Elasto-Plastic Analysis of the Active Support Part of a Shell-Type Power Transformers During a Short-Circuit

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Abstract

The design of Power Transformers is based on empirical knowledge and Elastic Theory of Mechanics of Materials. Due to the rise of materials' costs, nowadays the designers need to reduce the safety factors because they need to reduce the material used and their transportation cost. The short-circuit is the most expensive and common failures on Power Transformers. Based on a new geometry of the main frame for Shell type Power Transformer, this paper shows the results of a nonlinear dynamic simulation to study the behavior of main frame structure under a short-circuit forces. First, the short-circuit forces are calculated via traditional electrical equations. Then, using SolidWorks software, the simulation of short-circuit forces on main frame is presented. From the results of this study it can be concluded that the zones who exceeds the yield stress are mainly in interior side of main frame, specially next to the reinforcements.

Keywords

Short-circuit, Numerical Methods, Shell Type, Elasto-Plastic, Dynamic.

1. Introduction

Power Transformers are one of the most important and critical equipments in energy systems.
Nowadays, the market demands that transformers manufacturers and their customers increase the requirements of transformers mechanical and electrical properties. Due to the higher power, the materials price rise and the lowest profit, designers are forced to use small factors of safety.
Design based on empirical knowledge and Elastic Theory of Mechanics of Materials with larger factor of safety are no longer accepted. Today, with advanced numerical methods, e.g. Finite Elements Methods, it is possible make more complex simulations, e.g. magnetic leakage flux and short-circuit electromagnetic forces.
During a short-circuit, electromagnetic forces attain values that can make serious damage, or even destroy the transformer. As such, the basis of transformers structural design is to determinate the values of the forces during a short-circuit.
Thus, it's necessary for a Power Transformer, a software capable of showing the pattern forces for a short-circuit and their magnitude.
The literature about Power Transformer is almost based in 2D analysis for determinate the magnetic field or short-circuit forces acting on windings.[2][3][4] However, this methods aren't precise enough for Shell type due his complex geometry. Therefore, for Shell type transformer is necessary to use 3D methods. [5][6]
Other aspect is the similarity between short-circuit forces and impact forces, where the high velocities of forces cause different reactions of material according with variation of deformation and inertia. Thus, the dynamic behavior of the transformer has to be studied in order to calculate the stresses and displacements resulted by the short-circuit forces.
In this paper, the FEM in SolidWorks software is used to study the elasto-plastic response of four different steel alloys under dynamic short-circuit forces on a new geometry of main frame for Shell Type Power Transformers.[7]
The optimization of main frame, based on material and form, allows to attain a lighter structure and than a less cost for material and transportation of Power Transformer.

2. Short-Circuit

The most expensive and common failures on Power Transformers are caused by insulation and material.[8] This failures create short-circuits and all the structure of the transformer is affected by the severity of this event.
Stress resulting by the short-circuit can be mechanical or thermal. According [9] a Power Transformer is more

subject to mechanical stress due higher currents while Distribution Transformers are more subject to thermal stresses.
Between various types of short-circuit, the three-phase is the less frequent but it's the most dangerous for the transformer. Thus, the design of transformer is made for withstand to three-phase short-circuit.[10]
Between two types of Power Transformer, Core and Shell, is the second who present better capacity to withstand short-circuit forces [11]
Electromagnetic forces in pancake coils are 23% less than concentric coils [12].

3. Electromagnetic Force

Windings and main frame must be designed to withstand electromagnetic forces during a short-circuit.
Electromagnetic forces are proportional to electric current squared and magnetic field, and the direction of the force is perpendicular to the plane of the above vectors.
The pattern of the magnetic field depends on the geometry of transformer and the impermeability of the materials.
The electromagnetic force is expressed by the equation [13]:

$$F(t) = F_{\max}\left(\frac{1}{2} + e^{\frac{-2t}{\tau}} - 2e^{\frac{-t}{\tau}} \times \cos(\omega t) + \frac{1}{2}\cos(2\omega t)\right) \quad (1)$$

In this paper we studied a Shell Type Transformer, in which it's necessary make a 3D simulation to obtain the pattern of the magnetic field.
In Shell Type Transformer, the electromagnetic forces acts perpendicularly to the pancake coil (Fig. 2).[11]

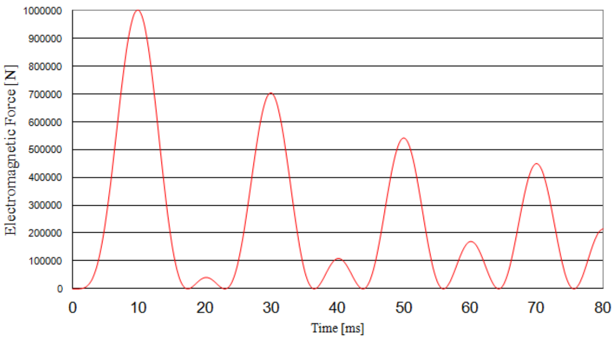

Fig. 1. Short-circuit force

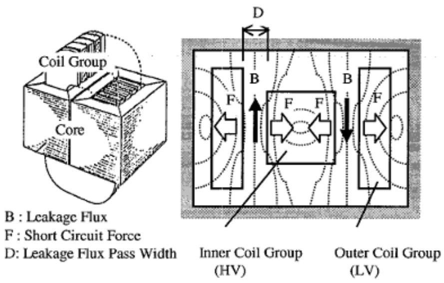

Fig. 2. Short-circuit forces of Shell Type Transformer [11]

4. Model

A. New Geometry

This paper presents a new geometry of the main frame of shell type transformer. In reference [7] this geometry and others were tested using static tests, and this geometry had the best results.
This structure is constituted by sheets steel and assembled by welding, and so it´s very difficult to simulate this last parameter. Therefore, for trust on results, the models were built on a scale in order to compare the experimental results with the simulation.

Fig. 3. Experimental Main frame

B. Materials

In this project, four different steels were analyzed, that can be divided in two types, S275 and S355 are structural steels, whereas Weldox 700 and Imex 700 are high strength steels.
The Fig. 4 illustrates the mechanical characteristics of the four steels alloys used in this study. The perpendicular and parallel are the directions of laminations for each specimen used in tensile testing.

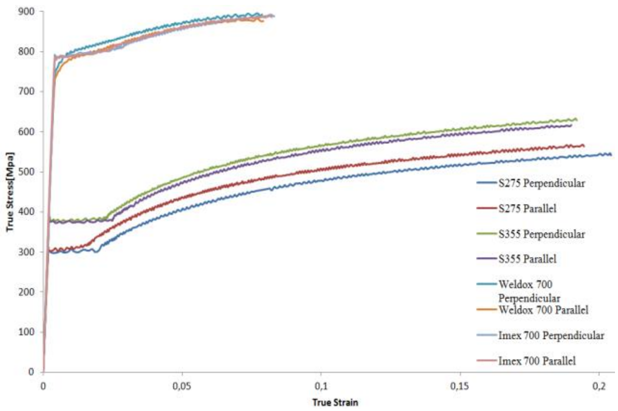

Fig. 4. True stress-strain curve

C. Nonlinear Studies

In the nonlinear dynamic analysis of the shell main frame the SolidWorks Simulation software was used, and the equilibrium equations at the time step are:

$$[M]^{t+\Delta t}\{U''\}^{(i)} + [C]^{t+\Delta t}\{U'\}^{(i)} + {}^{t+\Delta t}[K]^{(i)\,t+\Delta t}[\Delta U]^{(i)} = \\ = {}^{t+\Delta t}\{R\} - {}^{t+\Delta t}\{F\}^{(i-1)} \tag{2}$$

Where:

$[M]$ - Mass matrix of the system;

$[C]$ - Damping matrix of the system;

${}^{t+\Delta t}[K]^{(i)}$ - Stiffness matrix of the system;

${}^{t+\Delta t}\{R\}$ - Vector of internally applied nodal loads;

${}^{t+\Delta t}\{F\}^{(i-1)}$ - Vector of internally generated nodal forces at iteration (i-1);

${}^{t+\Delta t}[\Delta U]^{(i)}$ - Vector of incremental nodal displacements at iteration (i);

${}^{t+\Delta t}\{U\}^{(i)}$ - Vector of total displacements at iteration (i);

${}^{t+\Delta t}\{U''\}^{(i)}$ - Vector of total velocities at iteration (i);

${}^{t+\Delta t}\{U''\}^{(i)}$ - Vector of total accelerations at iteration (i).

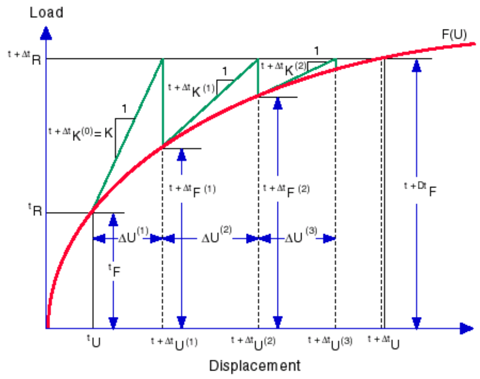

Fig. 5. Newton-Raphson Method

The Newton Raphson Method was the iterative method used to solve nonlinear equations. In this method, the tangential stiffness matrix is calculated at each iteration as shown in Fig. 5.

The materials are considered isotropy, that means that steel properties are uniformity in all orientations. However, as seen previously in Fig. 4, the curve of S355, Imex 700 and Weldox 700 are very similar for parallel and perpendicular directions.

5. Computer results

In simulations was used a quarter of the model for make the simulation simpler and hence faster.

The results from computer simulations are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9. They show the stress values for each of the four steels under short-circuit force in the same zone of the structure, next to the reinforcement (Fig. 10).

It shows the variation of stress for parallel and perpendicular directions of lamination, and also the variation of the short-circuit force for the first 80 milliseconds.

The curve of stress is very different from curve of short-circuit force when the small peaks occurs, on 20 or 40 milliseconds for example. This happens in all materials but it´s more significant on S275 and S355.

In the first peak of short-circuit all materials reach the plastic domain but S275 and S355 reach more times during 80 ms.

The Imex 700 and Weldox 700 curves are more smooth than others, this can be explain by permanent deformation on main frame.

Weldox 700 and Imex 700 are high strength steel and so they can resist to short-circuit force without reach plastic zone. Thus, this two materials can resist without or with very small permanent deformation.

However, the most of structure don't reach the yield stress. One of the solutions for optimization of structure of the main frame can be different thicknesses or materials for each sheet.

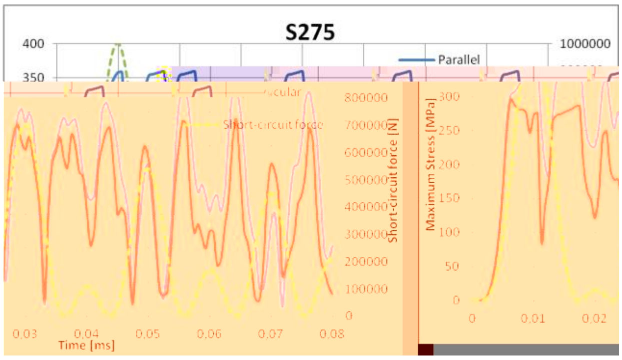

Fig. 6. Maximum Stress for Steel S275

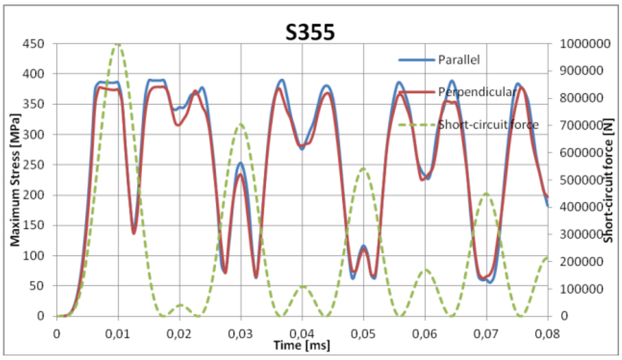

Fig. 7. Maximum Stress for Steel S355

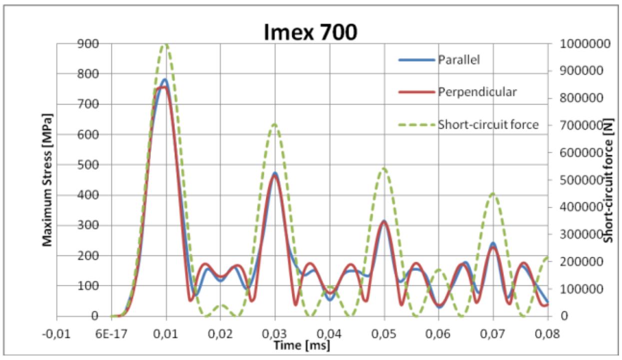

Fig. 8. Maximum Stress for Steel IMEX 700

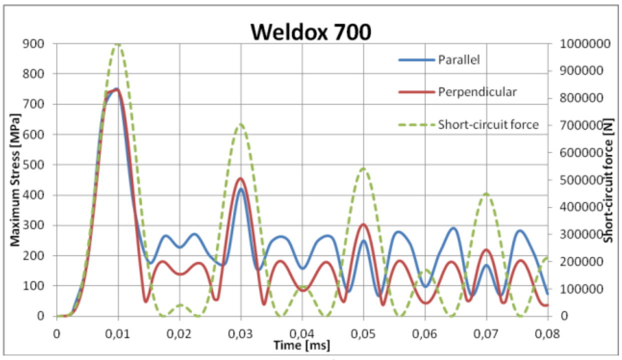

Fig. 9. Maximum Stress for Steel Weldox 700

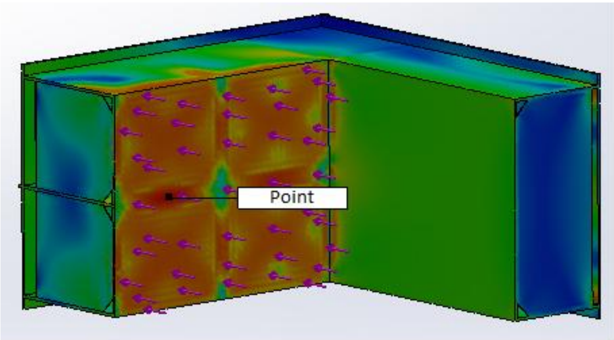

Fig. 10. Maximum stress next to reinforcements

6. Conclusion

This paper has presented a dynamic studied using Finite Element Method to obtain and analyze the behavior of a new geometry for main frame of Shell-Type Power Transformers

During a short-circuit, the electromagnetic forces reach several of tons only in a few milliseconds. The force act so fast that the material don't react with the same way as in a static situation. Therefore, it was necessary consider the dynamic behavior of structures subject to dynamic forces such as short-circuit.

A new geometry for main frame of Shell Type Power Transformer was modeled using finite element method and the short-circuit force on different steels were studied. In this study the effect of dynamic forces are considered and the analysis results indicate that the main zones in main frame affected for short-circuit are in interior side of yoke.

The results indicate that using Imex 700 or Weldox 700 the area above the yield stress is very small compared with S275 and S355.

However, there is many zones on main frame that they don't reach high stress, so they don't need to have the same thickness of the sheet or even be the same material.

It can be concluded that Weldox 700 and Imex 700 have better performance than S275 and S355, because they have less permanent deformation.

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