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Recognition and Location of Power Transformer Turn to Turn Fault by Analysis of Winding Imposed Force

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Abstract- *Turn to turn fault is one of the major internal failures in the power transformers that if it is not quickly detected, can be extended and led to a complete transformer breakdown. So, the diagnosis and location of the turn to turn fault of the power transformer, as one of the most important equipment in the power system, is the main objective of this paper. For this purpose, a detailed model of a three-phase transformer is presented by the finite element method (FEM) to investigate this fault in the different situations. Accordingly, the number of short-circuit turns as well as fault location, cause to generate the high forces between the short-circuit turns and the other healthy winding turns. Consequently, in this paper an appropriate method based on force analysis of winding turns for detecting, locating and determining fault severity is introduced.*

Keyword: Turn to turn fault, Recognition, location, imposed forces, FEM.

1. INTRODUCTION

Transformers are one of the most important and expensive basic equipment in the generation, transmission and distribution electricity power networks. In facts the transformer is the central part of any power system between the energy generation and the energy consumption point that their failures led to catastrophic failure of the electrical system network operation. Thus, the appropriate and continual performance of these equipment are great significance. The importance of the transformers failures is so high that, from far long ago and particularly in recent years, several studies have performed concerning modelling and analyze of different faults in transformers, ways to prevent failures' expansion and consequently, preventing from their exiting from the network [1-2].

Wide studies on different failures of power transformers, show that, about %70 of faults associated with this equipment is in relation with their inner faults [3-4]. Also, among internal faults to transformers, turn to turn fault within primary and secondary winding is from very probable cases, that is caused mainly by weakness to windings' insulation, high voltages and other cases [5-6]. Factors causing weakness of windings' insulation is usually based on extra voltages of lightning and switching, overload, and harmonic components. The nature of the turn to turn fault is so that, it could be considered as a secondary shorted circuit coil of a transformer. In such position, if number of turns with turn to turn fault is very low (e.g. one turn) a very high current may generate, with regard to its low impedance. Consequently, regarding ratio of primary coil turns number, to number of shorted turns coil, the primary current will have a slight change towards power supply. In deed in such condition, there may not generate some severe current changes and this fault is not identified in several traditional methods [7-8]. This is whilst, that the current in short circuit turns was very high and therefore, because of copper losses, the temperature of coil increases and provides the possibility of melting and expansion of the failure to adjacent coil turn and finally flawedness of the whole winding. Thus, the identification of this failure at initial stages is of great importance. In addition, the produce heat, mechanical force occurs also due to interaction between the magnetic field and the current of in short circuit turns, that leads to their deformity and displacement [9-10].

Since turn to turn failure is considered one of the most probable faults in transformers, several methods are presented to identify it in different references. Use of differential relay and also use of symmetry in leaking flux within transformer coils are the traditional methods to recognize this failure, that are used widely [11-12]. But

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anyhow if percent of short circuit turns number is low, these methods could not act properly regarding to low introduced current. One of the other wide used methods exploited nowadays too, is utilizing smart methods like neural network and wavelet transform in analyze of dissolved gases in transformer oil [13-14]. In these method, type and amount of dissolved gases in oil are measured, and based on that, the type of failure is recognized. In fact, these methods estimate inner context of the transformer and since it is possible that some undesired conditions including oil's aging, or other unclear cons with uncertain origination, occurs too. Thus, these methods are not much reliable and also use of them to determine fault location and especially in dry transformer is not applicable. One of the other methods is frequency response analysis (FRA), which is especially efficient in detecting mechanical defects of windings [15-17]. FRA is used to obtain the initial signature of a healthy transformer for future comparisons. Periodic checks are part of regular maintenance immediately after a major external event like a short circuit, transportation or relocation of the transformer, and recommissioning check. But the major drawbacks of this method are the offline nature and restricted use for unsymmetrical operations of transformers. Recently, the other methods, based on the symmetrical form of the magnetic flux distribution in the transformer windings, are used to detect the turn to turn fault in the transformer windings [18-21]. Although these methods can be considered as an appropriate criterion to achieve a protection algorithm, but during transformer energization, this algorithm was found to be not suited for turn-to turn faults detection. Also, during unsymmetrical conditions of transformer operation, these proposed techniques that based on the symmetrical distribution of flux, are not effective method.

However, the mentioned different schemes do not have sufficient sensitivity to detect low-level winding turn-to-turn faults. In failure of turn to turn short circuit with low turn number, the amount of three phase terminals current will have a very trivial change. But, the produced forces between coils, will experience impressing changes which, based on this, it is tried to find a solution to identify this failure in first stages. So, by means of the force sensors that are embedded between coils, one can to apply the proposed method in online conditions. In this paper, the proposed method can be used to achieve the more accurate, sensitive, and secure results versus the traditional methods based on the terminal currents. The advantages of the proposed method compared to the prior methods are the effective forces analysis, which can be used to evaluate the transient behavior of transformer in the different fault conditions.

With respect to a large application of transformers and also failures associated with them, having an accurate and detailed transformer modelling is very essential. So that, a detailed analysis of transformers performances is evaluated in various conditions. By certifying the transformer performance in ordinary conditions and also in faulty conditions, can be proposed a way to protect this equipment from unsustainability and damages. Therefore, the basic issue is to determine an accurate model for transformers, that all transformer's behavior is cover. In recent years, some studies to obtain accurate model to 3-phase transformers are performed in order to modelling their transient behavior. The saturation phenomenon of the transformer core is caused the complexity modelling and with respect to magnetic circuit structure, different models are offered to analyzing transformer's behavior. Use of an appropriate model, enabling consideration of magnetic structures saturation phenomenon in a transformer independently, has got an especial significance. The easiest method to modelling, is use of traditional equivalent circuit and the d-q modeling [22-24]. Usually in this method, the non-linear dynamical model of transformer based on non-linear inductances are not validated. Also, this modelling is established in balanced conditions, and therefore, unsymmetrical conditions do not take place properly in saturation conditions and in different failures. Another modelling method is the magnetic equivalent circuit method (MEC) or the reluctance network method [25]. This modelling is based on components modelling in electric and magnetic fields. Using MEC method, a geometrical model with saturation characteristic of individual magnetic circuit branches can be approximated by reluctance of magnetic paths depends on flux paths. Thus, this method, is capable to model an unsymmetrical condition of transformer including magnetic saturation. But use of this method in analyze of more accurate details and analyze of magnetic structures with more complex geometry will become very difficult. Also, prediction of flux paths in this method, is very important, and having key role, so that if not considered the probable flux path and directions, causing loss of method performance. In addition, more details to the MEC modelling, leads to much complexity in the model. In recent years, considering increasing improvements and high ability of computers to processing, numerical methods are preferred for modelling of electro-magnetic equipment widely [26]. One of these numerical methods is a worthy and detailed finite element method (FEM); so that, more and more accurate details of transformer could be investigated and analyzed. In fact, in different situations and conditions of transformer failures that power system's symmetry is not established, its nonlinear behavior can be evaluated by using this method.

In this article, with respect to above mentioned, by using finite element method, first an accurate model of a 400 KVA power transformer is presented with full details, and then in the mode of turn to turn fault in its winding is investigated. The number of shortened turns as well as short location in windings cause changing in the magnetic field distribution and also forces between short turn and other turn number of winding. Based on this, it is tried to find a solution to identify this failure in first stages.

2. ANALYSIS of FORCES BETWEEN TRANSFORMER WINDINGS

The base of inner forces between windings and transformer core are electromagnetic forces that are generated in reciprocal effect of magnetic field and coils current. In deed the electromagnetic forces among coils turn with each other, are obtained by the interaction between current density and leakage flux density. Also, the electromagnetic force between windings and core, are generated by the interaction between current density and linkage flux density. These electromagnetic forces can be calculated as [10]-[27]:

$$\vec{f} = \vec{J} \times \vec{B} \tag{1}$$

where B, J and f are vectors of the magnetic flux density, the current density and the force density respectively. With respect to horizontal and axial directions of the magnetic field distribution in transformer, the electromagnetic force is generated in two direction, horizontal (F_x) and axial (F_y) direction according to Fig. 1.

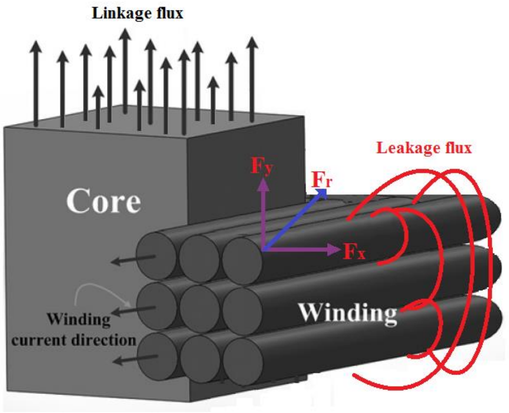


Fig.1 the distribution of electromagnetic force in two direction.

As can be seen in fig.1, the leakage flux can be flowed in axial and horizontal directions. Therefore, the horizontal electromagnetic force against the winding turns are produced from interaction of the axial leakage flux components and the coils current, and the axial electromagnetic forces against the winding turns are resulted from interaction of the horizontal leakage flux components and coils current. These force components are resulted as:

$$\overrightarrow{f_x} = \vec{J} \times \overrightarrow{B_y} \tag{2}$$

$$\overrightarrow{f_y} = \vec{J} \times \overrightarrow{B_x} \tag{3}$$

In normal conditions to transformer, that value of leaking fluxes is very limited, the produced axial and horizontal electromagnetic forces will be very trivial but in faulty conditions of transformer, amount and direction of leaking fluxes will have sensible changes. In this way, the produced forces are significant that impose severe tensions to winding and transformer core. As mentioned, in failure of turn to turn short circuit with low turn number, the amount of three phase terminals current will have a very trivial change, that in this situation, traditional protective devices are unable to remove this fault. But, the produced forces in this condition are significant and measurable. So, analyzing the forces components could recognized the fault and could find its location; so that, this phenomenon could be exploited in removing of turn to turn fault in this paper. In next section, transformer modelling with finite element method will be presented to evaluation of these forces.

3. 3-PHASE TRANSFORMER INITE ELEMENT MODELLING

Nowadays, numerical methods, are one of high powered methods with very high accuracy designation in electromagnetic systems. These methods allow the designer to predict machine behavior which can select the best and most optimal design without spending extra time and costs. From this perspective of transformer, FEM can predict the electric and magnetic fields behaviors on primary and secondary windings, and analyze their performances by performing Maxwell equations. To solve electromagnetic equations by FEM, throughout of problem area is dividing in to small finite areas (element) that each area is connected to adjacent areas. Then by entering Maxwell equations in to each of elements, the problem can be solved. The Maxwell equations in a transformer are resulted by use of Gauss's law for magnetic field, and Ampere law with respect to relationship between magnetic field and their resources as following:

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{4}$$

$$\nabla \times H = J + \varepsilon_0 \frac{\partial E}{\partial t} \tag{5}$$

where in these equations J is current density, E is electrical field intensity, B is the magnetic field density and H , is magnetic field intensity. For simplify, it is assumed that in ampere law, only current resource is available. Thus, with respect to proportionality of magnetic field intensity to flux density, the equation (5) is resulted as:

$$\nabla \times \frac{1}{\mu} B = J \qquad (6)$$

The relation of magnetic potential and electrical potential, in an electromagnetic problem, is obtained as following:

$$B = \nabla \times A \qquad (7)$$

$$\mathrm{E} + \frac{\partial A}{\partial t} = -\nabla\Phi \qquad (8)$$

By inserting relation (7) in relation (6) and by using Laplacian theorem of magnetic potential relation can be resulted as:

$$\frac{1}{\mu}[\nabla \times (\nabla \mathrm{A}) - \nabla^2 \mathrm{A}] = J \qquad (9)$$

And with respect to $(\nabla . \mathrm{A} = 0)$ the Poisson's equation for magnetic potential resulted as following:

$$\nabla^2 \mathrm{A} = -\mu J \qquad (10)$$

With respect to relation (8), current density could be achieved as following:

$$J = \sigma E = \sigma\left(-\nabla\Phi - \frac{\partial A}{\partial t}\right) \qquad (11)$$

where σ is the electrical conduction coefficient and by inserting relation (11) in relation (10), can be written:

$$\nabla^2 \mathrm{A} - \mu\sigma \frac{\partial A}{\partial t} = \mu\sigma\nabla\Phi = \mu J_a \qquad (12)$$

where $\sigma\nabla\Phi$ statement in this relation indicates the primary coil input source current, that is a alternated with parameter J_a for simplification.

Consequently, the resulted equation (12), is governing equation over a transformer with time variable field and with primary input current. By entering this equation in to all finite elements of transformer FEM model, the magnetic field distribution in whole transformer structure can be obtained. In this article, Maxwell software is used to calculate the resulted equation (12), and investigation of different modes of turn to turn fault in a sample transformer. Two dimensional model of 3-phase transformer structure and its electrical circuit connection are shown in Fig. 2 and 3 respectively.

Fig. 2 is shown that, the transformer core has 3 legs and the primary and secondary windings of each phase are placed over one leg. Fig. 3 shows the primary and secondary coils are connected in delta and star configurations, respectively. As it is observed in Fig.3, each of primary and secondary windings are consisted of a series of coils that in this way, one could evaluate properly the turn to turn fault in different locations. For instance, Figs. 2 and 3 are illustrated a turn to turn fault is occurred at the winding of phase A. In such condition, the short circuit turns, behave similar to shortened secondary winding.

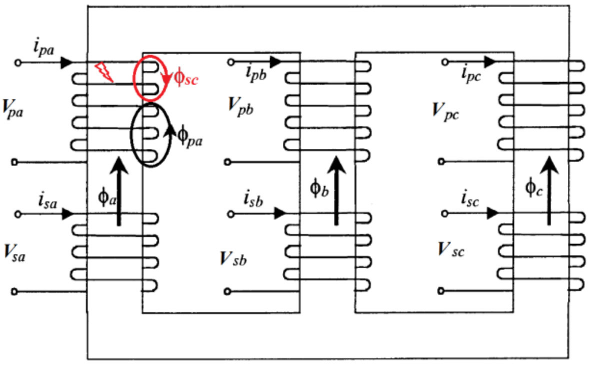


Fig. 2: Two-dimensional model of 3-phase transformer.

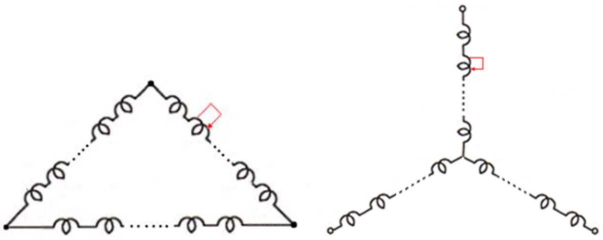


Fig.3: Δ and Y convections of 3-phase transformer.

4. FINITE ELEMENT METHOD RESULTS

In this section, the 2-D modeling of a 400 KVA transformer is used to evaluate turn to turn fault and its location. The nominal parameters and the dimensional specifications of transformer are introduced in Tables 1 and 2. A full transformer model was developed in the FEM software, and was simulated by setting the symmetry boundary. The size of the element is 10mm, and the primary side of the transformer is fed by a three-phase voltage source at full load condition.

Table 1. Electrical parameters of the transformer.

Quantity	Symbol	Values
Power	S	400 KVA
Frequency	f	50 Hz
Primary exciting voltage	V_1	15 KV
Secondary exciting voltage	V_2	400 V
Turn of primary coils	N_1	1440 turns

Turn of secondary coils	N_2	38 turns
Connection type	*Delta/Star*	-
Primary winding resistance	r_1	2 Ω
Secondary winding resistance	r_2	0.03 Ω

Table 2. Dimensions of transformer.

Quantity	**Symbol**	**Values**
Transformer Width	W	905 mm
Transformer Length	L	960 mm
Transformer Depth	D	187 mm
Yoke area	A_y	350 cm^2
legs area	A_l	350 cm^2
Primary coils area	a_1	62 mm^2
Secondary coils area	a_2	240 mm^2
Steel material	-	M_5

The plot mesh of the given transformer information, obtained by FEM, is displayed in Fig. 4. As it is observed, the density of meshes number is selected very high for high accuracy and acceptable calculations.

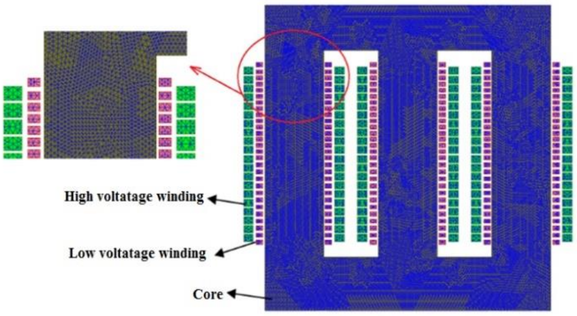


Fig. 4: The plot mesh of the given transformer.

In healthy conditions, three phase currents of the primary winding are shown in Fig. 5 and the detailed results of vector plot of magnetic flux density in different parts of core is displayed in Fig. 6 when the current in phase-b reaches its peak value at t=0.05sec (as shown in Fig. 5). As can be seen, the direction of the flux lines in limb b is different from the direction of limb a and limb c, because the current directions are different between phase-b and phase-a and b. As can be observed, the values of resulted parameters are in the nominal range and modelling.

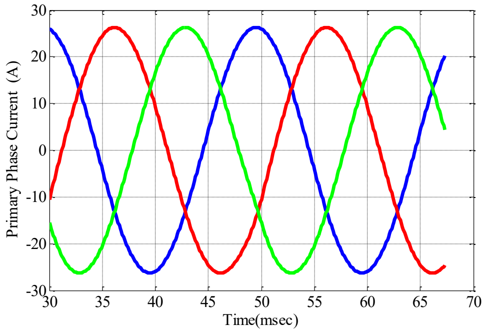


Fig. 5: three phase primary currents in healthy conditions.

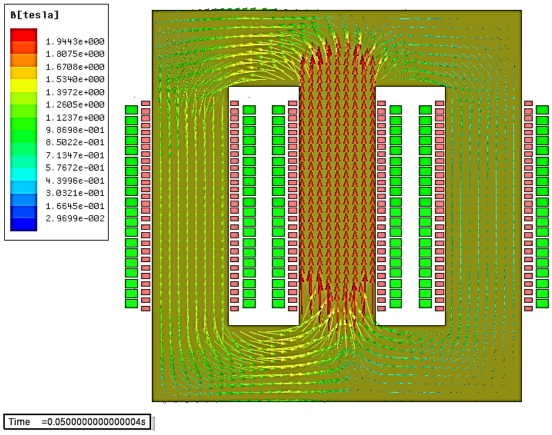
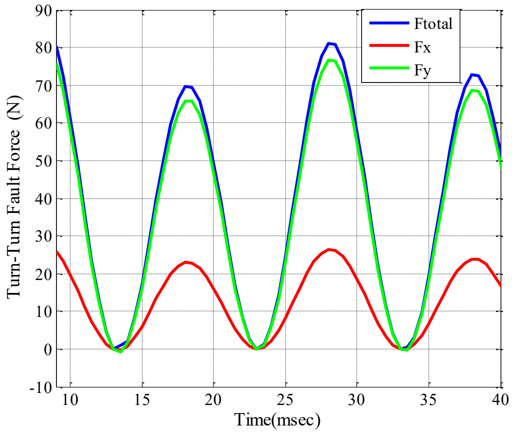
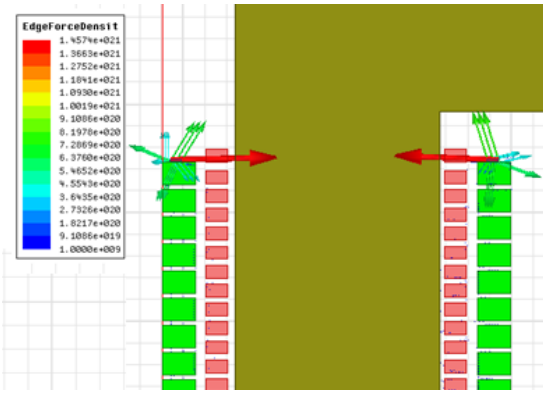


Fig. 6: the magnetic flux vectors of the transformer core in healthy conditions at the peak of the phase-c current.

In the presented modelling, access to various transformer turns of primary and secondary is possible at different locations. Thus, the turn to turn short circuit of windings in terms of number and location of fault will be implemented properly and with high accuracy. When the 20 turns fault at the beginning of phase A is occurred, the diagram of imposed forces to shortened coil turns and its two dimensional schematic are shown in Figs. 7-a and 7-b respectively. Imposed forces on short turn, push it in two axial and horizontal directions. As it is observed, imposed forces are much more in axial direction than horizontal direction and it means that, the possibility of coil displacement is much more in this direction.



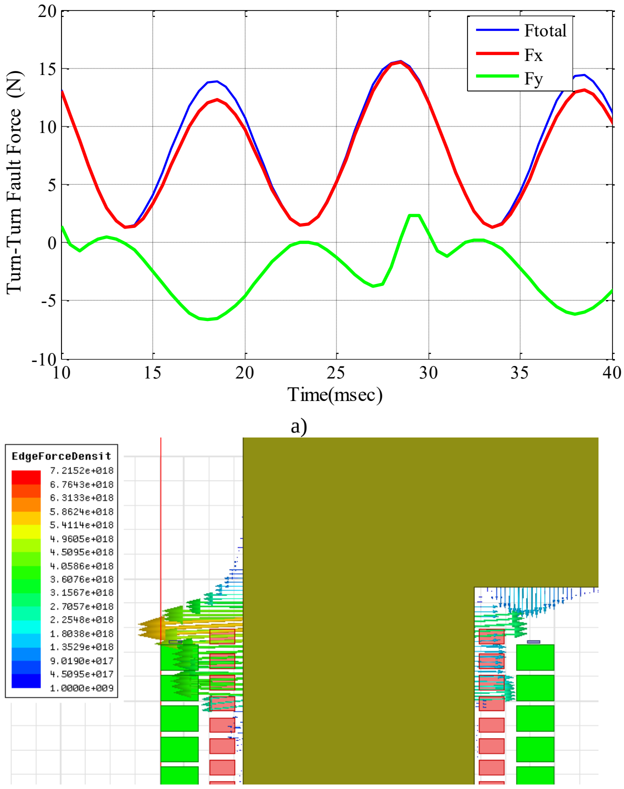
a)



b)

Figs. 7: a) the diagram and b) 2-D schematic of imposed forces to shortened coil turns in 20 turns fault.

In addition, the occurred fault, imposes forces to the transformer core and push it in two axial and horizontal directions as seen in Fig. 8. As can be seen, the imposed forces to the core in horizontal direction is much more than axial direction that is indeed contrary to imposed forces to short circuit turns. Also the amplitude of imposed force to the core, is more limited than imposed forces to shortened coil turns.

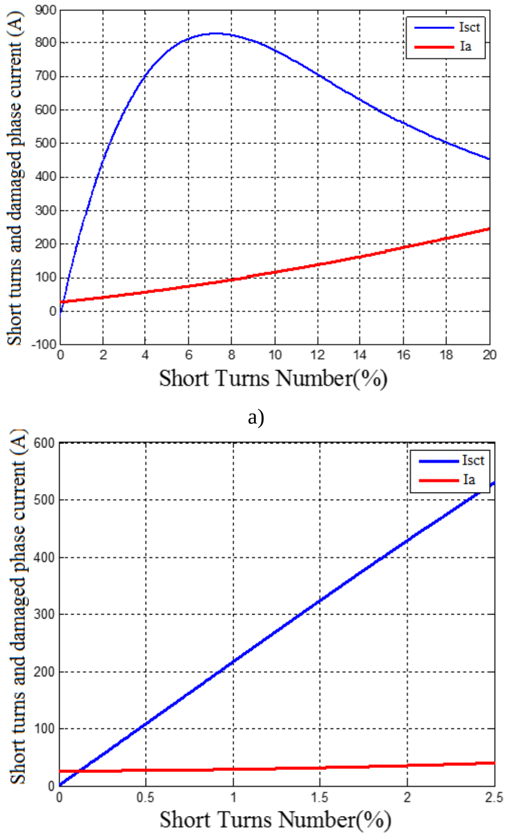


a)

b)

Figs. 8: a) the diagram and b) 2-D schematic of imposed forces to transformer core in 20 turns fault.

By increasing the number of turns of the turn to turn fault, the current amplitude in short turns (I_{sct}) and in the damaged phase (I_a) are increased as displayed in Fig. 9. This study for turn fault with number of turns from zero to 20 percent of rated turn, is simulated. As it is seen in Fig. 9, the input current amplitude of the damaged phase (I_a), has a little change for low turns number of turn to turn fault. But, the increasing rate of current amplitude of short circuit turns is very sensible and increases very much. This mode is magnified for zero to 2.5 percent of rated turn, in Fig. 9-b.

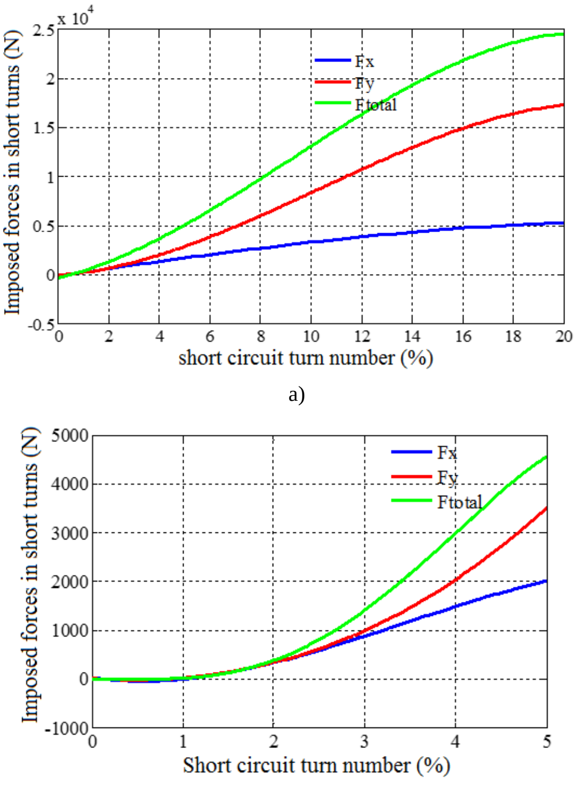


a)

b)

Fig. 9: short turns current (I_{sct}) and damaged phase current (I_a), with respect to a) zero to 20 percent and b) zero to 2.5 percent of rated turn.

In this case, the produced forces between windings and between core and coils, also will experience impressing changes. By increasing the number of turns of the turn to turn fault, the amplitude of imposed forces are increased. The imposed forces in short turns (F_{total}) and its component in two directions of horizontal axis (F_x) and vertical axis (F_y), with respect to the percent of turns number, are displayed in Fig. 10. The diagram of these forces, is magnified for zero to 5 percent of rated turn in Fig.10-b. As it is observed in this diagram, even for low percent of short turn number, the imposed forces are significant, and of course these forces are more towards perpendicular direction.



a)

b)

Fig. 10: The imposed forces in short turns with respect to a) zero to 20 percent and b) zero to 5 percent of rated turn.

In addition, for investigating the effect of change in fault location in diverse situations, the number of 20 turns fault in different locations of phase A is analyzed. In this investigation, the current amplitude of damaged phase and short circuit turns do not change for change in location of fault. But in these conditions, the total imposed forces to short circuit turns and its components in two directions of horizontal and vertical axis, change significantly. For this reason, the forces amplitude, for fault location from above phase column in %0 position till down of phase column in %100 position are resulted in Fig. 11. As can be considered, the imposed horizontal force is the least value at the beginning and end of phase column, and it increases with progress of short location to center of phase column, and it has highest value in the center. This condition, for the imposed axial force, is against horizontal axis, meaning that, at the beginning and end of phase column, has the highest value, and decreases with progress of short location to center, and finally it has the least value in than center. Thus, one could recognize the ring short failure location from these diagrams.

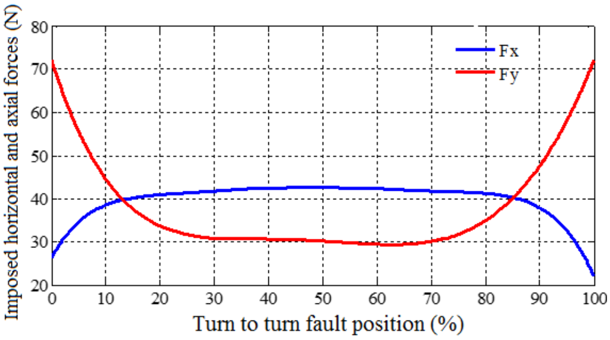


Fig. 11: imposed horizontal and axial forces, respect to fault position from above till down phase column position.

5. CONCLUSIONS

In this paper, a detailed dynamical model of a three phase transformer, using finite element method was presented. This model was very effective for modelling and analyzing of asymmetric faulty conditions such as turn to turn fault in a power transformer. Based on this modelling, the turn to turn fault with diverse turn number and in different locations of phase winding was assessed and analyzed. Finally, using the suitable analyze of generated forces occurred between windings turns, a practical approach was proposed to recognize and locate the turn to turn failure in its initial stages. So, by means of the force sensors that are embedded between coils, one can to apply the proposed method in online conditions. The advantages of the proposed method compared to the prior methods are the effective forces analysis, which can be used to evaluate the transient behavior of transformer in the different fault conditions.

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