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Modeling and Optimization of Electric Furnace Transformer Unit

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Abstract: In this paper the modelling and optimization of a single-phase electric furnace transformer unit is considered. First, the distribution of the magnetic fluxes is analysed, using 3D finite element analysis. Then, some possibilities for optimization of the core dimensions to diminish the maximum flux density and the power losses are shown.

Keywords: Electric transformer, finite element analysis, optimization.

1 Introduction

The investigation of the production of the leading electroheating equipment manufacturing companies shows that the electric furnace transformer units (EFTU) are designed mostly in a way to include booster transformers [1, 2].

In some single-phase transformer units, the main and the booster transformers have separate independent magnetic cores [1, 2]. In this paper, a design of EFTU that has a common magnetic core for the main and the booster transformer is considered [1]. This kind of transformer unit has its application in supplying electric furnaces and is remarkable for its simple design and manufacturing technology, improved utilization of the space in the tank and easy attachment of the structural parts of the transformer.

Because of the high rated power of the EFTU, often local overheating occurs due to high concentration of losses in the magnetic cores. This overheating may cause deterioration of the cores and the structural parts. To avoid the overheating,

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specific measures must be taken to diminish the core temperature - special shape of the core cross-sections, cooling ducts, etc.

In this work, the distribution of the magnetic fluxes in the cores is analysed using 3D finite element analysis. Next, an optimization of the magnetic core and windings dimensions is performed, in order to diminish the iron and copper losses.

2 The EFTU Physical Model

On Figure 1, the magnetic circuit and the windings of the single-phase EFTU under consideration are shown. The 3D solid model of the iron cores and the windings are shown on Figure 2.

The main transformer is mounted on the middle core *a*. The middle core winding 1 is the high-voltage winding, connected to the power supply.

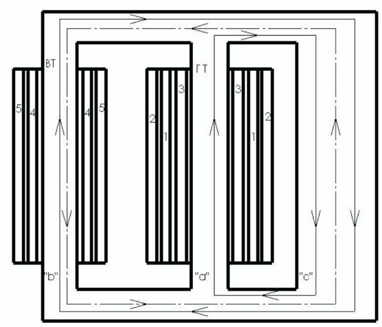

Fig. 1. Magnetic Circuit of a Single-Phase Electric Furnace Transformer Unit.

The innermost winding is the regulating winding 3. The low-voltage winding 2 has very high current (thousands of amperes) and very low number of turns, therefore it is the outermost winding. The booster transformer is mounted on the left core *b*. The innermost winding 4 is the regulating winding. It is powered by the regulating winding of the main transformer. There is possibility of reversing the regulating winding. The magnetic flux in the core of the booster transformer depends on the number of turns switched-on of the regulating winding 3. Besides, the direction of the magnetic flux in the booster transformer depends on the connection of the regulating winding 3.

The right magnetic core c has no windings and is called magnetic shunt core. It conducts the sum or the difference of the main and the booster transformer magnetic fluxes. Because the winding 2 of the main transformer and the winding 5 of the booster transformer are series connected, on their terminals the output voltage of the EFTU is obtained as

$$U_2 = U_{LV}^{MT} \pm U_{LV}^{BT} \tag{1}$$

The magnetic circuit of the EFTU is optimized with respect to the magnetic core construction, on the condition that regulating winding 3 is not reversed and the magnetic fluxes are always counter-directional in the right core.

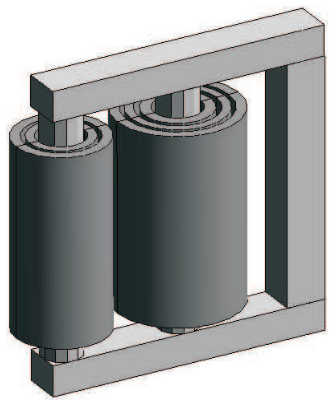

Fig. 2. 3D Solid Model of the Iron Cores and the Windings.

3 The Numerical Model

The transformer unit from Figures 1 and 2 has been modelled by 3D Finite Element Method, using the electromagnetic CAD system MagNet 6 [3].

There were two possibilities for the analysis:

1. Using time-harmonic solution,
2. Using full transient solution.

The full transient analysis is mathematically more correct, as the iron core has nonlinear BH characteristic. In this case, when the supply voltage is sinusoidal, the currents will be non-sinusoidal and this requires transient analysis. However, this analysis is very time-consuming as many time steps are necessary until the steady-state currents are reached (usually 20 time steps per period of the supply voltage).

The time-harmonic analysis is fully correct at linear materials. However, MagNet gives the possibility equivalent sinusoids (from energetic point of view) for all quantities to be used, and thus calculations with phasors are possible, accounting for the nonlinearity of the core material using BH curve and rms values. This diminishes the solution time considerably - to about 10' per analysis, and allows the optimization to be performed using genetic algorithm. The genetic algorithms, widely used nowadays for optimization, require computing of many variants of the device at different geometries and turn numbers, looking for the variant with minimum losses. This optimization can be speeded-up considerably using a cluster of computers and parallel computation of the objective functions.

Moreover, MagNet gives possibility to use excitation of the transformer under consideration by a voltage source, applied to the primary winding, at known load impedance. This gives the possibility to find the currents in the windings in a single nonlinear solution, without time-stepping.

These considerations led us to use a time-harmonic nonlinear solution using MagNet software, where the nonlinearity of the core material is accounted using its BH curve, and solving for the *rms* values.

The equations solved for time-harmonic solution are:

a) In conducting media

$$\Delta \times [(\sigma + j\omega\varepsilon)^{-1}\Delta \times \mathbf{H}] + j\omega\mu\mathbf{H} = 0 \tag{2}$$

b) In non-conducting media

$$\Delta[\mu(-\Delta\psi + \mathbf{H_s})] = 0 \tag{3}$$

where

$$\mathbf{H} = -\Delta\psi + \mathbf{H_s}, \tag{4}$$

with $\mathbf{H_s}$ being the field generated by the stranded coils.

In conducting media, the vector edge magnetic field $\mathbf{H}$ is solved for directly from (2). In non-conducting regions, the quantity that is solved for is the nodal scalar potential ψ from (3), and $\mathbf{H}$ is then obtained using (4).

The equations are solved at homogeneous Dirichlet boundary conditions, applied to the surface of the embracing the model airbox.

4 The Optimization Problem

The optimization of the transformer unit is done as minimization of the total losses - iron and winding losses. These losses determine the overheating and the reliability of the transformer unit and specify some important considerations in designing its cooling (providing cooling ducts, forced air- or water-cooling, etc).

As a first step in the minimization of the losses, only the dimensions of the iron core were varied. This allowed only a small reduction of the total losses - about 13%. Therefore, as a next step, the numbers of the turns were also included as variables. This allowed a bigger reduction of the losses.

The final optimization is performed using the total power loss (the sum of the Joule losses in the windings and the ferromagnetic core losses) as an objective function to be minimized.

Definition of the optimization problem:

Minimize Goal Function = Total losses (iron cores losses and copper winding losses).

Main restrictions:

1. Load current $I_2 > 1300$ A
2. $B_{\text{max}} < 1.8$ T

Optimization variables:

1. R_1 – left- and middle-core radiuses. Limits: $\pm 20\%$.
2. H_1 – height of horizontal top and bottom iron parts of the magnetic core. Limits: $\pm 50\%$.
3. w_4 – number of turns of the boost transformer control winding (left core, innermost winding) and the main transformer control winding (middle core, innermost winding): $w_3 = w_4$.
4. w_5 – number of turns of the booster transformer low-voltage winding (left core, outermost winding and the main transformer low-voltage winding (middle core, outermost winding): $w_2 = w_5$.
5. w_1 – number of turns of the main transformer high-voltage winding (middle core, middle winding).

Limits for all numbers of turns: $\pm 25\%$.

The parallel genetic algorithm [4] has been used on a cluster of 16 personal computers (Athlon XP 2500+ with 512 MB RAM). Two types of problems can be solved with this software:

1. Optimization problems (finding optimum using parallel GA).
2. Full discrete search in n-dimensional search space at given number of levels on each dimension – this is useful also for creating data for response surface methodology and training of neural networks.

The software uses specially developed high-level protocol, based on TCP and Windows Sockets. Availability of own protocol makes unnecessary using other products and libraries (like MPI, PVM, etc) for communication purposes. This facilitates the application installation and configuration. The parallel GA software allows using CAD systems MagNet (for 2D and 3D) and FEMM (for 2D) for calculation of the objective function.

A small disadvantage of using a CAD system for calculating objective function in optimization algorithm is that at some combinations of input parameters physically impossible models may be created. This requires some elaborated geometric constraints to be used to avoid such models and situations.

The parallel processing significantly decreases computation time, necessary for obtaining the optimal solution, because the multiple calculations of the objective function, required by the genetic algorithm, are distributed among the cluster computers, and thus, in our case, 16 objective functions are calculated simultaneously.

The communication time necessary for transferring input and output data from the client computers to the server computer is minimal, because these files are very short. They contain only several numbers: the five input parameters and the three output quantities. Compared to the calculation time of the objective function, the communication time is negligible, thus the cluster computing power is used fully and the total computing time decreases approximately n times, where n is the number of computers in the cluster. Exact n-times reduction of the computing time can be obtained only when:

1. All calculations of the objective function take the same computing time;
2. All computers in the cluster have the same computing speed;
3. The number of children per generation in GA is divisible to the number of the computers in the cluster.

If all of these three requirements are fulfilled, then all computers will be loaded fully and there will be no waiting of some computers until others finish their work.

In our case, the first and the third requirements are not fulfilled. At the different calculations of the objective function, the generated FEM models by MagNet are slightly different because of the different combinations of input parameters. This leads to different number of elements in the models, and in some cases - to different convergence of the nonlinear FEM procedure. Consequently, some of the computers are forced to wait some time until others finish their work. This diminishes the effectiveness of the use of the cluster computers and instead 16 times reduction of the wall-clock computing time at 16 computers in the cluster, we obtained 14 times reduction of the wall-clock computing time.

5 Results

The optimization is performed using the parallel genetic algorithm [4] on a cluster of 16 personal computers using 70 members per generation. The objective function (total losses) is computed by the electromagnetic CAD system MagNet v. 6.15 [3].

At the first step of the optimization, only the dimensions of the iron core were varied. Using the parallel GA with 70 members per generation and 12 generations, an optimum has been reached - the iron losses have been diminished by 36% and the total power losses have been diminished from 4931W to 4265W (by 13.5%). This reduction of the total losses was not sufficient, so next step was achieved - adding as variables the number of turns w_4, w_5, w_1 of the windings. This time the results were better, and the total losses were diminished from 4931W to 2056W, with 58.3% reduction. The cost for this was the higher optimization time, which attained 17 hours with 20 generations of the GA.

The magnetic flux density distribution over the transformer is computed using CAD system MagNet and is shown in Figure 3 for the case when the magnetic fluxes in the shunt core cancel each other. The iron losses are calculated using the "iron loss-flux density" curve of the ferromagnetic core silicon-steel M6-35.

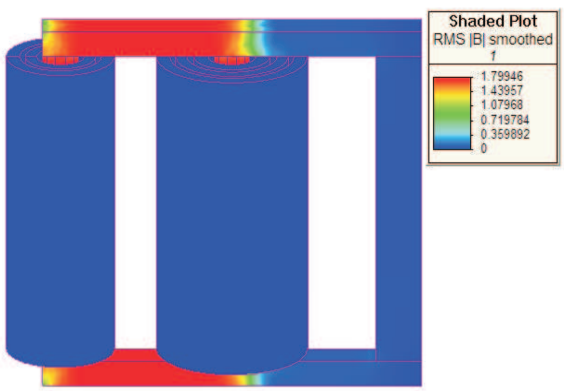

Fig. 3. Magnetic Flux Distribution on the Transformer.

The distribution of the losses over the components of the transformer unit is computed by the postprocessing functions of MagNet and is shown in Table 1. Two cases are shown - the initial non-optimized variant and the optimized variant with reduced total losses. Higher loss reduction is obtained in the windings, approximately 62%, whereas in the core the loss reduction is approximately 44%.

In the next Table 2 the initial and the optimized values of the design variables are shown.

Table 1. Distribution of the losses for the initial and the optimum cases

Part	Losses Initial [W]	Losses Minimal [W]	Difference [W]	Diff.percent [%]
Bottom	178.17	108.17	70.00	39.3
Right	0.546	0.3054	0.24	43.9
Left	333.12	184.11	149.01	44.7
Center	333.56	184.10	149.46	44.8
Top	178.19	108.42	69.77	39.2
Coil-4	347.65	121.9	225.75	64.9
Coil-5	453.4	168.71	284.69	62.7
Coil-3	292.13	103.28	188.85	64.7
Coil-1	2181.9	836.02	1345.91	61.7
Coil-2	632.24	241.43	390.81	61.8
Total losses	4930.9	2056.45	2874.48	58.3

Table 2. Design variables for initial and optimum case

Design Variables	R_1	H_1	w_4	w_5	w_1
-	mm	mm	turns	turns	turns
Initial	72.5	120	384	20	414
Optimum	58.39	71.79	408	15	327

For a proper functioning of the transformer unit at different work conditions, the output current has to be controlled also. This can be performed by switching the number of turns in the control winding c_3. The regulating characteristic - the function of the load current (at specified load impedance, representing the furnace in steady state) versus the number of turns w_3 in the control winding c_3, has been computed for the optimum case and shown in Table 3.

Table 3. Regulating characteristic $I_2 = f(w_3)$

w_3	68	136	240	272	340	408
I_2[A]	768	878	987	1096	1205	1314

Even smaller output currents can be obtained by reversing the direction of the current in the control winding c_3, but this control leads to higher losses in the transformer.

The results could be improved for a wider range of the load current if improved model for the electric furnace is used including the nonlinearity of the volt-ampere characteristic of the furnace. It can be measured by a suitable experimental setup.

The temperature distribution in the transformer will be solved in future investigations using the ThermNet package [3], which will allow to find the most important temperature hot-spots in the transformer and thus different cooling strategies could be investigated.

6 Conclusion

This paper shows the possibilities for using time-harmonic finite element analysis of an electric furnace transformer unit. The optimization of the core dimensions and windings turn numbers is found to give more uniform flux density distribution, to avoid saturation and to reduce the total losses in the transformer. The obtained reduction of the total losses by 58.3% is very promising and can lead to a better designed and more reliable electric furnace transformer unit. The parallel genetic algorithm used in this optimization decreases the computing time and allows even 3D finite element models to be used for calculating the objective function.

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