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# IMPACTS OF AMORPHOUS CORE TO REDUCE THE LOSSES IN DISTRIBUTION TRANSFORMER BASED ON TIME STEPPING FINITE ELEMENT METHOD

**A. Najafi  I. Iskender  B. Dokmetas**

*Department of Electrical and Electronic Engineering, Gazi University, Ankara, Turkey*
*najafi_atabak@yahoo.com, iresis@gazi.edu.tr, dok.burak@gmail.com*

**Abstract-** More than ever, electric utilities and industries today are searching for technologies that will reduce their operating costs and improve energy savings throughout their systems. New transmission and distribution technologies are now available to help utilities meet these goals. However, amorphous magnetic metal used for transformer cores does give the possibility of decrease core losses compared to standard core steel materials. In this paper magnetic fluxes and calculation of losses in 3-phase, 3-leg, 630 kVA, 34.5/0.4 kV distribution transformer with amorphous core have been studied. The computer-based simulation utilizing the two dimensional finite element methods (2-D FEM) as a tool for visualizing the magnetic flux and calculation of losses in amorphous core transformers is used. Finite Element Method (FEM) is one among popular numerical methods that is able to handle problem complexity in various forms.

**Keywords:** Distribution Transformer, Amorphous Core, Core Loss, Finite Element Method.

## I. INTRODUCTION

Transformers are an indispensable element in the transmission and distribution of electricity. We usually use thin sheets or strips of cold rolled, grain oriented silicon steel to build the transformer cores [1, 2]. In the traditional cores the sheets or strips are electrically separated by a thin coating of insulating material. In the amorphous alloy, the core losses are several times lower than in grain-oriented silicon steel. Thus, the amorphous core is more efficient for electromagnetic energy conversion devices than the traditional one.

First of all it is due to the smaller thickness then the silicon steel layers. As the amorphous alloys do not have crystalline anisotropy, the core manufacturer is able to anneal it in a desired domain pattern. Thus, an amorphous ribbon has the highest saturation induction along its length. Amorphous metal-based transformers have been used for more than 25 years. Initial interest in their use in electrical power distribution systems stemmed from the first oil shock in the mid-1970s, as improved energy efficiency in power distribution systems was increasingly needed [3].

The thickness of the steel layers with the insulation range from 0.2 to 0.5 mm, while the amorphous layer thickness is between 25 and 50 μm. Amorphous core have been used to improve the energy efficiency and reduction of worldwide $CO_2$ emission in distribution transformers.

In [4], a method presents to reduce the acoustic noises due to the vibration of electromagnetic cores. In [5], new high-permeability amorphous alloy ($Co_{64}Fe_4Ni_1Si_{15}B_{14}$) have been used as a current transformer for monitoring of a leakage current in surge arresters. HB1 amorphous material applied in [6] to reduce the Noise and vibration in fluxgate core. In [7], a shell type power transformers with amorphous alloy cores are used to investigate the withstanding ability and also noise level of this type of transformer under short circuit condition. The results of paper shows that the proposed prototype improved the withstanding ability of transformer under short circuit conditions. In [8], an amorphous core transformer consist of an air gap have been used to investigate the saturation and high-frequency pulse response of transformer. The results shows a small air gap improved the saturation characteristics of the amorphous core.

In this paper, to reduce the core losses in 630 kVA, 34.5/0.4 kV distribution transformer, 2605SA1 amorphous core have been used. The results of this paper shows that this type of amorphous core, significantly reduces the core losses in distribution transformers.

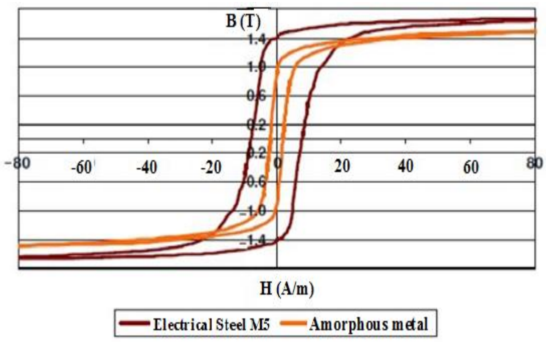



Figure 1. *B-H* curve of electrical steel and laminating type of 2605SA1 amorphous material

## II. ELECTROMAGNETIC ANALYSIS OF AMORPHOUS CORE DISTRIBUTION TRANSFORMER VIA 2-D TIME DOMAIN FINITE ELEMENT METHOD

Finite Element Method (FEM) was used for the magnetic field analysis. This technique will either resolve the differential equation and make the problem steady-state or approximate the equations in to a system of common differential equations and afterwards apply the scalar integrating method that provide by the Standard methods such as Euler's, Runge- Kutta methods, etc. A 3-phase, 630 kVA, 34.5/0.4 kV distribution transformer is studied in this paper.

Table 1 briefly illustrates the characteristics of the proposed transformer. In this paper, for laminations of the transformer amorphous type core with 25 μm thick are used. Figure 1 shows the *B-H* curve of the electrical steel and amorphous magnetic material. The soft magnetic material analyzed in the simulations is Metglas amorphous alloy 2605SA1 which has the saturation induction of 1.56 T. The core loss for SA1 is extremely low at about 0.29 W/kg at 1.35 T, however this value increases at higher frequencies but it is still lower than that for silicon steel. Amorphous metals are made of alloys which have no atomic order.

The lack of systematic structure has given them the additional name metallic glasses. Rapid cooling of molten metals prevents crystallization and leaves a vitrified solid with structure in the form of thin strips - a perfect energy saving substitute for CRGO. Table 2 summarized the specifications and difference between this material and M5 silicon steel that are used as input of the simulations in this study. The *P-B* curve provided by Metglas for SA1 and its regression curve is shown in Figure 2. In this figure, the blue curve is the *P-B* curve provided by Metglas and the red one is the regression curve.

Figure 3, demonstrated the two dimensional modeling of the distribution transformer under mesh operation. In order to increase accuracy of analysis, the number of mesh core and windings respectively is 125239, 31740 elements. FEM with utilize magnetic parameters and geometrical dimensions of the transformer applied to compute the magnetic-field distribution inside the transformer.

Table 1. Electrical parameters of studied transformer

| Quantity | Value | Unit |
|---|---|---|
| Primary rms voltage | 34.5 | KV |
| Secondary voltage | 0.4 | KV |
| Rated power | 630 | KVA |
| No. of primary winding turns | 2988 | …… |
| No. of secondary winding turns | 20 | …… |
| Primary winding resistance | 14.421 | ohm |
| Secondary winding resistance | 0.00081 | ohm |

The 0.2 ms time step has been chosen for all simulations of this paper. By using magnetic field in two dimensional model in Cartesian coordinate (*x*, *y*) [9]:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=\left(\sigma\frac{dA}{dt}\right)-j_0 \qquad (1)$$

The curl of the *B* is used to calculate the magnetic vector potential *A:*

$$B=\nabla\times A \qquad (2)$$

Table 2. Specifications of 2605SA1 amorphous core and M5 Steel

| Parties | Unit | Amorphous Metal | M5 Steel |
|---|---|---|---|
| Density | ($g/cm^3$) | 7.15 | 7.65 |
| Specific resistance | | 130.00 | 45.00 |
| Typical core loss (50 Hz, 1.42 Tesla) | Tesla | 1.56 | 2.03 |
| Thickness | mm | 25 μm | 0.3 mm |
| Space factor | | 0.82 | 0.97 |
| Brittleness | | Higher | Lower |
| Available form | | Ribbon foil (142.2 mm, 172.2 mm, 213.4 mm) | Sheet Roll |
| Annealing temperature | C | 360 | 810 |
| Annealing atmosphere | | Inert gas | Inert gas |
| Special annealing requirement | | Magnetic field annealing | ---- |

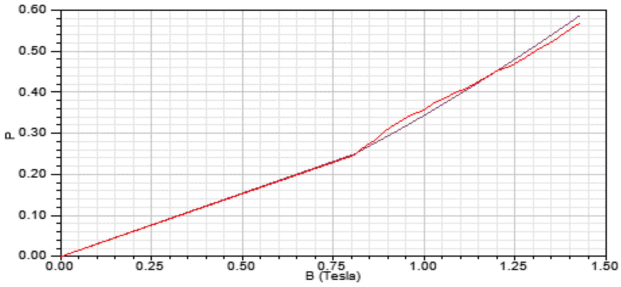



Figure 2. The *B-P* curve of laminating type of 2605SA1 amorphous material at 50 Hz and its regression curve

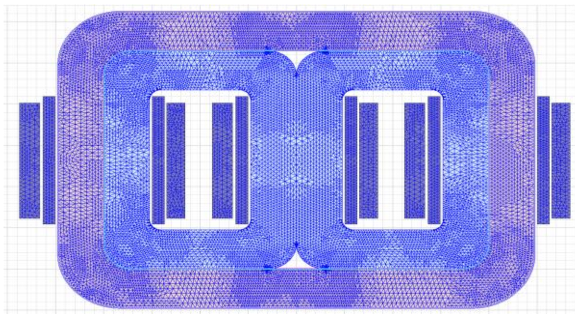


Figure 3. The mesh operation of studied transformer

To calculate the current from inrush current (startup) to the steady state condition, dynamic analysis of the transformer is required. So, it is necessary to model the voltage source as input. Figure 4 shows the circuit elements of the external circuit between the voltage source and the region under FEM analysis. The fundamental equation of the electric circuits is given by:

$$V_s=R_s i+L_s\frac{di}{dt} \qquad (3)$$

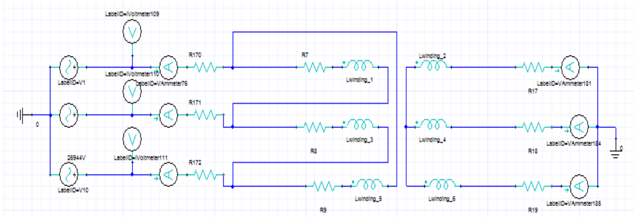


Figure 4. External Δ/Y connected of three-phase transformers

In this study, the magnetic flux inside the core and calculation on core loss are the main concerns. Figure 5 displayed the flux density distributions in a transformer core. It can be seen in this figure, the maximum flux density is 1.42 Tesla. This figure shows that, the right coils and left coils have the negative and positive value of the current, respectively. Hence, the magnetic flux from the right limb goes out and enters to the limb with negative value of current.

Nevertheless some small amount of the magnetic flux is exchanged between the side limbs and the middle one because the current in the middle limb is close to zero. One can also observe that in the middle limb there are both upward and downward fluxes. The reason is that the middle limb consists of two separated rings, which are connected to side limbs unlike a silicon steel transformer core, where each limb is a single structure. The primary current and voltage of studied transformer shows in Figure. 6. It can be seen in this fig that inrush current in amorphous core transformer after 500 ms reached to the nominal (steady state) value.

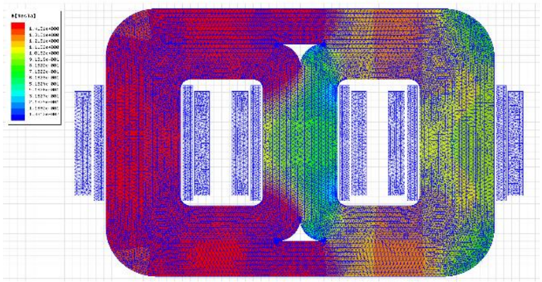
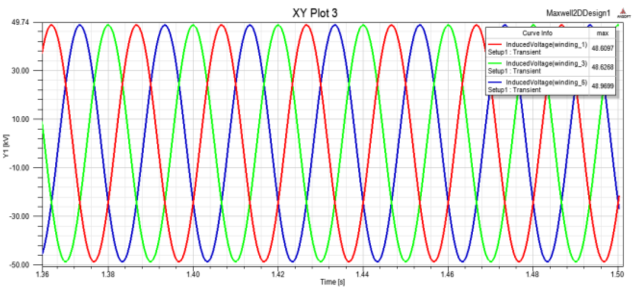
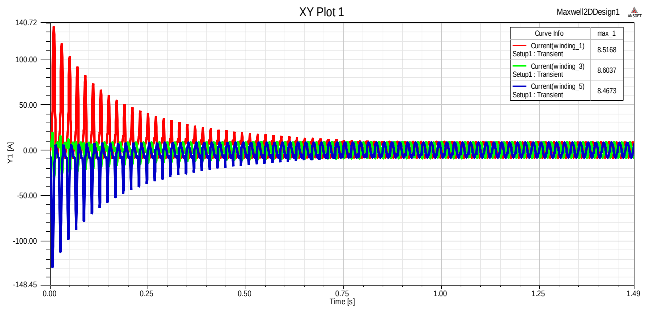


Figure 5. Distribution of magnetic field in amorphous core transformer




(a)




(b)

Figure 6. (a) Primary winding current, (b) Primary voltage of the studied transformer

## III. IMPACT OF AMORPHOUS CORE ON TRANSFORMER LOSSES

The no-load losses are essentially the power required to keep the core energized. These are commonly referred to as "core losses," and they exist whenever the unit is energized. No-load losses depend primarily upon the voltage and frequency, so under operational conditions they vary only slightly with system variations. They include losses due to magnetization of the core, dielectric losses in the insulation, and winding losses due to the flow of the exciting current and any circulating currents in parallel conductors. No-load losses can be calculated with the following mathematically expression [10, 11]:

$$P_T = P_{NL} + P_{LL} \quad (4)$$

where, $P_{NL}$ is the core losses because of the voltage excitation and $P_{LL}$ is load loss. In this paper, the impact of amorphous core especially on core loss have been investigated. The core losses divided to the hysteresis and eddy current losses. This losses can be given by Equations (5) and (6):

$$W_h = K_h f B_m^{1.6} \quad \text{(W/kg)} \quad (5)$$

$$W_e = K_e B_m{}^2 f^2 t^2 \quad \text{(W/kg)} \quad (6)$$

where, $K_e$ is Eddy current constant, $B_m$ is Maximum flux density (T), $t$ is Thickness of lamination strips, $K_h$ is the hysteresis constant, and $f$ is Frequency (Hz).

Table 2. Specifications of 2605SA1 amorphous core and M5 Steel

| Phase | Core type | Voltage (kV) | Frequency (Hz) | Capacity (kVA) | No-load loss (W) | Total loss (W) |
|---|---|---|---|---|---|---|
| 3P | Amorphous Steel | 34.5/0.4 | 50 | 630 | 401 | 5402.06 |
| 3P | M5 Steel | 34.5/0.4 | 50 | 630 | 1100 | 6130 |

Table 3. Reduce the losses using amorphous core

| Parties | Unit | Amorphous metal | M5 steel |
|---|---|---|---|
| Density | (g/cm$^3$) | 7.15 | 7.65 |
| Specific resistance | | 130.00 | 45.00 |
| Typical core loss (50 Hz, 1.42 Tesla) | Tesla | 1.56 | 2.03 |
| Thickness | mm | 25 µm | 0.3 mm |
| Space factor | | 0.82 | 0.97 |
| Brittleness | | higher | Lower |
| Available form | | Ribbon foil (142.2 mm, 172.2 mm, 213.4 mm) | Sheet Roll |
| Annealing temperature | C | 360 | 810 |
| Annealing atmosphere | | Inert gas | Inert Gas |
| Special annealing requirement | | Magnetic field annealing | ---- |

Figure 7. 2605SA1 amorphous core

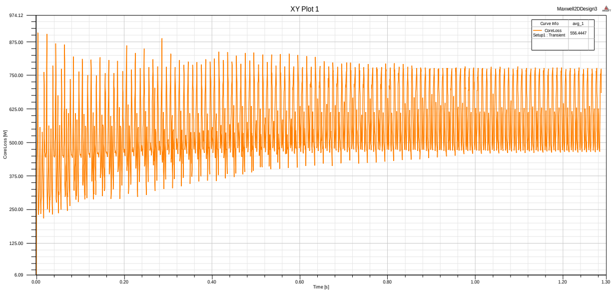



Figure 8. Core loss versus time for amorphous core

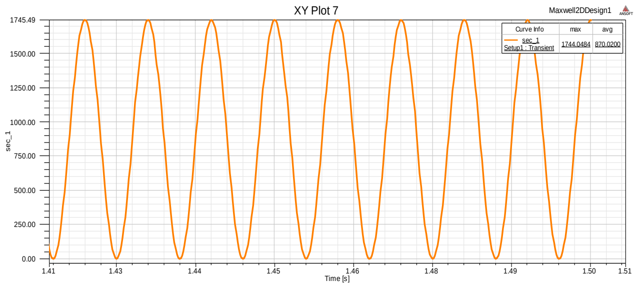



Figure 9. Winding loss for each phase of secondary side of studied transformer

Hysteresis losses are caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. These losses depend on the type of material used to build a core. Silicon steel has much lower hysteresis than normal steel but amorphous metal has much better performance than silicon steel.

Hysteresis losses are usually responsible for more than a half of total no-load losses (50% to 70%). This ratio was smaller in the past (due to the higher contribution of eddy current losses particularly in relatively thick and not laser treated sheets) Eddy current losses are caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat. These losses can be reduced by building the core from thin laminated sheets insulated from each other by a thin varnish layer to reduce eddy currents.

Eddy current losses nowadays usually account for 30% to 50% of total no-load losses. When assessing efforts in improving distribution transformer efficiency, the biggest progress has been achieved in mitigation of these losses.

In order to reducing the eddy losses in transformer core, higher resistivity and thinner lamination of core should be used. In this paper we used of 2605SA1 amorphous core with 25 μm thickness to reduce the core loss in distribution transformer. Figure 7 shows the amorphous core that is laminated to reduce the eddy current loss, therefore the effects of laminations on magnetic flux inside the core have to be considered. The instantaneous core loss and winding loss for each phase of secondary winding for the studied amorphous core transformer based on Finite element method is shown in Figures 8 and 9, respectively.

The average value of the core loss is 401 W which is clearly lower than the core loss in M5 type electrical steel core. The calculated core losses is summation of hysteresis and Eddy Current Losses. The results shown in Table 3. It can be observed in this table that transformer core loss about 63.5% reduced using the amorphous core in comparison with M5 silicon steel.

## IV. CONCLUSIONS

In this study, an amorphous core distribution transformer was designed. Finite element method have been used for visualizing the magnetic flux and calculation of losses in amorphous core transformers**.** The results were compared with classical steel core transformers that are used in existing electrical distribution systems. Core losses in the amorphous one are about 2.5 times lower ($P_{Fe}$=401 W) than that of the traditional one ($P_{Fe}$=1100 W). The results of simulation based on finite element method summarized in Table 3. This table indicates that amorphous core about 63.5% reduced the core loss in comparison with M5 silicon steel.

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## BIOGRAPHIES

**Atabak Najafi** received his M.Sc. degree in Electrical and Electronic Engineering from the University of Tehran, Tehran, Iran in 2009. He is currently pursuing the Ph.D. degree in Electrical Engineering at the Gazi University, Ankara, Turkey. His main interests are power electronics, power quality in power systems, digital signal processing and electrical machines.

**Ires Iskender** received his B.Sc. degree in Electrical Engineering from Gazi University, Ankara, Turkey in 1989. He received the M.Sc. and Ph.D. degrees in Electrical Engineering from Middle East Technical University, Ankara, Turkey in 1991 and 1996, respectively. From 1989 to 1996 he worked as a Research Assistant in Electrical and Electronics Engineering Department, Middle East Technical University. Since 1996 he has been with Department of Electrical Engineering, Gazi University, where currently he serves as a Professor. His interests include renewable energy sources, energy conversion systems, power electronics, fuzzy control, and electrical machines.

**Burak Dokmetas** received his B.Sc. degree in Electrical and Electronic Engineering in 2011, from the University of Inonu, Malatya, Turkey. He is currently pursuing the Master degree in Electrical Engineering at the University of Gazi, Ankara, Turkey. His main interests are power electronics, digital signal processing and Electrical Machines.