# Methodology for the Optimum Design of Power Transformers Using Minimum Number of Input Parameters

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***Abstract*—Transformer design is primarily determined by minimizing the overall manufacturing cost, including the cost of materials and the labor cost. This minimization, however, has to take into consideration constraints that are imposed by international specifications and customers' needs. In this paper, an innovative methodology in conjunction with Decision Tree technique is proposed that can design power transformers using only ten essential input parameters. The methodology is implemented through software. The developed package is suitable for users who are not experts in the field of transformers and also for transformer designers who desire a reliable and convenient way to reach a near optimum solution. Moreover, the minimum cost of a power transformer design is always calculated, in comparison with other methods that might not calculate a feasible solution in a first run. Furthermore, transformer design experiences are built into this particular program, which allows even a beginner to create an optimum transformer design. The proposed methodology and software constitute a handy tool that is already applied successfully in a transformer manufacturing industry.**

***Index Terms*—Decision Trees, Optimum Design, Power Transformers.**

## I. Introduction

Transformer design optimization seeks a constrained minimum cost solution by optimally setting the transformer geometry parameters and the relevant electrical and magnetic quantities, [1]. In order to set properly the values of these parameters, designers had to rely on their experience and judgment.

Early research in transformer design attempted to reduce much of this judgment to mathematical relationships, [2]. In the literature, a number of different design methodologies have appeared for power transformers. Computer-aided design techniques include mathematical models in an attempt to eliminate time-consuming calculations associated with reiterative design procedures, [3]-[5]. Furthermore, a technique was presented in [6] that started with assumed core geometry and afterwards found values of the electrical and magnetic parameters that maximize the VA capacity or minimize loss. An improved formulation and solution of the minimum loss problem, [6], was presented in [7]. Moreover, [8] proposed an optimizing routine, based on Monte-Carlo simulation, in order to choose the optimum transformer cost. A similar methodology to [8] was used in [9], but the optimum solution was derived from the response surface using classical optimization theory of continuous variables.

More recent research considered the use of artificial intelligence techniques in the optimum design of power transformers. Artificial neural networks (ANN), [10], [11], genetics algorithms (GA), [12], and decision trees (DT), [13] were used as alternative modeling methodologies to cope with the problem of optimum transformer design. Furthermore, there are methodologies in the literature that combine different artificial intelligence techniques so as to deal with the design optimization problem. More specifically, a DT method was presented in [14] in conjunction with ANN in order to select the appropriate winding material of power transformers. In [15], a technique was proposed for winding material classification that uses DT and ANN, along with finite element – boundary element modeling of the transformer for the calculation of the performance characteristics of each considered design. Moreover, an integrated 3D finite element model for power transformer optimization was presented in [16]. Finally, [17] introduced the application of a 3D mixed finite element - boundary element method, based on a particular scalar potential formulation, to the geometry optimization of magnetic shunts on power transformers.

In this paper, the design problem is defined as the minimization of the transformer manufacturing cost (i.e. material cost plus labor cost) while ensuring the satisfaction of the transformer rating specifications in conjunction with a number of design constraints. More specifically, an innovative methodology in collaboration with DT technique is proposed for the optimum design of power transformers using minimum number of input parameters. The need to develop such a methodology is coming from the fact that in today's competitive market environment, there is a need for the transformer manufacturing industry to very fast respond to the continuously increasing requests for few transformers or even for single transformer per transformer offer.

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The important feature of the proposed transformer design methodology is the usage of only ten input parameters during the optimization procedure, in comparison with the methodology presented in [5], which uses 134 input parameters (current methodology). This is achieved because transformer design experiences are built into the proposed transformer design technique. The proposed methodology has been already implemented in software that always has the capability of finding a feasible solution in less than 90 seconds, using an average computer. This is very important, compared to existing software tools that cannot guarantee the calculation of a feasible solution in a first run.

The developed software (based on the proposed methodology) is suitable not only for an experienced designer but also for a novice, because of its simplicity and implementation speed. This package is already used in a transformer manufacturing industry by transformer design engineers and by sales engineers. The transformer design engineers use this software in order to create a near optimum design very fast (afterwards, they can use the current software to further optimize the transformer design). The sales engineers use this package in order to quickly give to their customer an estimate of the sales price for a non-standard transformer. In brief, transformer design experiences are built into this particular program, which allows even a beginner to create an optimum transformer design.

The rest of the paper is organized as follows: Section II briefly describes transformer design specifications. Section III depicts the methodology for the selection of the input intervals of the transformer design variables using DT technique. Section IV presents the proposed transformer design optimization methodology using minimum number of input parameters. Section V is devoted to a case study, and Section IV is dedicated to experimental results and discussion. The work is concluded in Section VII.

## II. Transformer Design Specifications

Transformer manufacturing is based on international technical specifications (e.g., IEC, ANSI, CENELEC, DIN) and customer needs. Table I presents the tolerances according to IEC 60076-1 that should be applied to transformer load losses (*LL*), no-load losses (*NLL*), and short-circuit impedance ($U_k$) when they are subject to manufacturer's guarantees [18].

Table I. Tolerances for losses and impedance.

| Quantity | Tolerance |
|---|---|
| a) Losses | |
| a1) Total losses (*NLL*+*LL*) | +10% of the guaranteed total losses (*NLL*+*LL*) |
| a2) *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 $U_k \geq 10\%$<br>b) ±10% of the guaranteed $U_k$, when $U_k < 10\%$ |

## III. Proposed Methodology for the Selection of Input Intervals of Design Variables Using Decision Trees

### A. Overview of Decision Trees

The DT methodology [19] is a non-parametric technique able to produce classifiers in order to reduce information for new and unobserved cases. The attractiveness of DT is that it solves a problem by creating IF-THEN rules, which are readily comprehended by humans. The DT is a tree structured upside down, built on the basis of the learning set. The learning set comprises a number of pre-classified states defined by a list of potential attributes. Except of the root node (or top node), every node of a DT is the successor of its parent node. Each of the non-terminal nodes (or test nodes) has two successor nodes. Nodes that have no successor nodes are called terminal nodes. In order to detect if a node is terminal, i.e., "sufficiently" class pure, the classification entropy of the node is compared with a minimum preset value *Hmin*. If it is lower than *Hmin*, then the node is sufficiently class-pure and it is not further split. Such nodes are labeled LEAVES. Otherwise, a suitable test is sought to divide the node, by applying the optimal splitting rule [19]. In the case that no test can be found with statistically significant information gain, the node is declared a DEADEND and it is not split.

### B. Decision Trees and Transformer Design Optimization

In this paper, it is proposed that the DT method can identify the input interval of the transformer design variables, namely the upper (maximum) and lower (minimum) value of the input interval, in order to optimize the transformer design. As an example, Section III-C presents the application of DT for the selection of the magnetic induction interval. DT is also applied for the selection of winding material (copper or aluminum) that leads to the optimum transformer design [13]. The proposed DT technique is applied as an online tool to the transformer optimization technique employed in the proposed transformer design methodology of Section IV.

### C. Decision Trees for the Selection of the Magnetic Induction Interval

#### 1) Creation of the Knowledge Base:

In order to generate the knowledge base, 2646 actual transformer designs are considered. These transformer designs correspond to different technical characteristics (e.g., power ratings, no-load losses, load losses, impedance), different unit costs for the transformer materials (e.g., unit costs for the magnetic material and the winding material) as well as different labor costs. The knowledge base is composed of sets of final optimum designs (FOD) and each FOD is composed of a collection of input/output pairs. The input pairs or attributes are the parameters affecting the selection of the magnetic induction interval. Seven attributes, shown in Table II, are selected based on extensive research and transformer design experience. The output pairs comprise, for each one of the 2646 FOD, the magnetic induction interval that belongs to one of the following two classes: $11500 \leq B \leq 16000$ or $14000 \leq B \leq 18000$ (*B* in Gauss).

Table II. Candidate attributes.

| Symbol | Description |
|---|---|
| $I_1$ | Magnetic material unit cost (€/kg) |
| $I_2$ | Ratio of magnetic material unit cost (€/kg) over winding material unit cost (€/kg) |
| $I_3$ | Ratio of no load losses (W) over load losses (W) |
| $I_4$ | Rated power (kVA) |
| $I_5$ | Short-circuit impedance (%) |
| $I_6$ | Ratio of no load losses (W) over rated power (kVA) |
| $I_7$ | Ratio of load losses (W) over rated power (kVA) |

*2) Results:*

The knowledge base is divided into two sets: the learning set (that is composed of 1350 sets of FOD) and the test set (that it has 1296 independent sets of FOD). Fig. 1 illustrates the DT for the selection of the magnetic induction interval, which is automatically constructed by using the learning set of 1350 FOD with the seven attributes (Table II). Each terminal node of the DT produces one decision rule, on the basis of its magnetic induction index. It is also important to note that, among the seven attributes, the DT method automatically selects the four most important ones ($I_3$, $I_4$, $I_6$, and $I_7$) that appear in the various test nodes of the DT of Fig. 1. Thus, taking for granted the values of the above four attributes, the DT of Fig. 1 selects the appropriate interval from which the *B* has to be fluctuated, achieving a total classification success rate (CSR) of 97.61% on the unknown test set of 1296 FOD, which means that the DT of Fig. 1 correctly estimates the magnetic induction interval for the 1265 out of the 1296 FOD of the test set. This high CSR value renders the DT technique very suitable for industrial use.

## IV. Proposed Methodology for Transformer Design Optimization with Minimum Number of Input Parameters

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.

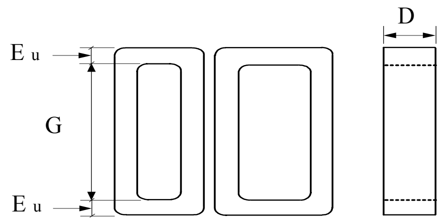


Fig. 2. Core constructional parameters (*G*: height of the core window, *D*: width of the core leg, *Eu*: thickness of the core leg).

The proposed method is able to design 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 for both low voltage and high voltage conductors.

The attractive feature of the proposed methodology is that it uses only 10 input parameters in comparison with the 134 input parameters that are used by the existing methodology [5] that is currently used in the considered transformer manufacturing industry.

According to the proposed methodology, ten input parameters are required: 1) transformer rated power (*RKVA*), 2) rated low voltage (*LV*), 3) rated high voltage (*HV*), 4) frequency (*f*), 5) short-circuit impedance ($U_k$), 6) maximum load losses (*CuLmax*), 7) maximum no load losses (*Femax*), 8) connection of low voltage winding (*LVCC*), 9) connection of high voltage winding (*HVCC*), and 10) maximum ambient temperature (*ta,max*).

Based on the above ten inputs in conjunction with DT methodology, the software automatically selects ten suitable alternative values from the selected interval for each one of the four design variables: 1) the number of turns of the low voltage coil ($n_{lv}$), 2) the width of the core leg (*D*; shown in

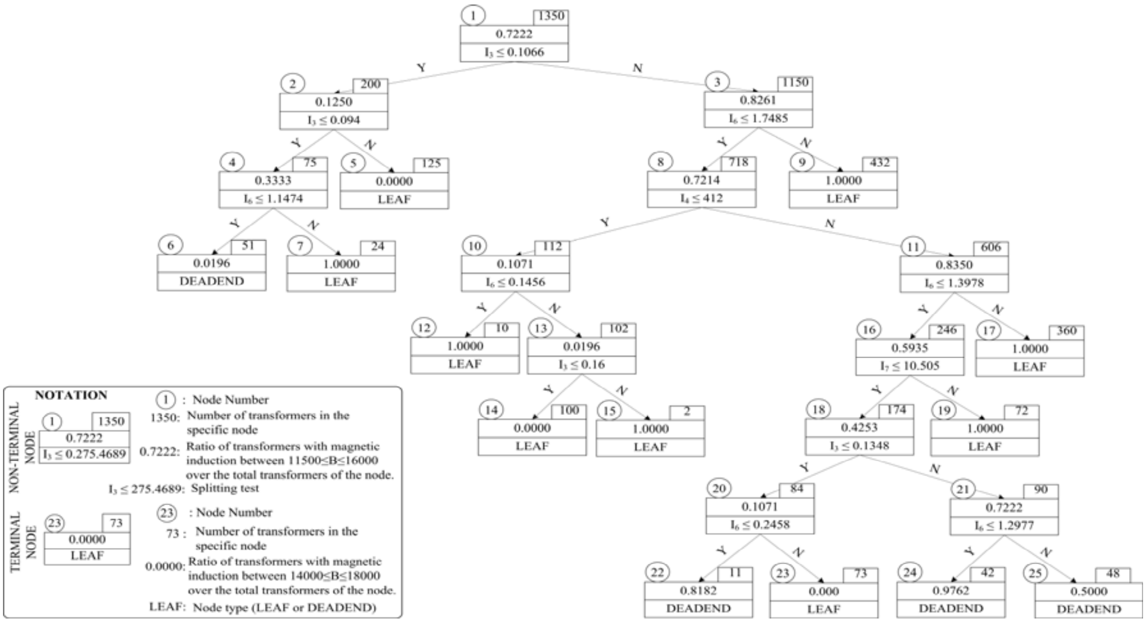


Fig. 1. Decision Tree for selection of the appropriate interval for the magnetic induction in power transformers.

Fig. 2), 3) the height of the core window (*G*; shown in Fig. 2), and 4) the magnetic induction (*B*). The DT technique, as shown in Section III, is able to find the appropriate interval of each one of the four design variables. Afterwards, each interval is uniformly divided into ten values that constitute the alternative values for each one of the four design variables.

For example, the 10 alternative values for the number of turns of the low voltage coil are calculated as follows. First, the interval [$VPT_{min}$, $VPT_{max}$] for the volts per turn (*VPT*) is computed using the DT technique. Afterwards, the following equation is used in order to define the interval [$n_{lv,min}$, $n_{lv,max}$]:

$$n_{lv} = \left( \frac{Vl_{nlv}}{VPT} \right) \quad (1)$$

where $Vl_{nlv}$ (V) is the line to neutral voltage of the low voltage coil. Next, the interval [$n_{lv,min}$, $n_{lv,max}$] is uniformly divided into ten values (which are rounded to the closest integer value) and in this way the 10 alternative values for the number of turns of the low voltage coil are calculated.

Similarly, the 10 alternative values for the rest three transformer design variables are calculated. For example, the interval for the magnetic induction (*B*) is based on the decision rules of Table III, which have been produced from the DT of Fig. 1.

The proposed transformer design optimization procedure is briefly presented in Table IV. In addition, the structure of the proposed technique is clearly illustrated in Fig. 3. As Table IV

Table III. If-then-else rules, based on the DT of Fig. 1, which are used for the selection of the appropriate interval for the magnetic induction.

| |
|---|
| Node 5: If $0.094<I_3\leq0.1066$ then $14000\leq B\leq18000$ |
| Node 6: If $I_3\leq0.094$ and $I_6\leq1.1474$ then $14000\leq B\leq18000$ |
| Node 7: If $I_3\leq0.094$ and $I_6>1.1474$ then $11500\leq B\leq16000$ |
| Node 9: If $I_3>0.1066$ and $I_6>1.7485$ then $11500\leq B\leq16000$ |
| Node 12: If $I_3>0.1066$ and $I_4\leq412$ and $I_6\leq0.1456$ then $11500\leq B\leq16000$ |
| Node 14: If $0.1066<I_3\leq0.16$ and $0.1456<I_6\leq1.7485$ and $I_4\leq412$ then $14000\leq B\leq18000$ |
| Node 15: If $I_3>0.16$ and $0.1456<I_6\leq1.7485$ and $I_4\leq412$ then $11500\leq B\leq16000$ |
| Node 17: If $I_3>0.1066$ and $1.3978<I_6\leq1.7485$ and $I_4>412$ then $11500\leq B\leq16000$ |
| Node 19: If $I_3>0.1066$ and $I_6\leq1.3978$ and $I_4>412$ and $I_7>10.505$ then $11500\leq B\leq16000$ |
| Node 22: If $0.1066<I_3\leq0.1348$ and $I_4>412$ and $I_7\leq10.505$ and $I_6\leq0.2458$ then $11500\leq B\leq16000$ |
| Node 23: If $0.1066<I_3\leq0.1348$ and $I_4>412$ and $I_7\leq10.505$ and $0.2458<I_6\leq1.3978$ then $14000\leq B\leq18000$ |
| Node 24: If $I_3>0.1348$ and $I_4>412$ and $I_7\leq10.505$ and $I_6\leq1.2977$ then $11500\leq B\leq16000$ |
| Node 25: If $I_3>0.1348$ and $1.2977<I_6\leq1.3978$ and $I_4>412$ and $I_7\leq10.505$ then $14000\leq B\leq18000$ |

Table IV. Proposed transformer design optimization procedure.

| Pseudocode of the main body of the proposed software |
|---|
| Read input data (ten input variables: *RKVA*, *LV*, *HV*, *f*, $U_k$, *CuLmax*, *Femax*, *LVCC*, *HVCC*, *ta,max*). |
| Basic calculations. |
| Select the transformer winding material using DT methodology [13]. |
| Define the interval [$VPT_{min}$, $VPT_{max}$] using DT methodology. |
| Using $VPT = (Vl_{nlv} / n_{lv})$ and the interval [$VPT_{min}$, $VPT_{max}$], define the interval [$n_{lv,min}$, $n_{lv,max}$] and select 10 values for $n_{lv}$. |
| Define the interval [$D_{min}$, $D_{max}$] using DT methodology, and select 10 values for *D* from [$D_{min}$, $D_{max}$]. |
| Define the interval [$B_{min}$, $B_{max}$] using DT methodology, and select 10 values for *B* from [$B_{min}$, $B_{max}$]. |
| Define the interval [$G_{min}$, $G_{max}$] using DT methodology, and select 10 values for *G* from [$G_{min}$, $G_{max}$]. |
| For i = 1 to $n_{loops}$ |
| Calculate the exact volts per turn. |
| Standardize conductors cross section. |
| Calculate layer insulations. Calculate coil dimensions. Calculate core weight and no-load losses. |
| If the no-load losses violate the specification, then the solution is rejected. |
| Calculate load losses. |
| If the load losses violate the specification, then the solution is rejected. |
| Calculate impedance voltage at rated current as percentage of rated voltage. |
| If the specification of short-circuit impedance is violated, then the suggested solution is rejected. |
| Calculate coil length and tank dimensions. |
| If the specification of tank's dimensions is violated, then the candidate solution is rejected. |
| Calculate oil-copper gradient. |
| If the specification of oil-copper gradient is violated, then the candidate solution is rejected. |
| Calculate corrugated panels dimensions. |
| If the transformer's cooling is not enough, then the candidate solution is rejected. |
| Calculate insulating materials dimensions. |
| Calculate duct strips weight. |
| Calculate oil weight. |
| Calculate cost of main materials. |
| Calculate manufacturing cost. |
| Optimum transformer is the one with the minimum manufacturing cost. |

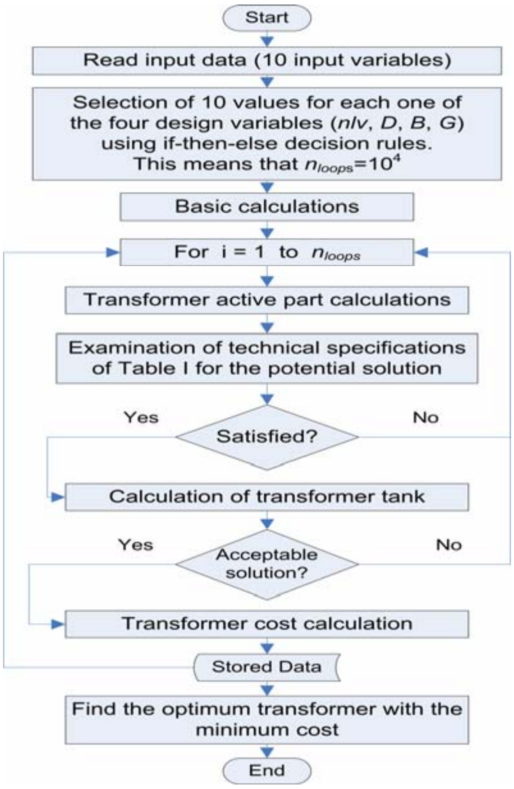


Fig. 3. The structure of the proposed methodology.

shows, 10 values are selected for each of the four aforementioned design variables ($n_{lv}$, $D$, $B$, and $G$) based on DT methodology, which means that in total $10^4$ candidate transformer designs are considered.

## V. Case Study

With the rapid development of digital computers, designers are no longer obliged to perform routine calculations. Computers are widely used for optimization of transformer design. Within a matter of seconds, today's computers can work out a number of designs (by varying flux density, core dimensions, current density, etc) and come up with an optimum transformer design [20].

The proposed transformer design methodology of Section IV is implemented in a software package, creating a suitable graphical user interface in which the user can set the values of the input parameters. This graphical user interface provides interactive and intuitive visual communication to transformer designers, enhancing the abilities of engineers to conduct studies with ease and flexibility. It is important to note that a database incorporating standard values for the components of a transformer is linked to the program in order to calculate all the necessary characteristics, such as the unit costs of the transformer materials, the dimensions of the conductors for the primary and secondary windings, coefficients of panel losses, tank convention and tank radiation constants, and so on. When the user chooses the desirable input parameters, the software finds a number of acceptable solutions that are stored into a database. This database is created automatically in every execution of the program where the user has the opportunity to find the technical characteristics of each acceptable solution, including the cheapest one.

Table V. Input parameters values for the study of 630kVA power transformer.

| Symbol | Description | Values | Units |
|---|---|---|---|
| *RKVA* | Rated power | 630 | kVA |
| *LV* | Rated low voltage | 400 | V |
| *HV* | Rated high voltage | 20000 | V |
| *f* | Frequency | 50 | Hz |
| $U_K$ | Short-circuit impedance | 4 | % |
| *CuLmax* | Maximum load losses | 6750 | W |
| *Femax* | Maximum no load losses | 1200 | W |
| *LVCC* | Low voltage winding connection | Y | – |
| *HVCC* | High voltage winding connection | D | – |
| *ta,max* | Maximum ambient temperature | 45 | °C |

Table VI. A number of the most important technical characteristics of the optimum design for the study of 630kVA power transformer of Table V.

| Symbol | Value |
|---|---|
| Cheapest cost | 5016 € |
| Rated power | 630 kVA |
| Magnetic induction | 17000 Gauss |
| Width of the core leg | 237 mm |
| Height of core window | 240 mm |
| Thickness of core leg ($E_u$) | 95.93 mm |
| No-load losses | 1196 W |
| Load losses | 6639 W |
| Total weight | 686 kg |
| Turns of the low voltage coil | 14 |

Table V illustrates the values of the 10 input parameters of a specific power transformer (630kVA) in order to find the optimum transformer, i.e. the one with the minimum cost.

Table VI presents the cheapest manufacturing cost (5016 euros) and some of the most important technical characteristics of the optimum power transformer that are calculated by the program.

## VI. Results and Discussion

Table VII shows the results of the proposed software in specific transformer designs. Eight different test cases are investigated and compared with the current methodology. For instance, a 630 kVA power transformer with *CuLmax*, *Femax* and $U_k$ equal to 6500W, 1300W, and 4% respectively, costs 4848€. This cost is 2.99% more expensive than that generated by the current software. In the same way, the last column illustrates the variation in the optimum cost between the solution generated by the proposed and by the current software in each different case. Generally, the proposed method achieves approximately 4.23% more expensive optimum transformer design than the current method. It is important to note that the current software is applied successfully in a transformer industry for more than 15 years and all the manufactured transformers have been designed with this software.

Table VIII shows the differences between the two methodologies illustrating the pros and cons of each

Table VII. Results using the proposed software.

| Case | *RKVA* (KVA) | *CuLmax* (W) | *Femax* (W) | $U_K$ (%) | Optimum cost (€) | Variation (%) |
|---|---|---|---|---|---|---|
| 1 | 250 | 3250 | 530 | 4 | 2987 | + 5.34 |
| 2 | 250 | 2750 | 650 | 4 | 2932 | + 3.53 |
| 3 | 630 | 6500 | 1300 | 4 | 4848 | + 2.99 |
| 4 | 630 | 5400 | 1300 | 4 | 5280 | + 2.68 |
| 5 | 1000 | 10500 | 1700 | 6 | 6834 | + 5.78 |
| 6 | 1000 | 13000 | 1700 | 6 | 6394 | + 4.75 |
| 7 | 1600 | 17000 | 2600 | 6 | 8767 | + 4.33 |
| 8 | 1600 | 20000 | 2600 | 6 | 9042 | + 4.42 |
| | | | | | Average | + 4.23 |

Table VIII. Comparison between the two methods.

| Proposed Software | Current Software |
|---|---|
| **1.** 10 input parameters. | **1.** 134 input parameters. |
| **2.** Constant number of iterations ($10^4$ loops). | **2.** Variable number of iterations (1 to $20^4$ loops). |
| **3.** An optimum solution is always found. | **3.** All the candidate solutions might be rejected. |
| **4.** Less than 90 seconds are required to optimize the transformer design (with a common PC). | **4.** Approximately 3 hours are required (multiple executions of the software by the transformer designer). |
| **5.** Low experience is required. | **5.** Expertise in transformer design is required. |
| **6.** The proposed software finds an optimum solution that is on average 4.23% more expensive than the current software. | |

methodology. The attractive features of the proposed software are that it uses only 10 input parameters in order to design an optimum transformer design, always in less than 90 seconds, necessitating no previous transformer design experience, in contrast with the current software that needs 134 input parameters so as to find a possible optimum transformer design in approximately 3 hours, and requires a lot of experience in transformer design. Moreover, ten thousands iterations are required by the proposed program in order to compute an optimum transformer design, in comparison with the current program which requires up to $20^4$ iterations (depending on users' choices). Finally, using the proposed methodology, it is easy to design an optimum transformer that is approximately only 4.2% more expensive than the current technique. The proposed method is already applied in transformer manufacturing industry.

## VII. Conclusion

Optimum transformer design is a thorny issue. Hence, many variations in design variables are included in order to minimize the material cost while complying with transformer specifications with respect to electric strength, and dynamic and thermal resistances of windings in the event of short circuit. In this paper, we introduced an innovative transformer design methodology in conjunction with Decision Tree technique that designs an optimum transformer by considering only 10 essential input values, which are very common to transformer users, sales engineers and designers. Although the suggested technique provides on average 4.2% more expensive transformer design than an existing design method, the proposed software constitutes a handy tool, which always reaches an optimum solution in less than 90 seconds. The proposed package is already applied in transformer manufacturing industry.

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