Optimization of the pulse transformer using circuit-field model

Wiesław Łyskawiński, Łukasz Knypiński, Lech Nowak, Cezary Jędryczka
Poznan University of Technology
60 – 965, ul. Piotrowo 3a, e-mail:{Lech.Nowak,
Wieslaw.Lyskawinski, Lukasz.Knypinski, Cezary.Jedryczka}@put.poznan.pl

The paper presents the new strategy of the optimization of pulse transformer (PT). In order to reduce calculation time the optimization problem has been decomposed into two stages. In the first stage, to determine functional parameters of PT the circuit model is used. The goal of circuit calculations is to limit the space of design variables that meets formulated requirements. The genetic algorithm has been applied for this task. In order to include constraints, the penalty function has been engaged. The transformer dimensions obtained in the first stage of calculations are used as initial values in the second stage of design process. In the second stage the field model of PT is employed. Obtained results prove that presented approach allows for fast optimization of the PT design.

KEYWORDS: pulse transformer, optimization, genetic algorithm

1. Introduction

The structure of the pulse transformer can be initially defined by the postulated power and input/output voltage and current. The several pre-selection methods for estimating the main dimensions of the magnetic circuit as well as the mechanical construction and electrical parameters of the windings have been presented in [1, 7, 11]. After this provisional pre-selection of main parameter the remaining parameters of the PT can be calculated on the basis of chosen PT model. In general there are two approaches that can be applied to determine the functional parameters of the considered PT: (a) approach based on the lumped parameters circuit model and (b) approach directly based on the PDE field model. In the first one, the lumped parameters as the inductance, capacitance and resistance in the equations of the model can be determined analytically [3, 7] or on the basis measurements over frequency domain [4, 9]. However on the design level the measured data are not available and the analytical relations are mostly not sufficiently accurate or to complex in case of taking into account nonlinearity or hysteresis phenomena. Therefore the numerical methods based on the analysis of the electromagnetic field distribution in the transformer have become more popular [2, 8, 10]. Nevertheless, in the optimization process due to time-consuming calculations of the field model equations, it is convenient to carry them out prior to design.

During design process of the pulse transformer, due to the time complexity of determining the functional parameters by using field model, it is advisable to perform calculations using less accurate circuit model of phenomena. The values of the design variables estimated in such way meets the formulated requirements of the considered pulse transformer. In the fine design process those data are used as initial values for the synthesis of the PT structure using field approach. The proposed design strategy of the PT based on the two-step optimization significantly reduces the computation time.

The first stage optimization can be repeated several times with the different initial structures of the PT. It can lead to a set of PT designs that meet the requirements. In order to assess the obtained designs and select the best solution is several criteria can be included for example, transformer weight, efficiency, cost of production and operating costs. To resolve the problem of choosing the optimal solution the methods of searching of the extreme of multi variable nonlinear objective function in respect to nonlinear constrain functions are applied.

2. Formulation of optimization problem of transformer magnetic circuit

In the optimization process it is convenient to use normalized design variables [12], which should be dimensionless and have comparable values. In order to normalize the variables introduced the dimensionless quantities x_i according to the relationship

$$x_i = \frac{s_i - s_{id}}{s_{ig} - s_{id}} \tag{1}$$

where s_{id} and s_{ig} are the lower and upper limits of each design variable s_i, respectively. If s_i $s_i \in \langle s_{id}, z_{ig} \rangle$ then $x_i \in \langle 0, 1 \rangle$.

The object was described by three design variables: diameter of the central column of the core $s_1 = d_{\mathrm{Fe}}$ and height $s_2=h_t$ and width $s_3 = b_t$ of the transformer window. The last two values must provide sufficient space to place the windings and required insulation. The minimal cross-section area of transformer window, that gives the minimal mass of the core, is equal to the cross-section area of insulation and copper occupied by the windings for given filing factor. On the basis of assumed current density in the wires and required turns ratio the turns number of primary and secondary windings are calculated.

After many testing calculations authors have proposed a compromise multiplicative objective function in the form:

$$F(\mathbf{x}) = \left[\frac{m_c(\mathbf{x})}{m_{c0\mathrm{sr}}} \right]^{a_1} \left[\frac{\Delta P(\mathbf{x})}{\Delta P_{0\mathrm{sr}}} \right]^{a_2} \tag{2}$$

where m_c is mass of active materials, ΔP is power loss of transformer, $m_{c0\mathrm{sr}}$, $\Delta P_{0\mathrm{sr}}$ are the average value of the mass and power losses in the transformer for the initial population, a_1, a_2 are weight factors, $\mathbf{x} = [x_1, x_2, x_3]^T$ is the vector of design variables.

During the optimization process, two major constraints are imposed:

– the steady temperature rise of windings $\Delta\vartheta_u$

$$g_1(\mathbf{x}) = \frac{\Delta\vartheta_u(\mathbf{x})}{\Delta\vartheta_{u\max}} - 1 \leq 0 \tag{3}$$

– the output power of transformer P

$$g_2(\mathbf{x}) = 1 - \frac{P(\mathbf{x})}{P_n} \leq 0 \tag{4}$$

The constrains in the form of external penalty function method has been taken into account. According to this method, the modified objective function is formed. In the modified function the term representing the penalty for overstepping the constrains is added [14].

The following data have been assumed: rated voltage $U_{1n} = 230$ V, supply voltage frequency $f_n = 100$ kHz, the nominal average output voltage $U_{2n} = 24$ V and load current $I_{2n} = 10$ A.

In the optimization process, due to the very large time-consuming calculations of functional parameters based on field model of phenomena, the concept of two-stage synthesis of transformer are proposed [12]. First, on the basis of less accurate circuit model of phenomena, and then in the second stage uses the structure parameters obtained from the first stage to optimize the transformer, as initial values for the synthesis of this construction in field approach.

3. Results of optimization using circuit model of transformer

To optimize the magnetic circuit of pulse transformer the software consisting of optimization procedures using a genetic algorithm and procedures involving circuit model of phenomena in the transformer [6] has been developed. The influence of the number of individuals, number of generations, and the probability of mutation in the convergence of the optimization process have been investigated. The change of the objective function defined by (2) and its sub-criteria ($m_{c0śr}/m_c(\mathbf{x})$ and $\Delta P_{c0śr}/\Delta P_c(\mathbf{x})$ respectively) during optimization process have been shown in the Figure 1 a), b), c), respectively.

The following parameters of the genetic algorithm have been assumed: the number of individuals in each generation equal to 200, the probability of mutation equal to 0.05%. It can be observed that for a number of generations higher than 30, the change of objective function was less than 0.01%.

On the basis of carried out simulations the values of genetic algorithm control parameters (i.e. mutation probability, etc.) giving the best convergence of the calculations have been determined.

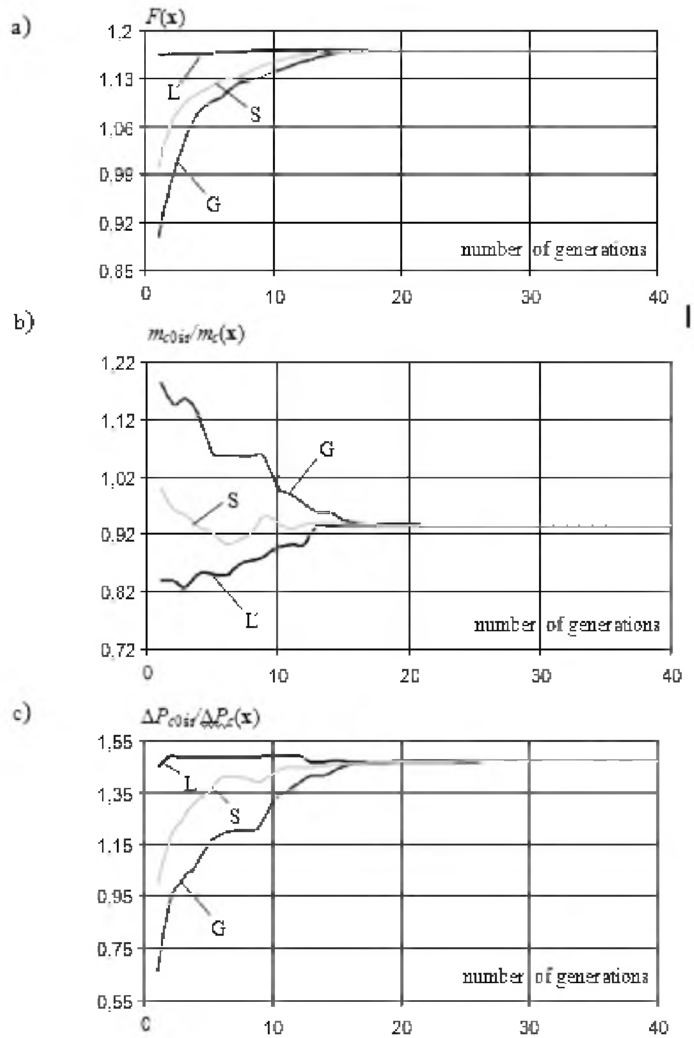

Fig. 1. Evaluation criteria (a) and sub-criteria (b), (c) as a function of the number of generations (**L**- best adapted individual, **G**- worst adapted individual, **S**- average in the generation)

The set of control parameters include the number of individuals, the number of generations, and the probability of mutation. From the other hand these parameters are chosen in such a way as to minimize the number of objective function calls. After many testing simulations it has been found that the optimization procedure has a good convergence for the following parameters: number of individuals not less than 100, number of generations greater than 40, and the probability of mutation within the range of 0.3 - 0.05%.

The result of the optimization process of 3 design variables h_t, b_t, d_{Fe} of transformer has been summarized in the Table 1. According to the idea of genetic algorithm, a set of initial solutions were obtained as a result of the random selection of the design variables in the space of feasible solutions. The first row shows the results of the optimization for number of turns calculated on base of the window size of the transformer. Obtained in this way, the number of turns is a real number. Due to the technological process typically the number of turns must be an integer. The next two rows in the Table 1 contains the results obtained assuming the constant window width of transformer and the number of turns z_1 rounded up or down to the nearest integer. The width of the transformer window results from the dimensions of wires and insulation.

Table 1. Results of first stage of optimization

z_1	h_t [mm]	b_t [mm]	d_{Fe}[mm]	η [%]	m_c [g]
35,34	28,96	7,74	14,25	97,62	273,26
36	29,50	7,80	14,71	97,32	299,51
35	28,75	7,80	14,05	97,52	266,02

It has been found that the core dimensions presented in the second row of Table 1 are similar to standard core type ETD-44. Choosing these dimensions for further discussion enables easy way for verification of proposed approach, by measuring performance of the built models of transformers.

In the next step the accurate synthesis of this variant were performed using the field model of electromagnetic phenomena in the PT. The impact on the PT efficiency of several parameters neglected in the circuit model, such as the thickness of the insulation δ between windings and winding placement have been investigated. The structure of considered pulse transformer with the ETD 44 core type has been shown in the Fig. 2.

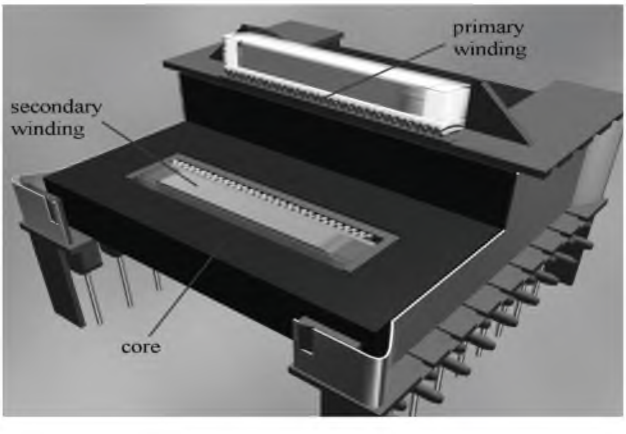

Fig. 2. The structure of considered pulse transformer

4. Second stage of the optimization

Using the field approach the more accurate determination of functional parameters can be achieved than for case of utilizing the circuit model [6]. Therefore, further optimization of the transformer is made using a complex field model of phenomena [5,6], which incorporates the nonlinear and hysteretic properties of the magnetic circuit, eddy currents in the core and windings, as well thermal processes and dielectric losses. The magnetic field distributions after power-on of the PT for chosen time instants $t = 0.4$ T, $t = 2.2$ T (T = 10 μs) are presented in the Figure 3a, 3b respectively.

As the initial values of considered design variables for the fine design of the PT transformer using the field model the design variables obtained in the optimization process by using the circuit model of phenomena (Table 1) have been used. On the basis of performed analysis it was found that the windings configuration has an important impact on functional parameters of transformer. Therefore, the investigations have been focused on optimizing the configuration of the windings, to get the highest efficiency [5]. Two variants of windings configuration have been examined. In first variant, the primary compact winding is placed near the center core leg and the secondary winding has been wound around primary. In the second studied case, the secondary winding is placed between the two halves of the primary winding (sectional primary winding). The thickness δ of the insulation between the windings has been optimized to minimize the losses in the windings and the core. The best efficiency has been achieved for δ = 0,5 mm.

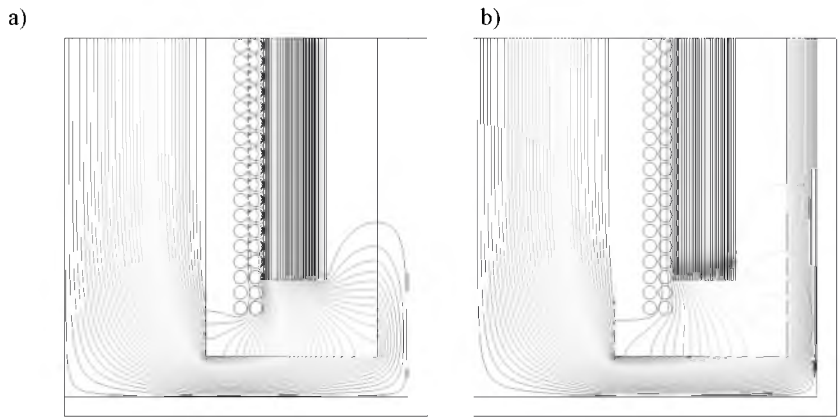

Fig. 3. Distribution of magnetic field in the pulse transformer for a) $t = 0.4$ T, b) $t = 2.2$ T (T = 10 μs)

The comparison of efficiency of the considered transformer as a function of the load current has been shown in the Figure 4. The first variant of the winding topology has been examined. Obtained characteristics have been determined on the basis of field

η_s and circuit η_o model of the PT. Calculated curves are compared with the results of measurements η_p. The good convergence of measurements and result of the simulations confirms the accuracy of the elaborated field model of the pulse transformer.

It can be observed that the efficiency curve η_o calculated using the circuit model differs significantly from the results of the measurements. It can be explained by the inaccurate identification of model parameters and neglecting the thermal phenomena. As it can bee seen the efficiency η_o is almost 3% higher than η_p for rated current of 10 A. To increase the accuracy of the circuit model the lumped parameters should be determined using field methods or on the basis of measurement.

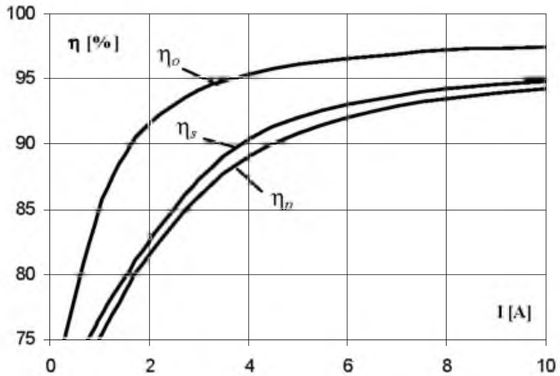

Fig. 4. Efficiency of pulse transformer as function of load current

In the next step the transformer with sectional primary winding has been investigated. The PT efficiency determined on basis the field model of the transformer was compared with the results of the measurements (Fig. 5).

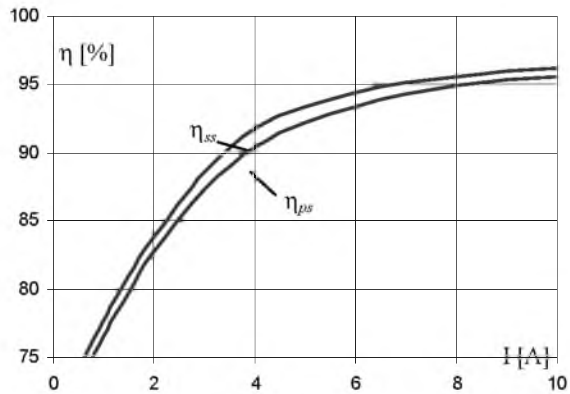

Fig. 5. Efficiency of pulse transformer with sectional primary winding as function of load current

It can be noticed that efficiency η_{ps} of the pulse transformer with sectional windings at rated load is about 1.5% higher than the efficiency η_p of the transformer with compact windings.

Presented results show that the optimization of transformer was performed correctly. Moreover it can be found the elaborated field model and developed software can be very useful in designing of studied type pulse transformers.

5. Conclusions

Because of high time-consuming calculations of the functional parameters using the field model of phenomena in the PT, the decomposition of the optimization task into two stages has been proposed. In the first stage, the simple circuit model of phenomena has been employed. Then in the second stage, obtained in the first stage the optimal values of the design variables are used as the initial values for the synthesis of the PT construction using field approach. The proposed design strategy of the PT based on the two-step optimization significantly reduces the computation time.

The procedures of the optimization of pulse transformers have been implemented as an own code. Elaborated software allows to determine the dimensions of the magnetic circuit, the number of turns and winding structure in respect to given properties of the materials to achieve the best performance to cost ratio expressed by proposed objective function. The good convergence of simulation and measurement results confirm the usefulness of the software developed for the design and optimization of pulse transformers. The usage of presented approach allows to reduce the cost of upgrading the existing and development of the new structures of pulse transformers by limiting the costs of developing number of prototypes.

References

[1] Billings K.H., Switchmode power supply handbook, McGraw-Hill 1999.

[2] Jianyong Lou, Yitong Chen, Deliang Liang, Lin Gao, Fei Dang, Fangjun Jiao, Novel network model for dynamic stray capacitance analysis of planar inductor with nanocrystal magnetic core in high frequency, Proceedings of the 14th IEEE Conference on Electromagnetic Field Computation, CEFC 2010, Biennial 2010.

[3] Kazimierczuk M.K., High-Frequency Magnetic Components, John Wiley & Sons Ltd., 2009.

[4] Laouamri K., Keradec J.-P., Ferrieux J.-P., Barbaroux J., Dielectric losses of capacitor and ferrite core in an LCT component, IEEE Transactions on Magnetics, 2003,Vol. 39, No. 3, s. 1574-1577.

[5] Łyskawiński W., Polowa analiza wpływu konfiguracji uzwojeń na straty mocy w transformatorze impulsowym, Przegląd Elektrotechniczny, nr 4/2010, s. 201-204.

[6] Łyskawiński W., Analiza stanów pracy i synteza transformatora impulsowego w ujęciu polowym, WPP, Poznań 2011.
[7] McLyman W.T., Transformer and inductor design, handbook, 3rd edn., Marcel Dekker, New York 2004.
[8] Moreau O., Michel R., Chevalier T., Meunier G., Joan M., Delcroix J.B., 3-D high frequency computation of transformer R, L parameters, IEEE Transactions on Magnetics, 2005, Vol. 41, No. 5, s. 1364-1367.
[9] Schellmanns A., Berrouche K., Keradec J.-P., Multiwiding transformers: a successive refinement method to characterize a general eqiuvalent circiut, IEEE Transactions on Instrumentation and Measurement, 1998, Vol. 47 No. 5, s. 1316-1321.
[10] Stadler A., Albach M., The influence of the winding layout on the core losses and the leakage inductance in high frequency transformers, IEEE Transactions on Magnetics, 2006, Vol. 42, No. 4, s. 735-738.
[11] Tomczuk K., Parchomik M., Projektowanie transformatora impulsowego w programie MATLAB-SIMULINK, Wiadomości Elektrotechniczne, nr 3/2010, s. 39-41.
[12] Knypiński Ł., Nowak L., Sujka P., Radziuk K., Application of a PSO algorithm for identification of the parameters of Jiles-Atherton hysteresis model, Archives of Electrical Engineering, Vol. 30, No. 2, June 2012, pp. 139 – 148.
[13] Knypiński Ł., Nowak L., Jędryczka C., Kowalski K., Algorytm optymalizacji magnetoelektrycznych silników synchronicznych z uwzględnieniem polowego modelu zjawisk elektromagnetycznych, Przegląd Elektrotechniczny, nr 2/2013, s. 143 - 147.
[14] Knypiński Ł., Nowak L., Optimization of the permanent magnet brushless DC motor employing finite element method, COMPEL, Vol. 32, No. 4, 2013, pp. 1189 – 1202.