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Research Article

Cost optimization of oil type distribution transformer using multi-objective genetic algorithm

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Abstract: The demand for electrical energy is increasing day by day with the development of technology in the world. Distributing electric energy to all regions that need energy is a principal issue, and this necessitates the use of transformers to convert the voltage to the desired level. Accordingly, the use of transformers, one of the electrical devices converting AC voltage level at a defined frequency has grown significantly. In this study, design parameters of a 25 kVA, 33/0.4 kV, Yzn11, oil-type distribution transformer are optimized using the Multi-Objective Genetic Algorithm (MOGA) technique by decreasing the weight of the significant materials and manufacturing cost. Electromagnetic analysis of the transformer is performed with ANSYS Maxwell based on the design results obtained from the optimization study for validation of the method. The experimental design parameters are also compared with the optimization results. It is observed that optimum results are achieved by using the proposed approach.

Keywords: *Cost optimization, Finite element method, Multi-objective genetic algorithm, Transformer design*

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Nomenclature

Abbreviations			
AC	Alternative Current	kVA	Kilo volts ampere
CFD	Computational Fluid Dynamics	K	K constant number
FEA	Finite Element Analysis	K_{AL}	Constant number as 12.61
FEM	Finite Element Method	mm	Millimeter
GA	Genetic Algorithm	MVA	Mega volts ampere
HV	High Voltage	N_{HV}	HV turn number
LV	Low Voltage	N_{LV}	LV turn number
NSGA	Non-Dominated Sorting Genetic Algorithms	P_K	Load losses
ONAN	Oil Natural Air Natural	P_0	No-Load losses
Symbols		rms	Root mean squre
A	Ampere	S	Rated power of the transformer
A_g	Gross core area in sq cm	T	Tesla
B_m	Magnetic flux density	U_K	Short circuit impedance
cm	Centimeter	U_R	Resistive component of impedance
cm^2	Square Centimeter	U_X	Reactive component of impedance
d_{core}	Core diameter	V	Volt
E / T	Volt per turn	V_{ll}	Line to line voltage
f	Frequency as 50 Hz	V_{ph}	Phase voltage
f_{obj}	Objective function	$V_{HV_{ph}}$	Transformer HV phase voltage
Hz	Hertz	$V_{LV_{ll}}$	Transformer LV line to line voltage
I_{ll}	Line to line current	w/kg	Watt per kilograms
I_{ph}	Phase current	W	Watt
j	Current density	W_{core}	Total weight of core
kg	kilograms	$W_{winding}$	Total weight of winding
kV	Kilovolts	$W_{transformeroil}$	Total weight of transformer oil

1. INTRODUCTION

Transformers are one of the principal electromagnetic equipment used in the transfer and distribution of electrical energy. These devices help the transmission and distribution of energy by reducing the energy losses between the production point and the consumption point of electrical energy [1]. Due to competitive markets, optimization of transformer design is critical. For this reason, in the last few years, several studies have been carried out for a variety of criteria that would impact the transformers design, such as weight, efficiency, performance, losses and cost as reviewed in the following.

It is aimed to increase the efficiency of the transformer by optimizing the iron section suitability factor and current densities of the transformer using Tree Seed Algorithm, Simulation Annealing and Particle Swarm Algorithm techniques in [2]. In this study a time-dependent FEM analysis is conducted, and current-voltage graphs are produced. In [3], cooling channels and HV-LV coil widths are optimized using the Genetic Algorithm method to improve the heat dissipation and losses of the transformer. The CFD-EMAG model is used to verify the results in this study. Transformer losses and weight are minimized with NSGA-III, and the results are confirmed by FEA in [4]. The current density and iron cross-section conformity factor of the oil type, 50 kVA, 34.5/0.4 kV transformer is optimized using MATLAB in [5]. The weight of the considered transformer is reduced by 11% in this study.

In Ref. [6], Gray Wolf Optimization method (GWO), is used for the first time. The objective of this study is to keep the total cost of manufacture and power loss of a power transformer as low as possible. Four different design optimization strategies are applied in the related study. By comparing the outcomes of this study, the GWO method is proven to be effective.

Study [7], proposes an optimization method that enables the selection of the most appropriate conductor sizes for the windings during the transformer design stage. The goal of this optimization approach is to determine the best key design parameters for the simplified transformer model using evolutionary algorithm-based search. The short-circuit impedance and the magnetic field distribution in the transformer are calculated using a FEM calculation in this study. In [8], the author employed the Tree Pruning Method to minimize the weight of the 200 MVA oil type transformer. The transformer is modeled using FEM while taking the optimization-derived design parameters into account. This approach is given for evaluation of the method used for optimization and supported by test results. Investigation of how a 10 kVA dry type transformer with H-class insulation responds thermally under various temperature conditions is carried out in [9]. The transformer maximum temperature point can be discovered and examined with this thermal model. In Ref. [10], the finite element approach is used to calculate a distribution transformer winding temperature. This methodology can be used as a design tool to modify and enhance transformer performance. A novel method is developed in Ref. [11] to minimize the cooling system cost of the transformer. The accuracy of the proposed method is supported by Computational Fluid Dynamics analysis and experimental tests. Although many studies have been carried out in the relevant field, research on optimizing the electrical design of the transformer by considering the main parameters has not been conducted before.

The basic purpose of this study is to optimize the five design parameters of an oil-type distribution transformer using the Multi-Objective Genetic Algorithm. The reduction of transformer losses and weight, which greatly affects the cost, are also considered in this paper. When the results of the same transformer designed with traditional methods are compared with the results obtained using the Multi-Objective Genetic Algorithm optimization method, it turns out how effective the optimum cost of the Multi-Objective Genetic Algorithm optimization method is.

2. TRANSFORMER DESIGN

Two-winding with 3-phase, 25 kVA, 33/0.4 kV, Yzn11 oil-immersed distribution transformer is considered in this study. The design procedure starts with the design of the active part of the transformer, which consists of core and windings. Thermal analysis is not considered in this study. Therefore, the tank dimension and cooling surface of the transformer is obtained in accordance with the determined active part of the transformer with the help of conventional method. The design specification of the transformer is shown in Table 1.

Table 1. Transformer Requirements

Technical Specifications	Values
Power (kVA)	25
Frequency (Hz)	50
Cooling System	ONAN
Primary Voltage (V)	33000
Secondary Voltage (V)	400
Vector Group	Yzn11
Off Circuit Taps on HV	+2, -3 x 4.54% steps
Ambient Temperature (°C)	40
Top Oil Temperature Rise (°C)	60
Average Winding Temperature Rise (°C)	65
HV Basic Insulation Level (kV)	170
AC Test Voltage (kV)	70
P_0 (W)	81
P_k (W)	660
U_k (%)	4.5% ± 10%

2.1. Design of Transformer Core

The cross-section of the transformer core is considered as round in this study. The voltage per turn and the initial LV turn number is calculated with the help of the Eqs. (1,2) respectively. The K is an empirical coefficient which is taken between 0.25 and 0.55 in this study [12].

$$^{E}/_{T} = K\sqrt{kVA} \tag{1}$$

$$N_{LV} = \frac{2}{3}\frac{V_{LV_{ll}}}{^{E}/_{T}}, \tag{2}$$

where $V_{LV_{ll}}$ is the line voltage of the low voltage winding. The number of turns on the primary side of the transformer is determined with the help of the Eq. (3).

$$N_{HV} = \frac{V_{HV_{ph}}}{V_{HV_{ph}}} N_{LV}, \tag{3}$$

where, $V_{HV_{ph}}$ is the phase voltage of the high voltage winding. The transformer core material is selected as MOH with specification of 0.23 mm thickness and 0.80 w/kg at 1.7 T. The core cross-sectional area is obtained using Eq. (4). The stacking factor and frequency are taken as 0.97 and 50 Hz in the considered design [12].

$$^{E}/_{T} = 4.44\, f\, B_m\, A_g\,, \tag{4}$$

where B_m represent the maximum magnetic flux density. The transformer core diameter is found by taking the rounding-off factor of 0.94 from the following equation in Ref. [12]:

$$d_{core} = \sqrt{\frac{4\, A_g}{0.94\, \pi}} \tag{5}$$

2.2. Design of Transformer Windings

In this study, the conductor size in the winding is taken as variables and are determined in the optimization study using Multi-Objective Genetic Algorithm. The LV and HV winding conductor cross-section are selected as rectangle and round type, respectively.

3. MULTI-OBJECTIVE GENETIC ALGORITHM OPTIMIZATION TECHNIQUE

The design optimization of the transformer is based on minimizing the defined objective function in line with certain constraints based on the requirements. Finding an acceptable balance between the transformer performance and cost may be challenging. Therefore, designers have turned to artificial intelligence methods to solve transformer design optimization (TDO) problems [13]. The theory of evolution served as the basis for the development of the GA optimization method. The Genetic Algorithm selection technique uses the regular prediction and genetics [14]. In contrast to traditional optimization algorithms where each individual is parallel evolved and the result is included in the last population, genetic algorithms are based on populations [15]. After conducting significant investigation, in 1975 John Holland employed GA for the first time. This method is obtained by selecting, crossover and mutation. The selection process involves picking out the best individuals from the population and passing them on to the next generation. By combining the genes of two persons, a new person is created through the process of crossover. Mutation is the process of changing genes in order to increase the genetic diversity of the population. At the conclusion of the procedure, each individual has a cost function that provides the best answer to the identified issue [16]. The Multi-Objective Genetic Algorithm has a respectable job at implementing the Genetic Algorithm population-based characteristic. The quantity of Pareto solutions is the definition of a Multi-Objective Genetic Algorithm. The reasons for choosing Multi-Objective Genetic Algorithm optimization in this paper can be explained as follows [13-17]:

- *It is not necessary to know derivatives or other related concepts to calculate derivatives or other auxiliary functions.*
- *Genetic Algorithm simultaneously consider solutions and conduct various searches. As a result, there is a greater probability of achieving the best result rapidly rather than being limited to the best outcomes available locally.*
- *By utilizing Genetic Algorithm for a variety of objectives, various parameters can be optimized.*

3.1. Multi-Objective Genetic Algorithm

In the scope of this paper, transformer design cost optimization is made by using the Multi-Objective Genetic Algorithm method. The optimization objective function of the transformer is given in Eq. (6).

$$f_{obj} = (W_{core} \;\; 6\,\$) + (W_{winding} \;\; 3\,\$) + (W_{transformeroil} \;\; 2\,\$) \qquad (6)$$

Where W_{core}, $W_{winding}$ and $W_{transformeroil}$ represent the weight of core, conductor and transformer oil, respectively. During the optimization process, some restrictions in relative to the design parameters should be considered. These parameters and constraints are given in Table 2.

Table 2. Design parameters symbols, lower and upper boundaries.

Design Parameter	Symbol	Lower Bound	Upper Bound
K	X_1	0.25	0.55
LV conductor length (mm)	X_2	4.00	25.00
LV conductor width (mm)	X_3	2.00	5.50
LV layer number	X_4	3.00	6.00
HV conductor diameter (mm)	X_5	0.55	5.50

The desired design criteria of the transformer are shown in Table 3.

Table 3. Design criteria of the transformer.

Constraint	Boundary Condition
Short Circuit Impedance (U_k)	$4.5\% \pm 10$
No Load Loss (P_0)	81 W (max)
Load Loss (P_k)	660 W (max)
Magnetic Flux Density (B_m)	1.8 T

4. RESULT

4.1. Design of Transformer Windings

Transformer core parameters obtained from the MATLAB software based on the Multi-Objective Genetic Algorithm method are given in Table 4.

Table 4. Core parameters

Parameter	Value
$Core\ Cross\ section\ cm^2$	54.19
$Core\ diameter\ mm$	90.00

By optimizing the parameters shown in Table 2, the HV and LV winding design parameters are shown in Table 5.

Table 5. Design parameters of the transformer.

Parameter	LV	HV
Number of turns per phase	134	8268-10444
Number of layers	4	28
Length of conductor, mm	7.8	-
Width of conductor, mm	2.7	0.61
Area of conductor, mm2	21.06	0.3
Current density, A/mm2	1.67	1.48
Inner diameter, mm	95	147
Insulation layer, mm	0.125	0.220
Radial Thickness, mm	11	27
Outer diameter	117	201
Winding Axial Height, mm	305	305

The short circuit impedance is the impedance value displayed by the transformer in the network at the time of the short circuit and consists of resistive and reactive components and could be realized using the following equation.

$$U_K = \sqrt{U_X^2 + U_R^2} \tag{7}$$

where U_X and U_R represent the resistive and reactive components respectively. The calculated impedances are given in Table 6.

Table 6. Short circuit impedance values.

Impedance	Values
$\%U_X$	3.74
$\%U_R$	2.61
$\%U_K$	4.57

The results of the conventionally designed transformer are compared with those obtained from Multi-Objective Genetic Algorithm in Table 7. These results indicated that the weight and cost of the transformer are decreased by using the optimization design approach.

Table 7. Experimental and optimization result.

Parameter	Experimental Results	Optimization Results
K	0.36	0.396
LV conductor length (mm)	8.9	7.8
LV conductor width (mm)	2.2	2.7
LV layer number	4	4
HV conductor diameter (mm)	0.7	0.61
Number of turns per phase for HV winding	148	134
Number of turns per phase for LV winding	9132 - 11535	8268 - 10444
LV Winding Inner diameter, mm	91	95
LV Winding Outer diameter, mm	117	117
HV Winding Inner diameter, mm	147	147
HV Winding Outer diameter, mm	209	201
LV Radial Thickness, mm	13	11
HV Radial Thickness, mm	31	27
LV winding weight, kg	8.4	7.77
HV winding weight, kg	20	13.619
Core weight, kg	81.989	78.338
Load Loss, Watt	660	654
No Load Loss, Watt	81	80
Transformer Cost, $	577.134	534.22

4.2. Simulation Result

The transformer 3D model which is achieved in ANSYS/Maxwell software is shown in Fig. 1.

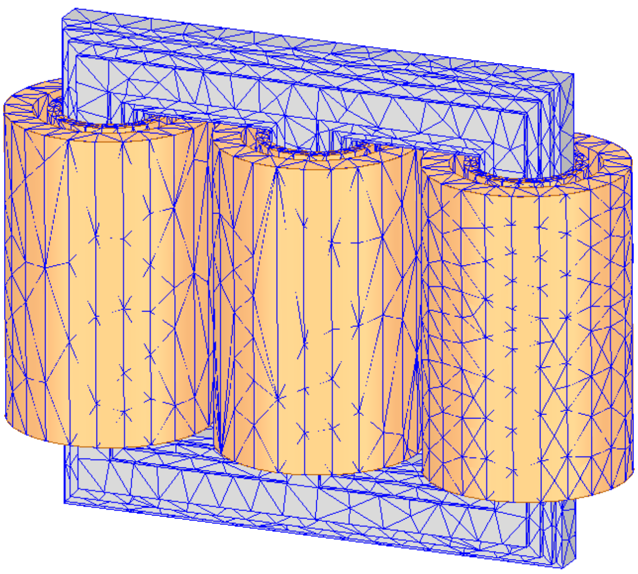

Figure 1. Meshing of the transformer.

The rated line voltage of the HV side of the transformer is shown in Fig. 2.

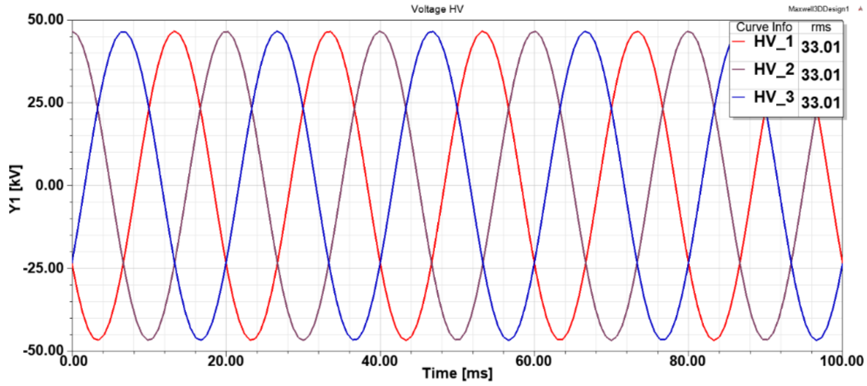

Figure 2. HV line voltage waveform.

The HV side of the transformer is star connected. In this type of connection, line and phase current are calculated by Eqs. (8,9).

$$I_{ll} = \frac{S}{\sqrt{3}\, V_{ll}} \quad (8)$$

The rated line current in the HV winding of the transformer is indicated in Fig. 3.

$$I_{ll} = I_{ph} \quad (9)$$

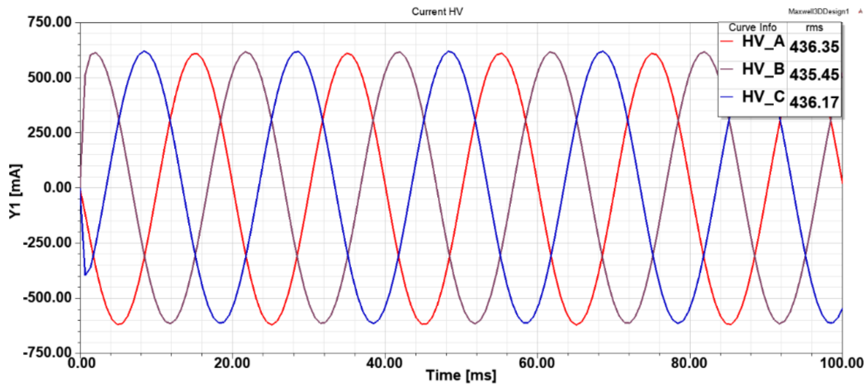

Figure 3. HV line current waveform.

The line voltage on the LV side of the transformer is 400 V. The phase voltage of the LV winding is calculated as 230 V by Eq. (10).

$$V_{ph} = \frac{V_{ll}}{\sqrt{3}} \quad (10)$$

The result of the LV phase voltage is shown in Fig. 4.

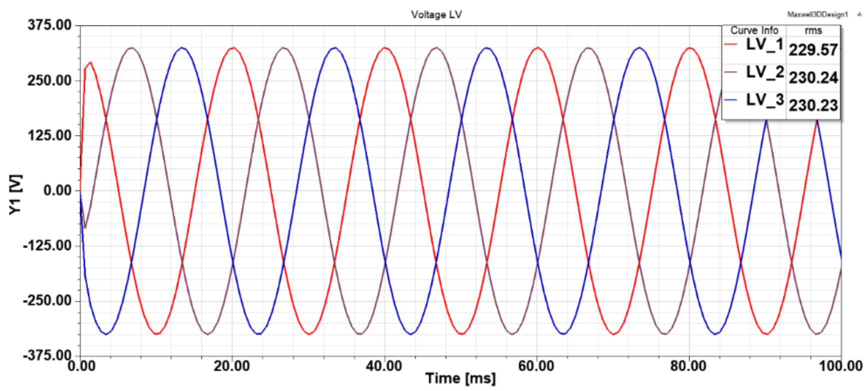

Figure 4. LV phase voltage waveform.

The rms value of line current in the LV winding of the transformer is calculated as 36.08 A and shown in Fig. 5.

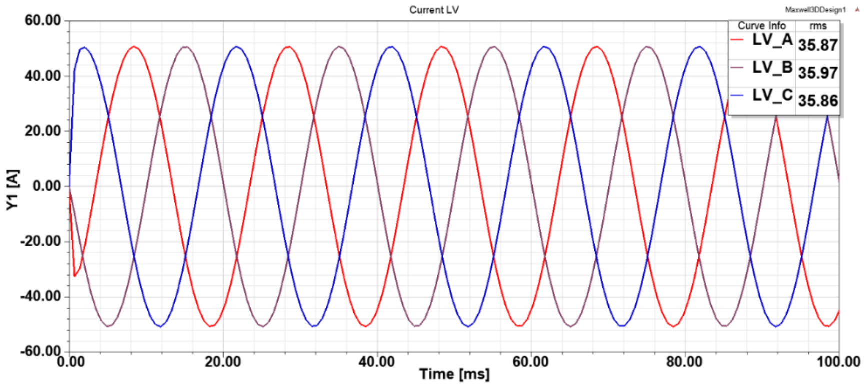

Figure 5. LV line current waveform.

Load loss of the transformer is calculated by Eq. (11). This is the losses caused by the current passing through the windings [18].

$$P_K = K\, j^2\, W_{winding} \tag{11}$$

Where K is 12.61 for Aluminum [19], j represent the current density and $W_{winding}$ is weight of the windings. The load loss of both primary and secondary winding are calculated separately. Fig. 6 shows the total load loss in each winding of the transformer. In this study the stray loss of the transformer is neglected.

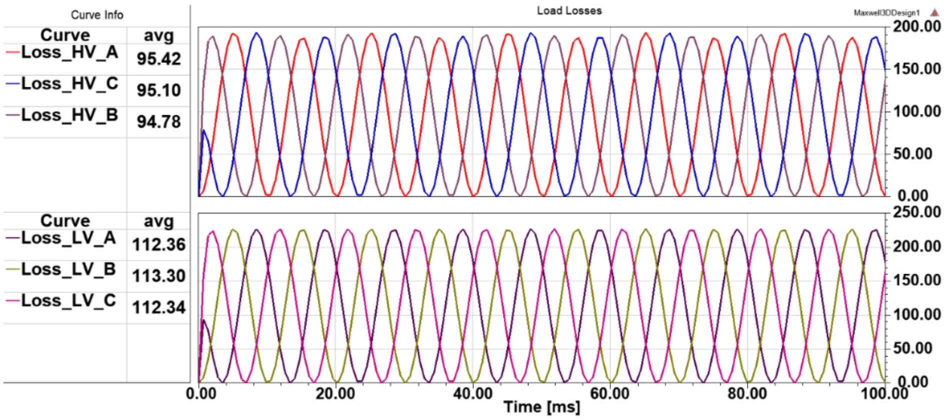

Figure 6. Transformer load loss.

No Load Loss occurs due to the changing flux in the core of the transformer. It is calculated by the following Eq. (12).

$$P_0 = W_{core}\left({}^{watt}/_{kg}\right) Building\ factor \tag{12}$$

Where the W_{core} is defined as total core weight, building factor is taken as 1.25 and ${}^{\text{watt}}/_{\text{kg}}$ is the specific loss of the core material at working flux density. Fig. 7 shows the no load loss of the studied transformer.

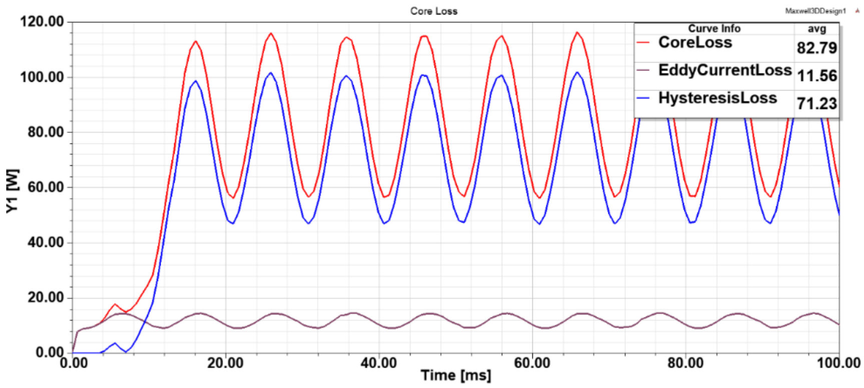

Figure 7. Transformer no-load loss.

The results of FEM analysis and the results of Multi-Objective Genetic Algorithm optimization are shown in Table 8.

Table 8. FEM and optimization result.

Result	Multi-Objective Genetic Algorithm (MOGA)	Finite Element Method (FEM)	Deviation (%)
LV Line Current, A	36.08	35.90	-0.50
LV Phase Voltage, V	230.94	230.01	-0.40
HV Line Current, A	0.437	0.44	-0.23
HV Line Voltage, kV	33	33.01	0.03
Load Loss, Watt	654	626.3	-4.69
No Load Loss, Watt	80	82.79	3.49

5. CONCLUSION

This paper established the design of a 3-phase, Yzn11, 25 kVA, 33/0.4 kV two-winding, oil-immersed distribution transformer. During the design process, five design parameters are determined by using the Multi-Objective Genetic Algorithm method. It is observed that the lower cost corresponds to the optimal design approach. The weight of the transformer is also decreased as a result of the optimization. The results of the optimized design are compared with the results obtained from 3D FEM under the same conditions to verify the accuracy of the method. The corresponding result given in Table 8 shows that the related deviation is within an acceptable range. The approach used in this work to design a transformer has a significant advantage over experimental methods as the total cost of the transformer is decreased. The results of this study are expected to be useful in the design stage of transformers regarding to achieve both optimal performance and cost.

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