditions and transient state. According to Fig. 11, it is concluded that the amount of this force in the center of the winding has the highest value, because the lines of flux in the center of the winding are axial. As we move from the center of the winding to the edges of the winding, the lines of the flux are closer to the radial position, which reduces the radial force. As shown in Fig. 11, this force is applied in a radial and positive direction, which causes the HV to open.

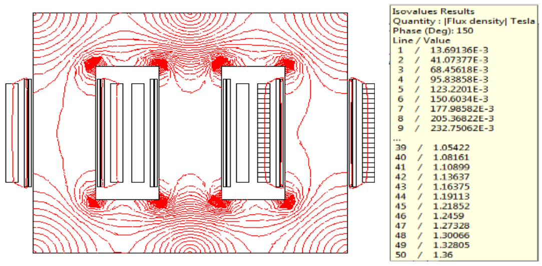

Fig. 10. Magnetic flux density in normal conditions

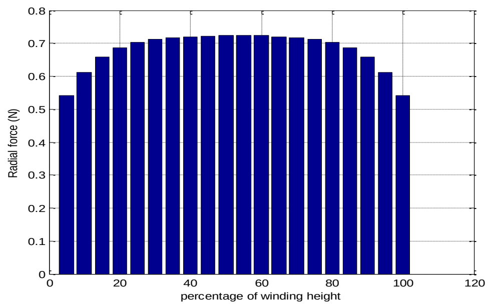

Fig. 11. Distribution of radial force on a winding in normal working conditions

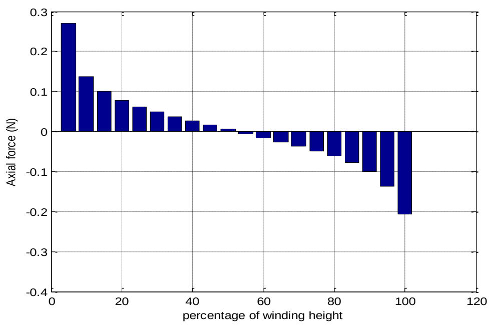

Fig. 12. Distribution of axial force on the winding in normal working conditions

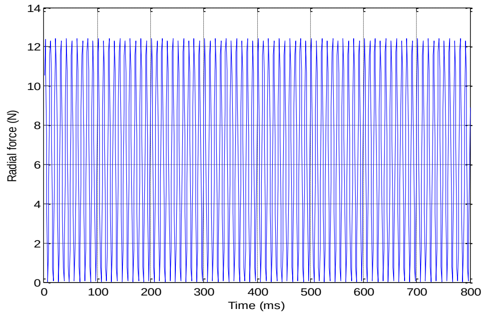

Fig. 13. Transient radial force in normal working conditions

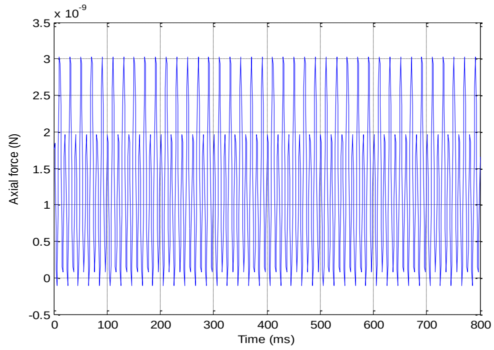

Fig. 14. transient axial force in normal working conditions

According to Fig. 12, it follows that the axial force in the center of the winding is small and gradually moving towards the edges of the winding reaches its maximum value. The reason for this is that the lines of flux on the edges of the winding are radially and in the center of the winding Axial form. In the normal state, the value of this axial force is close to zero, and the reason that half of the positive-power and the other half have a negative force is due to the fact that for the radial component of the flux in the two edges of the coil, they are opposite to each other and compress the coil It turns out.

Figures 13 and 14 show the radial and axial dynamics of the winding on the winding, in Fig. 13, the maximum radial force is 12N, and Fig. 14 is the value of this force equal to zero.

B) Distribution of force in ferroresonance conditions

In order to investigate the electromagnetic force of the coil in the ferroresonance mode, assuming that the transformer is unloaded, the length of the cable is considered to be 600 meters, with a capacitance of 120 nF in this case, and at a moment of 0.3 seconds, one of the unloaded transformer phases cut off in order to appear at this maximum peak flow rate due ferroresonance.

When the transformer is fitted for this capacitance in the ferromagnetic mode, the overvoltage and pulse currents, as shown in Figures 15 and 16, appear on the transformer winding. With reference to Fig. 16, with the formation of a ferroresonance phenomenon, pulsed currents with a range of approximately three times the nominal current of the transformer pass through which transformer winding is affected by severe dynamic forces. Figures 17, 18, and 19 show the density of magnetic flux, radial force, and axial force during the occurrence of ferroresonance.

With respect to the values of Fig. 17, it is seen that in flux density, the flux density is increased in comparison with normal conditions.

The radial force in the ferroresonance mode is 18, in the worst case, according to Fig. 18, which is close to 200 N, which is large in comparison to the normal operating conditions of the transformer. This increase in power can cause severe damage to the primary socket of the transformer. According to Fig. 19, as shown, the amount of axial force in the ferroresonance state is also negligible, due to the fact that the axial component of the flux in the two halves of the winding has been modified to cause the resulting value to be zero.

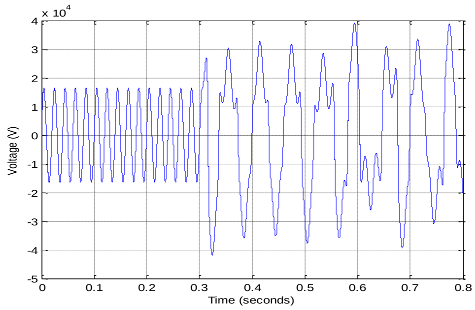

Fig. 15. phase voltage waveform at the time of ferroresonance inertia

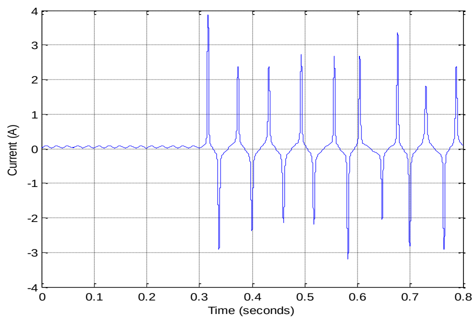

Fig. 16. The waveform of the winding current at the time of the ferroresonance of occurrence

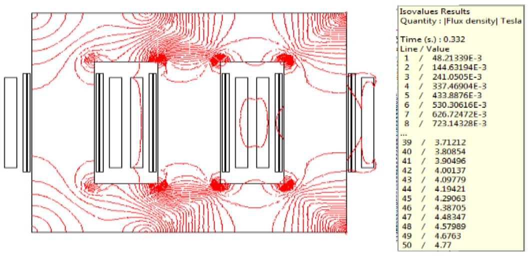

Fig. 17. Magnetic flux density during ferroresonance

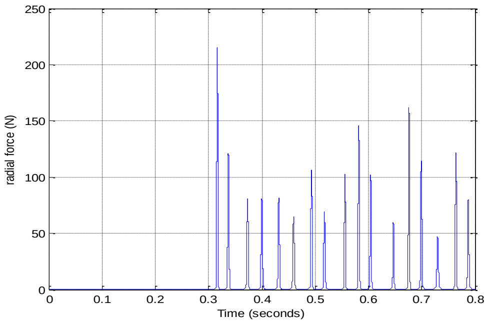

Fig. 18. Radial force during ferroresonance

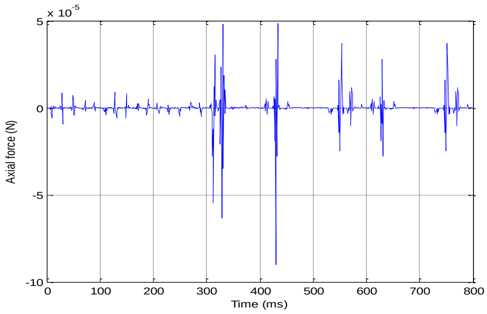

Fig. 19. axially force during ferroresonance

6. Conclusion

In this paper, the finite element method was used to investigate the electromagnetic force on the winding of a distribution transformer at the moment of the occurrence a ferroresonance phenomenon with pulsed currents. The results of the study show that radial forces have more than 10 times the normal conditions on transformer coils, which can cause severe damage to the primary winding of the transformer and, consequently, cause mechanical faults on the winding. Also, these currents can increase the axial force, but due to the fact that the axial force in the ridge of the axis is in opposite directions, the yield of this force is also zero in the ferroresonance state.

The proper understanding of the forces applied to transformer coils and their accurate description is a subject that is addressed in this paper and plays an important role in the electrical and mechanical design of the transformer and its winding.

References

[1] Steurer, Michael, and Klaus Fröhlich. "The impact of inrush currents on the mechanical stress of high voltage power transformer coils." Power Delivery, IEEE Transactions on 17.1, pp. 155-160, 2002.

[2] Ahn, Hyun-Mo, et al. "Finite-element analysis of short-circuit electromagnetic force in power transformer." Industry Applications, IEEE Transactions on 47.3, pp. 1267-1272, 2011.

[3] Bátora, Branislav, and Petr Toman. "Using of PSCAD Software for Simulation Ferroresonance Phenomenon in the Power System with the Three-phase Power Transformer." TRANSACTIONS ON ELECTRICAL ENGINEERING 102. 2013.

[4] Charalambous C, Wang ZD, Osborne M, Jarman P. Sensitivity studies on power transformer ferroresonance of a 400 kV double circuit. Gener Trans Distri, IET;2(2):159–66. 2008.

[5] field-Bakar AHA, Rahim NA, Zambri MKM. Analysis of lightning-caused ferroresonance in Capacitor Voltage Transformer (CVT). Electric Power Energy Syst;33:1536–41. 2011.

[6] Radmanesh H, Rostami M. Effect of circuit breaker shunt resistance on chaotic ferroresonance in voltage transformer. Adv Electric Comput Eng;10(3):71–7. 2010.

[7] Barbisio E, Bottauscio O, Chiampi M, Crotti G, Giordano D. Parameters affecting ferroresonance in LCR electric circuits. IEEE Trans Magn;44(6):870–3. 2008.

[8] Model for ferroresonance analysis of a transformer. IEEE Trans Power Deliv;23(3):1448–56. 2008.

[9] Milicevic Kruno, Emin Zia. Impact of initial conditions on the initiation of ferroresonance. Electric Power Energy Syst;31:146–52. 2009.

[10] Li Yunge, Shi Wei, Li Furong. Novel analytical solution to fundamental ferroresonance power frequency excitation characteristic. IEEE Trans Power Deliv;21(2):788–93. 2006

[11] Moses PS, Masoum MAS, Toliyat HA. Impacts of hysteresis and magnetic couplings on the stability domain of ferroresonance in asymmetric threephase three-leg transformers. IEEE Trans Energy Convers;26(2):581–92. 2011.

[12] Piasecki W, Florkowski M, Fulczyk M, Mahonen P, Nowak W. Mitigating ferroresonance in voltage transformers in ungrounded MV networks. IEEE Trans Power Deliv;22(4):2362–9. 2007.

[13] Lima L, Semlyen A, Iravani RM. Harmonic domain periodic steady-state modeling of power electronics apparatus: SVC and TCSC. IEEE Power Eng Rev:56. 2002.

[14] Tseng KH, Cheng PY. Mitigating 161 kV electromagnetic potential transformers' ferroresonance with damping reactors in a gas-insulated switchgear. Gener Trans Distrib – IET;5(4):479–88. 2011.

[15] Charalambous CA, Wang ZD, Jarman P, Sturgess JP. Frequency domain analysis of a power transformer experiencing sustained ferroresonance. Gener Trans Distrib – IET 2011;5(6):640–9.

[16] Kavasseri Rajesh G. Analysis of subharmonic oscillations in a ferroresonant circuit. Electric Power Energy Syst;28:207–14. 2005.

[17] Moses, Paul S., Mohammad AS Masoum, and Hamid Toliyat. "Impacts of hysteresis and magnetic couplings on the stability domain of ferroresonance in asymmetric three-

ISSN: 2251-9246
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phase three-leg transformers." Energy Conversion, IEEE Transactions on 26.2 581-592. (2011).

[18] Behjat, V., A. Shams, and V. Tamjidi. "Characterization of Power Transformer Electromagnetic Forces Affected by Winding Faults." Journal of Operation and Automation in Power Engineering 6.1 (2018): 40-49.

[19] Rasheed, K. "Finite element calculation of leakage reactance in distribution transformer wound core type using energy method." Journal of Engineering and Development 16, pp. 297-320. 2012.

[20] Bagheri, Mehdi, Mohammad Salay Naderi, and Trevor Blackburn. "Advanced transformer winding deformation diagnosis: moving from off-line to on-line."Dielectrics and Electrical Insulation, IEEE Transactions on 19.6, pp. 1860-1870. 2012.

[21] Kulkarni, Shrikrishna V., and S. A. Khaparde. Transformer engineering: design and practice. Vol. 25. CRC Press, 2004.

[22] De Azevedo, Ana C. "Investigation of transformer electromagnetic forces caused by external faults using FEM." Transmission & Distribution Conference and Exposition: Latin America, 2006. TDC'06. IEEE/PES. IEEE, 2006.