Optimally designed energy efficient transformer using global iterative algorithms

Mihail Digalovski, Goran Rafajlovski, Krste Najdenkoski

The reduction of total losses for transformers is of great importance both from economic and environmental aspects. In the paper two optimization techniques, Global Search and Pattern Search, to minimize the total power losses of a distribution transformer are applied and evaluated. Object of investigation is an existing oil immersed three-phase transformer 50 kVA, 20/0.4 kV, Yz$_n$5, u$_k$=4%, available on the market. By using the output results, a new design of the transformer is developed. After, a prototype transformer, with reduced losses and improved efficiency is built. The computational results are validated through measurements. They show an excellent agreement and present a significant benefit in the total transformer losses reduction.

Key words: *optimization, transformer losses, energy efficiency, prototype, Pattern Search and Global Search optimization techniques.*

Introduction

Energy efficiency of the electric equipment in use is closely related to the environmental concerns, and is currently a key issue to which an important attention is paid worldwide. In accordance with the national regulations, big efforts in saving energy are evident. Hence, the equipment installed in the power sector should have higher energy efficiency. Distribution transformers are one of the elements in the power systems and networks that create the greatest loss of electricity. Thus, reduction of their loss can bring significant economic and environmental benefits. Reducing the total losses of the transformer is a complex issue and the solution should be sought in optimal designing of transformers, creating new materials with better quality for manufacturing the active parts of transformers, and also optimal management of power systems. In this paper two global optimisation techniques for transformer designing are applied and assessed, wherein the reduction of total losses is adopted as objective function, leading to increased energy efficiency of the transformer.

Problem analysis

Many authors treat the problem of optimal designing of transformers [1-3], applying variety of methods and selecting various objective functions as optimisation targets. In the paper are implemented and analysed two direct iterative optimisation techniques, in MATLAB environment: *Global Search* and *Pattern Search*.

The main idea behind *Global Search* (GS) algorithm is to find starting points for gradient based local non-linear programming (NLP) solvers. Essentially, GS is a multistart type method which runs from a variety of starting points in order to find a global minimum or multiple local minima, using a scatter-search mechanism for generating starting points; the solver analyses them and rejects those that are unlikely to improve the best local minimum found so far, and accepts a start point only when it has a good chance of obtaining a global minimum. The GS method uses the *fmincon* function as the local search gradient type method, and can be applied mostly to problems with a smooth and derivative objective function. The combination of global optimization along with powerful local search makes this algorithm very effective in solving complex optimization problem both with linear and non-linear constraints easily.

Another used direct search algorithm is *Pattern Search* (PS). It computes a sequence of points that approach an optimal point. At each step, the algorithm searches a set of points, called a *mesh*, around the *current point*, that is the point computed at the previous step of the algorithm. The mesh is formed by adding the current point to a scalar multiple of a set of vectors called a *pattern*. The value of the objective function either decreases or remains the same from each point in the sequence to the next. If the pattern search algorithm finds a point in the mesh that improves the objective function at the current point, the new point becomes the current point at the next step of the algorithm. Typically, the objective function values improve rapidly at the early iterations and then level off as they approach the optimal value.

When applying the both methods, same starting point and same objective function are used. The total transformer losses [4], accepted as target function, are minimised. They are expressed by nine independent variables x_1–x_9 representing some of the more important geometry dimensions and specific magnetic and electric properties of iron and copper. The target function of optimization is defined in a general form as:

$$\mathbf{X} = \text{Total Losses} = f\,[x_1 \;\; x_2 \;\; x_3 \;\; x_4 \;\; x_5 \;\; x_6 \;\; x_7 \;\; x_8 \;\; x_9]^T \qquad (1)$$

In Table 1 are presented the design variables x_1 – x_9 along with their description, as well as their constraints through the values of lower bound (lb) and upper bound (ub). The definition of each particular constraint is depending on the standards, recommendations and best practices.

Table 1

Design variables and their constraints

#	Description	lb	ub
x_1	B_m magnetic flux density (T)	1.65	1.75
x_2	λ leg length to leg diameter ratio (pu)	2.2	2.5
x_3	q_1 current density of high voltage winding (A/mm^2)	2.87	3.5
x_4	q_2 current density of low voltage winding (A/mm^2)	3.34	3.5
x_5	γ no-load loss to rated load loss ratio (pu)	0.14	0.2
x_6	υ_2 distance between low voltage winding and yoke (m)	0.02	0.03
x_7	k distance between leg and low voltage winding (m)	0.004	0.006
x_8	υ_1 distance between high voltage winding and yoke (m)	0.02	0.03
x_9	ξ distance between low and high voltage windings (m)	0.007	0.015

Accordingly, the boundaries for the variable x_1 are taken to be around the saturation point of the magnetising characteristic (1.7 T); values for x_2 are chosen so that the overall transformer can be immersed in a typical transformer tank; variables x_3 and x_4 are adjusted to the standard dimensions of copper wires. The variable x_5 has to be harmonised with standard EN 50464-1, where the no-load to rated load loss ratio in power transformers is standardised; the boundaries for the variables x_6 – x_9 are taken from best practices and technical recommendations for safety distances between the windings including other transformer parts, and are dependent on the higher voltage rating.

Here is noted that materials used for building the new transformer are of the same quality as for the original; an additional constraint is the default weight of copper and iron of prototype transformer must not exceed those of the original one. Consequently, the total losses are reduced neither by using better quality materials nor by increasing mass of the transformer active parts. Also, it is obligatory to keep percentage impedance in the prescribed bounds ±10%. To provide feasibility of the optimal solution, linear and non-linear constraints are also taken into consideration [3]. The additional nonlinear constrained functions are presented in Table 2.

Table 2

Additional constrained functions

#	Description	Min	Max
m_{fe}	Mass of transformer core: iron (kg)	120	140.7
m_{Cu}	Mass of winding: copper (kg)	40	50.04
P_{Cu}	Rated load loss (W)	900	1187
P_{Fe}	No-load loss (W)	190	240
u_k	Short circuit voltage (%) – standardised value 4%±10%	3.6	4.4
e	Distance between two phase winding (mm)	8	30

Results

The starting point of optimisation is taken from the original transformer design:

$$\mathbf{X_0} = [1.675 \;\; 2.393 \;\; 2.87 \;\; 3.42 \;\; 0.181 \;\; 0.01 \;\; 0.006 \;\; 0.025 \;\; 0.014]^T \qquad (2)$$

In Fig. 1 and Fig. 2 is presented convergence trend through iterations of the optimization process for the two global techniques. By comparing the obtained solutions, obviously the more suitable method for solving the transformer design optimisation problem is *Pattern Search*. Selecting the minimised value of total losses, the output results in a vector form are:

$$X_{opt} = [1.668 \quad 2.2 \quad 2.87 \quad 3.34 \quad 0.20 \quad 0.0126 \quad 0.004 \quad 0.03 \quad 0.008]^T \tag{3}$$

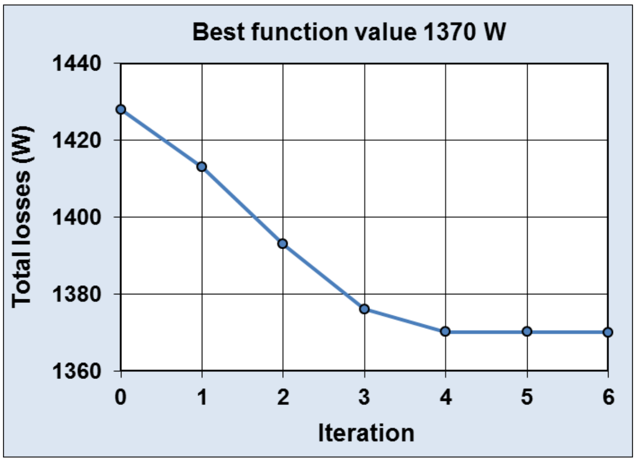

Fig. 1. Global Search optimisation process.

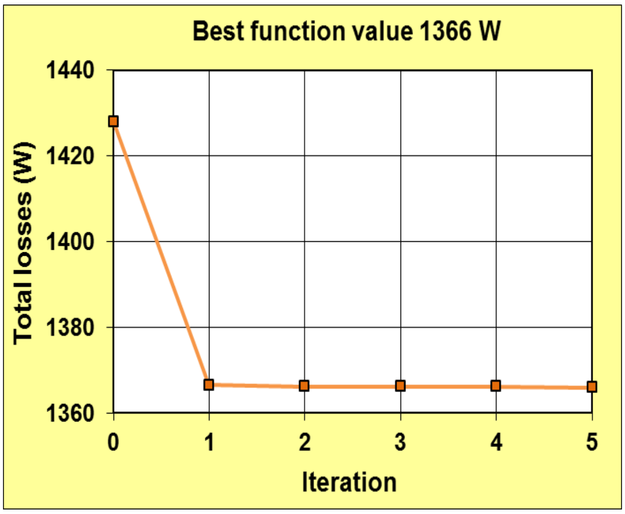

Fig. 2. Pattern Search optimisation process.

According to the accepted optimal results, a full design project for building new –transformer is developed. The prototype transformer is produced and thoroughly investigated, including experimental measurements. Series of measurements have been performed, and transformer parameters and characteristics have been obtained. The most relevant results are presented in Table 3, where original transformer values and measured results of the prototype are compared.

Table 3

Comparison of original and prototype transformer measured values

#	Original	Prototype	Difference (%)
P_{Fe} (W)	240	228	-5
P_{Cu75° (W)	1194	1136	-4,86
P_γ (W)	1434	1364	-4,88
η (%)	97,212	97,344	+0,136
u_k (%)	4,25	3,84	-9,65
m_{Fe} (kg)	140,5	135,9	-3,27
m_{Cu} (kg)	50,04	46,29	-7,49

In Rade Koncar factory Skopje, the *prototype* transformer, has been produced. In Fig. 3 is presented prototype transformer.

Fig. 3. Prototype transformer (in courtesy of Rade Koncar factory, Skopje).

Conclusion

The presented work introduces a novel approach to design of an energy efficient transformer, using one of the most recent optimisation techniques – the pattern search. The core issue of each optimisation procedure is a development of the best fitted objective function, which describes the transformer behaviour as close as possible. The study is applied on an existing transformer, from a line production of Rade Koncar factory, which is used to investigate the accuracy of the derived mathematical model. The optimisation procedure results in a new design of energy efficient transformer – prototype, with decreased total loss for 4,88%. It is worth to emphasise, that the improvement of the efficiency is attained at reduced iron and copper weight for 3,27% and 7,49%.

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