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A heuristic solution to the transformer manufacturing cost optimization problem

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Abstract

The aim of the transformer design is to completely obtain the dimensions of all the parts of the transformer based on the given specification, using available materials economically in order to achieve lower cost, lower weight, reduced size and better operating performance. In this paper, a transformer design optimization method is proposed aiming at designing the transformer so as to meet the specification with the minimum cost. Results from the application of the proposed methodology demonstrate the effectiveness and practicality of this approach.

Keywords: Oil-immersed power transformer; Wound core type transformer; Transformer design; Transformer manufacturing; Specifications; No-load losses; Load losses; Impedance; Tolerances; Optimum transformer; Transformer manufacturing cost

1. Introduction

In today's competitive market environment there is an urgent need for the transformer manufacturing industry to improve transformer efficiency and to reduce costs, since high quality, low cost products and processes have become the key to survival in a global economy. Transformer efficiency is accomplished by reducing load and no load (iron) losses [1]. On the other hand, for maximum economy, the costs for the production of transformer, its installation, maintenance and losses must represent the minimum long-term cost to the transformer user [2]. Minimum no-load losses in particular are particularly important considering the fact that since a transformer is continuously energized, i.e., 24 h per day, every day, considerable energy is consumed in the core (no-load losses), while load losses occur only when a transformer is on load [3].

The aim of the transformer design is to completely obtain the dimensions of all the parts of the transformer in order to furnish these data to the manufacturer [4]. The transformer design should be carried out based on the given specification, using available materials economically in order to achieve lower cost, lower weight, reduced size and better operating performance [1].

The transformer design is worked out by using various methods based on accumulated experience realized in different formulae, equations, tables and charts. The transformer design methods vary between the several transformer manufacturers.

While designing a transformer, much emphasis should be placed on lowering its cost by saving the materials and reducing to a minimum labor consuming operations in its manufacture. The design should be satisfactory with respect to dielectric strength, mechanical endurance, dynamic and thermal withstand of windings in the event of short-circuit [1].

In order to meet the above requirements, the transformer designer should be well familiar with the prices of the basic materials used in the transformer. He should also be well familiar with the amount of labor consumed in the production of transformer parts and assemblies.

In this paper, a transformer design optimization method is proposed aiming at designing the transformer so as to meet the specification with the minimum manufacturing cost.

The paper is organized as follows: Section 2 presents the transformer specifications. The proposed transformer design optimization method is presented in Section 3 and an application of the proposed methodology to an actual transformer design is described in Section 4. Section 5 concludes the paper.

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Table 1
Transformer specifications

Specification	Description
IEC 60076-1	Power transformers—general
IEC 60076-2	Power transformers—temperature rise
IEC 60076-3	Power transformers—insulation levels and dielectric tests
IEC 60076-5	Power transformers—ability to withstand short-circuit
IEC 60137	Bushings for alternating voltages above 1000 V
IEC 60354	Loading guide for oil-immersed power transformers

2. Transformer specifications

The transformer manufacturing is based on the international technical specifications and customer needs. The specifications related to transformer manufacturing are shown in Table 1. Table 2 presents the tolerances according to IEC 60076-1 to be applied to transformer losses and impedance (short-circuit voltage) when they are the subjects of manufacturer's guarantees [5]. In this paper, the symbols NLL, LL, and U_k are used for no-load losses, load losses and impedance, respectively.

3. Transformer design optimization method

This section describes the method for the determination of the optimum transformer, namely the transformer that satisfies the technical specifications and the customer needs with the minimum manufacturing cost.

The methodology concerns the optimization of transformers with the following technical characteristics:

- three-phase, oil-immersed power transformers,
- magnetic circuit of shell type and wound cores,
- foil, round wire, or rectangular wire technology for both low voltage (LV) and high voltage (HV) conductors.

Fig. 1 presents the small and large core of a wound core type transformer.

The process of finding the optimum transformer is implemented with the help of a suitable computer program, which uses 134 input parameters in order to make the transformer program as parametric as possible. These 134 input parameters are split into the following eight types:

1. *Description variables* (e.g., rated power, rated low voltage and high voltage, frequency, material of LV and HV coil, LV and HV connection, etc.).
2. *Variables that rarely change* (e.g., core space factor, turns direction space factor, specific weight of materials used, etc.).
3. *Variables with default values* (e.g., LV and HV taps, tolerance for NLL, LL, and U_k, etc.).
4. *Cost variables* (e.g., cost per weight unit for LV and HV conductor, magnetic steel, oil, insulating paper, duct strips, corrugated panels, etc.).
5. *Optional variables* (e.g., variables that can either be calculated by the program or defined by the user).
6. *Various parameters* (e.g., type of LV and HV conductor, number of LV and HV ducts, LV and HV maximum gradient, maximum ambient temperature, maximum winding temperature, etc.).
7. *Variables for conductor cross-section calculations* (LV and HV conductor cross-sections can be defined by the user or can be calculated using current density, or thermal short-circuit test).
8. *Solution loop variables* (e.g., LV turns, width of core leg, height of core window, magnetic induction, LV and HV cross-section area). It should be noted that the magnetic material properties (e.g. type, grade, thickness, specific losses, etc.) are given as input data when defining the values of magnetic induction within the solution loop variables [6].

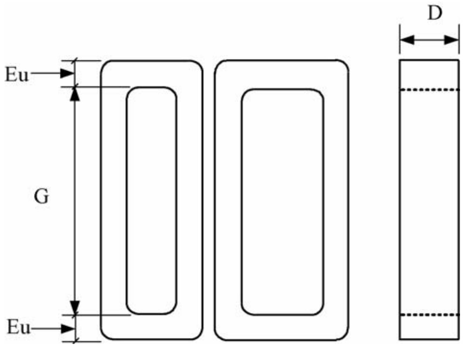

Fig. 1. Core constructional parameters.

The computer program allows many variations in design variables. These variations permit the investigation of enough candidate solutions. For each one of the candidate solutions, it is checked if all the specifications (limits) are satisfied, and if they are satisfied, the manufacturing cost is estimated and the solution is characterized as acceptable. On the other hand, the candidate solutions that violate the specification are characterized as non-acceptable solutions. Finally, among the acceptable

Table 2
Tolerances for losses and impedance

Quantity	Tolerance
(a) Losses	
(a_1) Total losses (NLL + LL)	+10% of the guaranteed total losses (NLL + LL)
(a_2) NLL (LL)	+15% of the guaranteed NLL (LL), provided that the tolerance for total losses is not exceeded
(b) U_k on principal tapping	(a) ±7.5% of the guaranteed U_k, when $U_k \geq 10\%$ (b) ±10% of the guaranteed U_k, when $U_k < 10\%$

Table 3
Optimization algorithm

```
For $i = 1$ to $n_{LV}$
  For $j = 1$ to $n_D$
    For $k = 1$ to $n_{FD}$
      For $l = 1$ to $n_G$
        Calculate volts per turn and $E_u$ (shown in Fig. 1) [7]
          For $m = 1$ to $cs_{LV}$
            For $n = 1$ to $cs_{HV}$
                Calculate layer insulations
                Calculate coil dimensions
                Calculate core weight and NLL [6]
                If NLL violate the specification, then the solution is rejected and the next loop is executed
                Calculate inductive part of impedance voltage at rated current as percentage of rated voltage [8,9]
                Calculate LL
                If LL violate the specification, then the candidate solution is rejected and the next loop is executed
                Calculate $U_k$ at rated current as percentage of rated voltage
                If the specification of $U_k$ is violated, then the solution is rejected and the next loop is executed
                Calculate coil length
                Calculate tank dimensions
                If the specification of tank's dimensions is violated, then the candidate solution is rejected and the next loop is executed
                Calculate oil–copper gradient
                If the specification of oil–copper gradient is violated, then the candidate solution is rejected and the next loop is executed
                Calculate corrugated panels dimensions
                If the transformer's cooling is not enough, then the candidate solution is rejected and the next loop is executed
                Calculate insulating materials dimensions
                Calculate duct strips weight
                Calculate oil weight
                Calculate cost of transformer's materials
                Calculate transformer manufacturing cost
Optimum transformer is the one with the minimum manufacturing cost
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solutions, the transformer with the minimum manufacturing cost is selected, which is the optimum transformer.

Giving n_{LV} different values for the turns of the low voltage (LV) coil, n_D values for the core's dimension D (shown in Fig. 1), n_{FD} tries for the magnetic induction (flux density), n_G different values for the core's dimension G (shown in Fig. 1), cs_{LV} different values for the calculation of the cross-section area of the low voltage coil and cs_{HV} different values for the calculation of the cross-section of the high voltage (HV) coil, the total candidate solutions (loops of the computer program), n_{loops}, are calculated from the following equation:

$$n_{loops} = n_{LV} n_D n_{FD} n_G cs_{LV} cs_{HV} \tag{1}$$

The search algorithm of the optimum transformer is presented in Table 3.

4. Case study

The proposed transformer design optimization method is already applied in a transformer manufacturing industry. The efficiency of the proposed transformer design optimization algorithm is presented through an actual design example of the 160 kVA, 20/0.4 kV transformer of Table 4.

Copper sheet is used for the low voltage conductor and copper wire is used for the high voltage conductor. The thermal calculation of transformer is realized through the number of ducts.

The calculation of the cross-section area of the conductors is implemented from the current density. More specifically, current density of 3.2 A/mm^2 is chosen for the internal coil and current density of 3.7 A/mm^2 is chosen for the external coil.

4.1. Solution loop variables

This subsection presents the values of the solution loop variables, i.e. the input variables with alternative values.

For the dimension *G* of the core (height of core window), 10 alternative values are given: from 190 to 235 mm with a step of 5 mm.

For the dimension *D* of the core (width of core leg), two alternative values are selected: 170 and 190 mm.

For the turns of the low voltage conductor, eight alternative values are given: from 28 turns to 35 turns with a step of one turn.

For the magnetic induction, seven alternative values are used: from 14000 to 17000 G with a step of 500 G. For each one of the 10 different levels of the magnetic induction, the respec-

Table 4
Transformer data

Parameter	Value
Rated power (kVA)	160
Internal (LV) coil voltage (V)	400
External (HV) coil voltage (V)	20000
Connection of internal (LV) coil	Y
Connection of external (HV) coil	D
Frequency (Hz)	50

Table 5
Acceptable solutions sorted by manufacturing cost

Number	Manufacturing cost ($)	G (mm)	D (mm)	LV turns	B (G)	LV conductor cross section area (mm^2)	HV conductor diameter (mm)
1	2457.82	210	190	29	16500	192 × 0.4	1.06
2	2459.31	205	170	29	16500	187 × 0.4	1.06
3	2468.63	215	190	29	16500	197 × 0.4	1.06
4	2470.26	215	170	30	16500	197 × 0.4	1.06
5	2474.44	200	190	28	16000	182 × 0.4	1.06
197	2722.31	215	170	28	14000	197 × 0.4	1.10
198	2724.17	215	170	29	14000	197 × 0.4	1.12
199	2725.02	220	170	29	14000	202 × 0.4	1.12
200	2733.01	210	170	28	14000	192 × 0.4	1.12
201	2733.87	215	170	28	14000	197 × 0.4	1.12

tive specific three-phase losses (W/kg) of the transformer are given.

For each dimension G, only one cross-section area of low voltage conductor is used.

Four values for the cross-section area of the external conductor are considered.

From the total number of values of the solution loop variables and with the use of Eq. (1) it is concluded that the total loops, which are executed by the computer program, are:

$$n_{\mathrm{loops}} = n_{\mathrm{LV}} n_{\mathrm{D}} n_{\mathrm{FD}} n_{\mathrm{G}} \mathrm{cs}_{\mathrm{LV}} \mathrm{cs}_{\mathrm{HV}} \Rightarrow n_{\mathrm{loops}} = 8 \times 2 \times 7 \times 10 \times 1 \times 4 \Rightarrow n_{\mathrm{loops}} = 4480.$$

4.2. Constraints

The following constraints are related with transformer losses and impedance:

- guaranteed LL 2350 W (so, among the 4480 candidate solutions, the solutions which have LL over 2350 W will be rejected),
- guaranteed NLL 425 W (so, among the 4480 candidate solutions, the solutions which have NLL over 425 W will be rejected),
- U_{k} 4% with tolerance ±10% (so, among the 4480 candidate solutions, the solutions which have U_{k} less than 3.6% or greater than 4.4% will be rejected).

4.3. Transformer optimum cost

The computer program calculates which of the 4480 candidate solutions are acceptable (the constraints are satisfied) and which are rejected.

For all the acceptable solutions, their technical characteristics are calculated and their manufacturing cost is estimated. The manufacturing cost is equal to the sum of the costs of the transformer's materials plus the labor cost.

For all the non-acceptable solutions, the reasons of rejection are recorded to a computer file.

From the 4480 candidate solutions, 201 are acceptable solutions and the rest 4279 are rejected. More specifically, 383 are rejected due to the violation of NLL specification, 3453 are rejected due to the violation of LL specification, and 443 are rejected due to the violation of U_{k} specification.

Table 5 presents the first five (cheapest) and the last five (more expensive) solutions from the total 201 accepted solutions. It is noticed that the cheapest solution (optimum transformer) costs $2457.82 and the most expensive solution costs $2733.87. Namely, the optimum solution is 11.2% cheaper than the most expensive solution.

The optimum transformer is the transformer number 1 of Table 5, which has the following technical characteristics:

- NLL = 415 W,
- LL = 2325 W,
- $U_{\mathrm{k}} = 3.90\%$.

Table 6
Variation of magnetic induction (solutions are sorted by manufacturing cost)

Input variables						Output variables			
G (mm)	D (mm)	LV turns	B (G)	LV conductor	HV conductor	NLL (W)	LL (W)	U_{k} (%)	Manufacturing cost ($)
210	190	29	16600	192 × 0.4	1.06	420	2321	3.90	2451.87
210	190	29	16500	192 × 0.4	1.06	415	2325	3.90	2457.82
210	190	29	16400	192 × 0.4	1.06	409	2329	3.91	2463.68
210	190	29	16300	192 × 0.4	1.06	402	2334	3.92	2469.96
210	190	29	16200	192 × 0.4	1.06	395	2338	3.93	2476.13
210	190	29	16100	192 × 0.4	1.06	388	2342	3.94	2482.21
210	190	29	16000	192 × 0.4	1.06	381	2347	3.94	2485.07

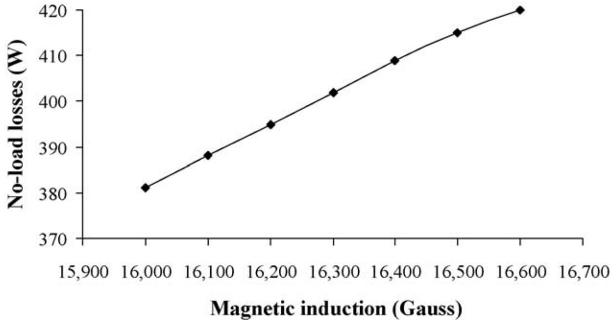

Fig. 2. NLL vs. magnetic induction.

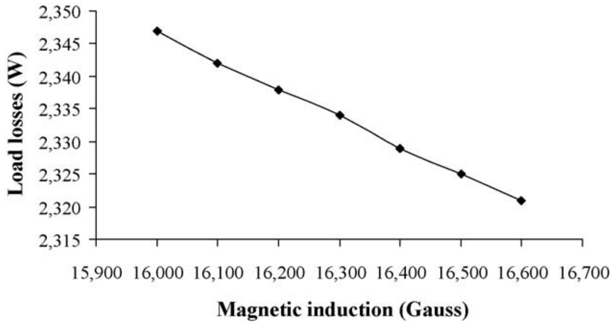

Fig. 3. LL vs. magnetic induction.

So the optimum solution satisfies the constraints of Section 4.2.

4.4. Sensitivity analysis

4.4.1. Variation of magnetic induction

Table 6 presents the values of the output variables (NLL, LL, U_k, and manufacturing cost), when only one of the input variables is varied, and more specifically the magnetic induction, which takes 31 values from 14,000 to 17,000 G with a step of 100 G. All the rest solution loop variables (G, D, LV turns, dimension of LV and HV conductor) remain constant and equal to the respective values of the optimum transformer (transformer number 1 of Table 5). Table 6 shows that among the 31 candidate solutions, only seven candidate solutions are accepted. Comparing Tables 5 and 6, it is concluded that the optimum solution has now a manufacturing cost of $2451.87. This means that with the specific variation of the magnetic induction, a cheaper solution was found. In Fig. 2, the NLL versus the magnetic induction is plotted, while Fig. 3 plots the LL versus the magnetic induction. From Figs. 2 and 3 it can be concluded that, in general, the NLL are increased and the LL are decreased with the increase of magnetic induction B.

4.4.2. Variation of CSA of LV coil

Table 7 presents the values of the output variables (NLL, LL, U_k, and manufacturing cost), when only one of the input variables is varied, and more specifically the cross-section area (CSA) of the low voltage (LV) coil, which takes nine values: 192×0.36, 192×0.37, $192 \times 0.38, \ldots$, and 192×0.44. All the rest solution loop variables remain constant and equal to the respective values of the optimum transformer (transformer number 1 of Table 5). Table 7 shows that among the nine candidate solutions, only four candidate solutions are accepted. Comparing Tables 5 and 7, it is concluded that the new optimum solution has now a manufacturing cost of $2451.83. This means that with the specific variation of the CSA of the LV coil, a cheaper solution was found.

4.4.3. Exploitation of the results

Table 8 shows how changing core and conductor design can reduce no-load and load losses but also affects the cost of the transformer, when we try to further improve the optimum design.

The optimum design is implemented through the following steps:

1. Initially the input variables are entered in the computer program. A lot of different values to the solution loop variables are given, so a lot of candidate solutions are considered.
2. The computer program calculates the candidate solutions that are acceptable and the candidate solutions that are rejected (they violate one or more of the constraints).
3. The acceptable solutions are sorted according to their cost. The optimum transformer corresponds to the least-cost solution.

It is possible that all the candidate solutions are rejected. Then the computer file of non-acceptable solutions must be studied and the reasons of rejection must be understood.

Generally, the following cases may appear:

1. necessity to decrease or increase no-load losses,
2. necessity to decrease or increase load losses,
3. necessity to decrease or increase impedance.

The no-load losses are decreased by one of the following methods (linked to solution loop variables):

Table 7
Variation of cross-section area (CSA) of low voltage (LV) coil

Input variables							Output variables			
G (mm)	D (mm)	LV turns	B (G)	LV conductor	LV CSA (mm^2)	HV conductor	NLL (W)	LL (W)	U_k (%)	Manufacturing cost ($)
210	190	29	16500	192×0.39	74.88	1.06	415	2346	3.89	2451.83
210	190	29	16500	192×0.40	76.80	1.06	415	2325	3.90	2457.82
210	190	29	16500	192×0.41	78.72	1.06	415	2303	3.92	2463.84
210	190	29	16500	192×0.42	80.64	1.06	415	2283	3.94	2470.19

Table 8
Loss reduction alternatives

	No-load losses	Load losses	Cost
To decrease no-load losses			
A. Use lower-loss core material	Lower	No change	Higher
B. Decrease flux density by			
1. Increasing core cross section area (CSA)	Lower	Higher	Higher
2. Decreasing volts per turn	Lower	Higher	Higher
C. Decrease flux path length by decreasing conductor CSA	Lower	Higher	Lower
To decrease load losses			
A. Decrease current density by increasing conductor CSA	Higher	Lower	Higher
B. Decrease current path length by			
1. Decreasing core CSA	Higher	Lower	Lower
2. Increasing volts per turn	Higher	Lower	Lower

1. increasing the number of turns of the LV coil,
2. decreasing the magnetic induction *B*,
3. decreasing the dimension *G* of core.

The no-load losses are increased by one of the following methods (linked to solution loop variables):

1. decreasing the number of turns of the LV coil,
2. increasing the magnetic induction *B*,
3. increasing the dimension *G* of core.

The load losses are decreased with the following ways (related to solution loop variables):

1. decreasing the number of turns of the LV coil,
2. increasing the magnetic induction *B*,
3. increasing the cross-section area of the HV coil,
4. increasing the cross-section area of the LV coil,
5. increasing the dimension *G* of core.

The impedance is decreased as follows:

1. decreasing the number of turns of the LV coil,
2. increasing the dimension *G* of core.

Generally, the cost of transformer is decreased as follows:

1. increasing the no-load losses,
2. increasing the load losses.

From the above it is derived that there is an interaction between the input and output variables. For example, the no-load losses are decreased with the decrease of magnetic induction (with the rest input parameters to be constant), but unfortunately the load losses are increased. The optimum solution is derived from selecting such values for the input variables so that the transformer satisfies the constraints with the minimum manufacturing cost. The selection is implemented through many tries (many different values for the input parameters) and is executed with the help of a suitable computer program.

5. Conclusion

Transformer design is a complex task that includes many variations in design variables so as to manage lowering transformer materials cost, minimizing labor cost and satisfying transformer specifications with respect to electric strength, mechanical endurance, dynamic and thermal resistances of windings in the event of short-circuit. This paper proposes a transformer design optimization method aiming at designing the transformer so as to meet the specification with the minimum manufacturing cost. The efficiency of the proposed transformer design optimization algorithm is presented through a design example. The proposed transformer design optimization method is already applied in a transformer manufacturing industry.

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