Distribution Transformer Loss Reduction using Brute Force Search Algorithm

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Abstract: Losses in distribution transformers are estimated as 30% of overall transmission and distribution losses. It is further estimated that the losses in all of the world's electrical distribution systems are about 1715 TWh. One-third of these losses are emitted by the distribution transformers. In this paper, a mathematical model is done and a new objective function that minimizes losses in a distribution transformer is used. This study presents a loss-reduced optimal design of three phases, 315 kVA, 15/0.4 kV, 50 Hz, oil-immersed, core type distribution transformer. A Brute force search algorithm is written on Java Netbeans IDE 8.0.2 to obtain an optimum design of a distribution transformer that has minimum losses which met the requirements and constraints. The loss of a distribution transformer designed using the Brute force search algorithm is compared with transformer manufacturer's used design based on analytical method. The results from the optimization algorithm show that the design reduces the total losses on the existing distribution transformer selected for the study from 4,030-2,687.56 W by 1,342.44 W, thus, representing a percentage reduction of 33.31%. If this saving is applied to the existing 48, 315 kVA distribution transformers of the Jimma town route of the case study area, the saving will be 64,437.12 W. If the optimally designed transformer is to be implemented on a larger scale across the electrical distribution networks of Ethiopia, the magnitude of savings would be huge.

INTRODUCTION

Background: Electrical power systems utilize several voltage levels using transformers to transfer voltages and connect parts of the power system with different voltage levels. One of these voltage transformations is being performed in the key component called a distribution transformer. A transformer that takes primary voltage and steps down it to a secondary distribution circuit is called a distribution transformer. A distribution transformer reduces the primary voltage to the utilization voltage[1].

Losses in distribution transformers are estimated as 30% of overall transmission and distribution losses. The efficiency of a typical distribution transformer is over 97% which seems that it is satisfactory. But, this means that up to 3% of all electrical power generated is wasted in the transformer. These losses are far from negligible and anything that can be done to reduce them has the potential to deliver huge savings[2].

The losses of the transformer consist of no-load losses and load losses. No-load losses are constant and appear throughout the lifetime of a transformer, while load losses vary and are only significant under higher load conditions[3, 4].

The total electrical energy use per annual of the world is estimated at 21500 TWh (1 TWh is equal to 109 kWh) and it is further estimated that the losses in all of the world's electrical distribution systems are about 1715 TWh or about 7.97% of the total electrical energy consumed. About 30-35% of these losses are emitted by the distribution transformers.

Studies estimate that 40-60% of these transformer losses 206-360 TWh are potentially saveable by increasing transformer efficiencies[5]. As a distribution transformer data from Ethiopian Electric Utility (EEU), Jimma Distribution System (JDS) office indicates, here in Jimma town, on a single 315 kVA distribution transformer there is a total loss of 4030 W. Reducing a small number of losses from the above-stated value per transformer brings substantial energy savings for the utility.

MATERIALS AND METHODS

Methodology of transformer design optimization

Data collection

Secondary data: The data presented by transformer manufacturer Ethiopian Power Engineering Industry (EPEI) and the data from the study area presented by EEU, JDS office are used as secondary data for this study. The secondary data found from the above-mentioned two areas are shown in Table and 2.

Methodology: The procedural steps which are followed to realize and complete this research work are portrayed in Fig. 1.

Optimization of a distribution transformer design: This section will list and discuss the objective function to find the optimal design, that has the minimum losses, the design variables that will be included in the design optimization tool to reach the needed design and finally, the design constraints that are needed to ensure that obtained design functions with all the required operational characteristics and at high efficiency.

Design variables: A number of the design variables have to be optimized for the objective function to reach accepted designs. These design variables are:

Table 1: Distribution Transformer (DT) secondary data from EPEI and EEU Jimma distribution office

	Values	
Specifications	EPEI	EEU, Jimma
Serial No.	31501483	31502552
Connection of HV/LV	Delta/Star	Delta/Star
Number of phases	3	3
Frequency, Hz	50	50
Rated continuous power, kVA	315	315
Primary voltage (HV side) in V	15000	15000
Secondary voltage (HV side) in V	400	400
Core material grade	27M4	27M4
Percentage impedance	3.80	3.80
LL in W	3300	3300
NLL in W	730	730
Efficiency	98.73	98.73

Table 2: Distribution transformer design variables from EPEI

Design variables	Values
Secondary number of turns	32
Core radius (mm)	98
Primary wire diameter (mm)	2.1
Secondary foil width (mm)	319
Secondary foil thickness (mm)	2.5
Primary number of cooling ducts	2
Secondary number of cooling ducts	2
Turns per HV layer	74
Primary number of layers	18

- Secondary number of turns (N_{LV})
- Core radius (R_C)
- Primary wire diameter (D_{wire})
- Secondary foil width (W_{foil})
- Secondary foil thickness (T_{foil})
- Secondary number of cooling ducts ($N_{LV\text{-}duct}$)
- The primary number of cooling ducts ($N_{HV\text{-}duct}$)
- Turns per HV layer (N_{HVPL})
- The primary number of layers (NL_{HV})

The design variables all depend on each other in some way or another for example increasing the number of ducts will result in using a longer copper wire or foil for the winding as the ducts are placed in between the core and the windings.

Objective function: The main goal of experienced designers is to come up with an appropriate design that barely satisfies the operating requirements and characteristics requested by the customer. Conventional methods are normally used resulting in several designs that satisfy the customer's request, however, these designs will have different losses and any manufacturer tends to keep the losses as low as possible. Thus, a priority has to be selected when comparing different designs that specify operational constraints to select the best design to be used. This priority upon which the optimal design is selected is known to be the objective function of the design.

In this study, the Brute force search algorithm is used with an objective function of minimizing the total losses of a distribution transformer. Therefore, the objective function is:

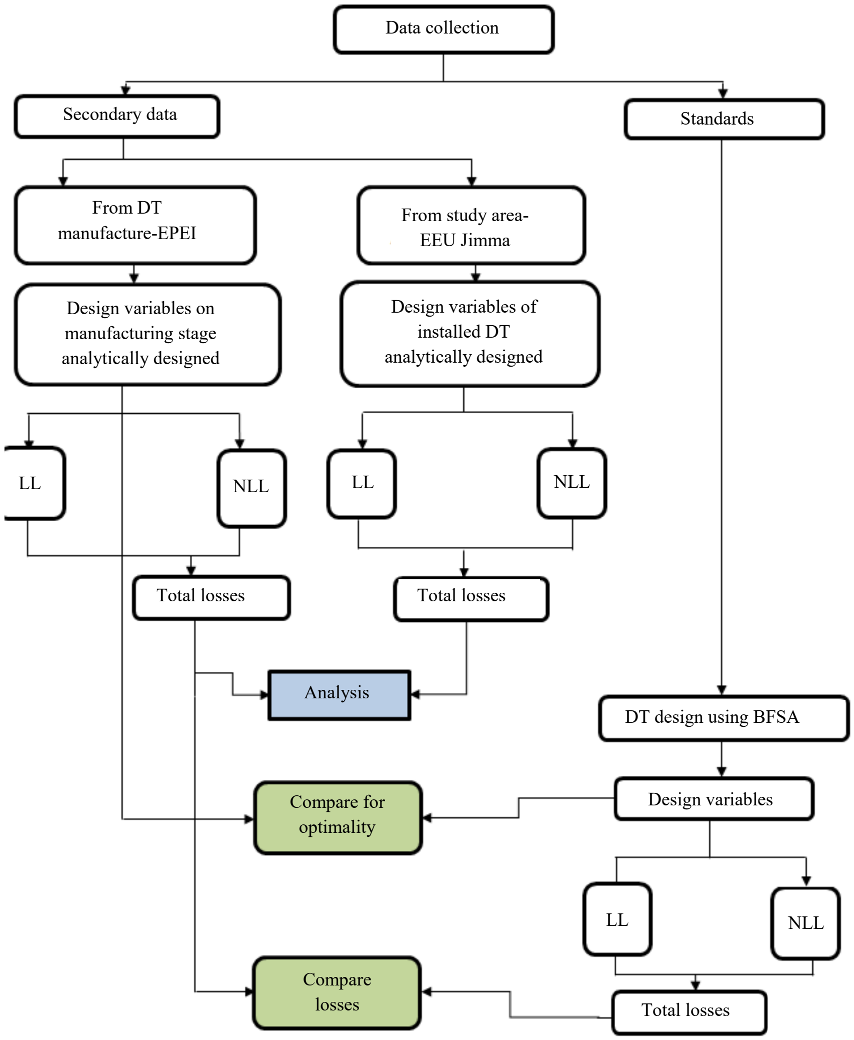

Fig. 1: Methodology flow chart

$$\text{Minimize}\,TL = \sum(NLL + LL) \quad (1)$$

Where:

TL = Total losses in a distribution transformer

NLL = No-load loss of a distribution transformer in W, LL is load loss of a distribution transformer in W

No-load loss: The no-load loss of a distribution transformer is calculated by:

$$NLL = W_C \times BF \times Loss / Kg \quad (2)$$

Where:

W_C = The weight of the core

BF = A building factor, Loss/kg is a specific loss

But:

$$W_C = \left[A_G \times SF \times \left(3 \times CWH + 2 \times CYL\right) \times 7.65 \times 10^{-4}\right]$$

Where:

A_G = The gross area of the core

SF = Stacking factor

CWH = Core window height

CYL = Core yoke length

So:

$$NLL = \left[A_G \times SF \times \left(2 \times CYL + 3 \times CWH\right) \times 7.65 \times 10^{-4}\right] \times BF \times loss/kg \quad (3)$$

From:

$$E_t = 4.44 \times f \times Bm \times A_G \times 10^{-4}$$

$$A_G = \frac{E_t}{4.44 \times f \times B_m} \times 10^{-4} \quad (4)$$

Where:
E_t = Volt per turn
F = Frequency
Bm = A magnetic flux density

It is known that, $E_t = K\sqrt{KVA}$ substitute this equation into Eq. 4. Where, K is empirical constant, KVA is a rating of the transformer:

$$A_G = \frac{10000 \times K\sqrt{KVA}}{4.44 \times f \times B_m}$$

$$A_G = \frac{2252.25 \times K\sqrt{KVA}}{f \times B_m} \quad (5)$$

The core yoke length is given by:

$$CYL = 2\begin{bmatrix} \text{Core diameter} + 2(Gap_{Core-LV}) + \\ 2(RB_{LV Coil}) + 2(Gap_{HV-LV}) + \\ 2(Gap_{HV limb-phase}) \end{bmatrix}$$

But, core diameter = $2R_C$:

$$CYL = 4\begin{bmatrix} R_C + 2(Gap_{Core-LV}) + (RB_{LV Coil}) + \\ (Gap_{HV-LV}) + (Gap_{HV limb-phase}) \end{bmatrix} \quad (6)$$

It is known that CWH is equal to the axial length of the LV coil with packing. Further, it is assumed that the ratio of core window height to core window width for 315 kVA distribution transformer is 3. Thus:

$$\frac{CWH}{CWW} = 3 \quad (7)$$

From Eq. 7:

$$CWH = 3 \times CWW \quad (8)$$

But:

$$CWW = \frac{CYL}{2} - \text{Core diameter}$$

Where, CWW is Core Window Width:

$$CWW = \frac{CYL - 4R_C}{2} \quad (9)$$

Substitute Eq. 6 into Eq. 9:

$$CWW = 2\begin{bmatrix} (Gap_{Core-LV}) + (RB_{LV Coil}) + \\ (Gap_{HV-LV}) + (Gap_{HV limb-phase}) \end{bmatrix} \quad (10)$$

Substitute Eq. 10 into Eq. 8:

$$CWH = 6\begin{bmatrix} (Gap_{Core-LV}) + (RB_{LV Coil}) + \\ (Gap_{HV-LV}) + (Gap_{HV limb-phase}) \end{bmatrix} \quad (11)$$

The corresponding stacking factor for 0.27 mm lamination thickness is 0.965. The specific loss (loss/kg) at a given for a 27-M4 grade of core (value is taken from standard core characteristics curve available) is 1.0 W/kg.

Now, substitute the above equations 5, 6, 11 and SF as well as loss/kg values on Eq. 3:

$$NLL = \frac{43.23 \times K \times \sqrt{KVA} \times BF \times \begin{bmatrix} R_C + (Gap_{Core-LV}) + \\ (RB_{LV Coil}) + (Gap_{HV-LV}) + \\ (Gap_{HV limb-phase}) \end{bmatrix}}{f \times B_m} \quad (12)$$

where, NLL is a no-load loss in W, objective function to be minimized, K is an empirical constant value, input data, kVA is the rating of transformer in kilo volt-ampere, input data, BF is building factor, input data, R_C is core radius in mm, the initial value of design variable, $Gap_{Core-LV}$ is core to LV coil clearance in mm, input data, RB_{LVCoil} is radial build of LV coil in mm, input data, Gap_{HV-LV} is HV and LV coil clearance in mm, input data, $Gap_{HVlimb-Phases}$ is HV limb and phases clearance in mm, input data, f is a frequency in Hz, input data, B_m is magnetic flux density in T, input data.

Load loss: The load loss in the transformer is given by:

$$LL = \text{Ohomic losses} + \text{Stray losses} \quad (13)$$

where, LL is load loss in ad distribution in W. Further, the ohmic loss is given by:

$$\text{Ohmic losses} = I_{HV}^2 R_{HV} + I_{LV}^2 R_{LV} \quad (14)$$

where, I_{HV} is primary (HV side) current per phase in A, R_{HV} is HV winding resistance per phase in Ω I_{LV} s primary (LV side) current per phase in A, R_{LV} is LV winding resistance per phase in Ω. It is known, the primary (HV side) current per phase is given by:

$$I_{HV} = \frac{1000 \times KVA}{3 \times V_p} \quad (15)$$

where, VP is the primary voltage in V. It is also known that the HV winding resistance per phase is given by:

$$R_{HV} = \frac{\rho_{Copper} \times MLT_{HV} \times N_{HV} \times 10^{-3}}{A_{Wire}} \quad (16)$$

where, ρ_{Copper} is the resistivity of electrolytic copper and is equal to 0.021, MLT_{HV} is the mean length of HV winding in mm and is given by:

$$MLT_{HV} = \pi(ID_{HV} + RD_{HV}) = \pi\begin{bmatrix}(OD_{LV} + (2 \times Gap_{HV-LV})) + \\ NL_{HV} \times D_{Wire} + N_{HV-duct} + \\ (NL_{HV} - 1) \times T_{HV-ins}\end{bmatrix} \quad (17)$$

But:

$$OD_{LV} = Core\,diameter + 2 \times Gap_{Core-LV} + 2 \times RB_{LV\,Coil}$$

And it is known that core diameter = $2R_C$. So:

$$OD_{LV} = 2(R_C + Gap_{Core-LV} + RB_{LV\,Coil}) \quad (18)$$

Hence:

$$MLT_{HV} = \pi\begin{bmatrix}2\begin{pmatrix}R_C + Gap_{Core-LV} + RB_{LV\,Coil} + \\ Gap_{HV-LV}\end{pmatrix} + \\ NL_{HV} \times D_{Wire} + N_{HV-duct} \times T_{duct} + \\ (NL_{HV} - 1) \times T_{HV-ins}\end{bmatrix} \quad (19)$$

But:

$$N_{HV} = \frac{V_p}{K \times \sqrt{KVA}} \text{ and } T_{HV-ins} = \frac{K\sqrt{KVA} \times N_{HV\,PL}}{4400} \quad (20)$$

Therefore:

$$MLT_{HV} = \pi\begin{bmatrix}2\begin{pmatrix}R_C + Gap_{Core-LV} + \\ RB_{LV\,Coil} + Gap_{HV-LV}\end{pmatrix} + \\ NL_{HV} \times D_{Wire} + N_{HV-duct} \times \\ T_{duct} + (NL_{HV} - 1) \times \frac{K\sqrt{KVA} \times N_{HV\,PL}}{4400}\end{bmatrix} \quad (21)$$

$$A_W = \frac{\pi \times D_{Wire}^2}{4} \quad (22)$$

Now, substitute Eq. 20-22 into Eq. 16:

$$R_{HV} = \frac{0.084 \times \frac{V_p}{K \times \sqrt{KVA}} \times 10^{-3}\begin{bmatrix}2\begin{pmatrix}R_C + Gap_{Core-LV} + \\ RB_{LV\,Coil} + Gap_{HV-LV}\end{pmatrix} + \\ NL_{HV} \times D_{Wire} + N_{HV-duct} \times T_{duct} + \\ (NL_{HV} - 1) \times \frac{K\sqrt{KVA} \times N_{HV\,PL}}{4400}\end{bmatrix}}{D_{Wire}^2} \quad (23)$$

Secondary current per phase:

$$I_{LV} = \frac{1000 \times KVA}{\sqrt{3} \times V_S} \quad (24)$$

$$R_{LV} = \frac{\rho_{Copper} \times MLT_{LV} \times N_{LV} \times 10^{-3}}{T_{foil} \times W_{foil}}$$

But $\rho_{Copper = 0.021}$:

$$MLT_{LV} = \pi(ID_{LV} + RD_{LV}) = \pi\begin{bmatrix}\begin{pmatrix}Core\,diameter + \\ (2 \times Gap_{Core-LV})\end{pmatrix} + \\ N_{LV} \times T_{foil} + N_{duct} \times T_{duct} + \\ (N_{LV} - 1) \times T_{LV-ins}\end{bmatrix} \quad (25)$$

where, MLT_{LV} is mean length of LV winding (mm). It is known that core diameter = $2R_C$. So:

$$MLT_{LV} = \pi\begin{bmatrix}2(R_C + (Gap_{Core-LV})) + N_{LV} \times \\ T_{foil} + N_{duct} \times T_{duct} + (N_{LV} - 1) \times T_{LV-ins}\end{bmatrix} \quad (26)$$

So:

$$R_{LV} = \frac{0.0659 \times \begin{bmatrix}2(R_C + (Gap_{Core-LV})) + \\ N_{LV} \times T_{foil} + N_{duct} \times \\ T_{duct} + (N_{LV} - 1) \times T_{LV-ins}\end{bmatrix} \times N_{LV} \times 10^{-3}}{T_{foil} \times W_{foil}} \quad (27)$$

Therefore, the ohmic loss for a three-phase distribution transformer is calculated:

$$Ohmic\,losses = 3I_{HV}^2 R_{HV} + 3L_{LV}^2 R_{LV}$$

$$\text{Ohmic losses} = \left[\frac{1000\times \text{KVA}}{\sqrt{3}\times V_S}\right]^2 \times \frac{0.252\times\frac{V_p}{K\times\sqrt{\text{KVA}}}\times 10^{-3}\left[2\begin{pmatrix}R_C+\text{Gap}_{\text{Core-LV}}+\\ RB_{\text{LV Coil}}+\text{Gap}_{\text{HV-LV}}\end{pmatrix}+\begin{matrix}NL_{HV}\times D_{\text{Wire}}+N_{\text{HV-duct}}\times\\ T_{\text{duct}}+(NL_{HV}-1)\times\\ \frac{K\sqrt{\text{KVA}}\times N_{\text{HV PL}}}{4400}\end{matrix}\right]}{D^2_{\text{Wire}}} + \left[\frac{1000\times \text{KVA}}{\sqrt{3}\times V_S}\right]^2 \times \frac{0.0001977\times\begin{bmatrix}2(R_C+(\text{Gap}_{\text{Core-LV}}))+\\ N_{LV}\times T_{\text{foil}}+\\ N_{\text{duct}}\times T_{\text{duct}}+\\ (N_{LV}-1)\times T_{\text{LV-ins}}\end{bmatrix}\times N_{LV}}{T_{\text{foil}}\times W_{\text{foil}}} \quad (28)$$

where, kVA is the rating of transformer, input data V_P is primary side voltage (v), input data, K is an empirical constant value, input data, R_C is core radius (mm), the initial value of design variable, $\text{Gap}_{\text{core-LV}}$ is core to LV Coil Clearance (mm), input data, RB_{LVCoil} is radial build of LV Coil (mm), input data, $\text{Gap}_{\text{LV-HV}}$ is HV and LV Coil Clearance (mm), input data, NL_{HV} is the HV Number of Layers, the initial value of the design variable, D_{wire} is copper wire diameter (mm), the initial value of design variable, N_{HV}-duct is the number of primary cooling ducts, the initial value of design variable, T_{duct} is cooling duct thickness (mm), input data, is primary (HV) turns per layer, the initial value of design variable V_s is secondary side voltage (v), input data, N_{LV} is LV number of turns, the initial value of design variable, Tfoil is secondary copper foil thickness (mm), the initial value of design variable, $N_{\text{LV-duct}}$ is the number of secondary cooling ducts, the initial value of design variable, TLV-ins is the thickness of insulation between LV turns (mm), input data, Wfoil is Secondary Copper foil width (mm), the initial value of design variable:

$$\text{Stray losses} = \text{Ohmic losses}\times(0.0393)\times(\text{KVA})^{0.2056} \quad (29)$$

Therefore, LL (W) = ohmic losses+stray losses:

$$\text{LL} = \text{Ohmic losses} + \text{Ohmic losses}\times(0.0393)\times(\text{KVA})^{0.2056} \quad (30)$$

where, LL is Load Loss in W, objective function to be minimized, kVA is the rating of transformer, input data. Therefore, the objective function becomes:

$$\text{Minimize TL} = \sum(\text{NLL}+\text{LL})$$

Design constraints: Although, each design variable is chosen arbitrarily from within a given range, the combination of the variables for the transformer's complete design has to adhere to all the operational constraints.

Load and no load losses: The total loss in a transformer is equal to the sum of the no-load and load losses. Manufacturers are forced to have designs with a limited amount of these losses, the constraint for the maximum losses are:

$$\text{NLL}\le\text{NLL}_{\max} \quad (31)$$

$$\text{LL}\le\text{LL}_{\max} \quad (32)$$

Percentage impedance (%Z): Transformer designers aim to achieve an optimal design that operates within the limits of the minimum and maximum specified transformer impedance value. For this reason, the main objective of a transformer designer is to obtain the best possible compromise between very low levels of impedance which in turn limits the fault current to a tolerable magnitude and a high level of the impedance value that can be dealt with without the need of excessive system regulation. This puts pressure on manufacturers to have the smallest possible range of impedance values for their transformers. Manufacturers usually abide by international standards by which a very tight tolerance is allowed based on the standard. A tolerance of ±10% is accepted according to the IEC60076 standard. The impedance value constraints can be expressed as the following:

$$\%Z_{\min}\le\%Z_G\le\%Z_{\max} \quad (33)$$

where, $\%Z_{\min}$ is the minimum accepted impedance = $0.900\%Z_G$ as per IEC, $\%Z_{\max}$ is the maximum accepted impedance = $1.100\%Z_G$ as per IEC. In which $\%Z_G$ is the guaranteed impedance value requested by the customer. The formula commonly used for calculating percentage reactance is as follows:

$$X(\%) = \frac{7.91\times f\times I_{LV}\times N^2_{LV}\times\pi\times MD_{\text{LVHV}}}{\left(\frac{V_S}{\sqrt{3}}\right)\times A_L}\times\left(\text{Gap}_{\text{HV-LV}}+\frac{RB_{\text{LV Coil}}+RB_{\text{HV Coil}}}{3}\right)\times 10^{-7} \quad (34)$$

where, f is rated frequency in Hz, input data, ILV is rated secondary current:

$$I_{LV} = \frac{1000\times\text{KVA}}{\sqrt{3}\times V_S} \quad (35)$$

where, kVA is the rating of transformer, input data, V_S is rated secondary voltage per phase, input data, NLV is LV number of turns, the initial value of design variable, MD_{LVHV} is the mean diameter of LV and HV coil in mm:

$$MD_{LVHV} = \left(\frac{\left(\begin{array}{l} 4R_C + 4Gap_{Core-LV} + 3RB_{LVCoil} + \\ 2Gap_{HV-LV} + Gap_{HVlimb-phase} \end{array} \right)}{2} \right) \quad (36)$$

where, R_C = Core Radius (mm), initial value of design variable, $Gap_{core-LV}$ is core to LV Coil Clearance (mm), input data, RB_{LVCoil} is radial build of LV Coil (mm), input data, Gap_{HV-LV} is HV and LV Coil Clearance (mm), input data, $Gap_{HVlimb-Phases}$ is HV limb and Phases Clearance (mm), input data. A_L is the average length of LV and HV coil in mm:

$$A_L = CWH = 6\left[\begin{array}{l} (Gap_{Core-LV}) + (RB_{LVCoil}) + \\ (Gap_{HV-LV}) + (Gap_{HVlimb-phase}) \end{array} \right] \quad (37)$$

where, GapHV-LV is the radial gap between HV and LV coil in mm, input data, RB_{LVCoil} is radial build of LV coil in mm, input data and RB_{HVCoil} is radial build of HV coil in mm, input data. The formula commonly used for calculating percentage resistance is as follows:

$$R(\%) = \frac{LL(in\,KW)}{KVA} \times 100 \quad (38)$$

where, LLis Load Loss(W),kVA is the rating of transformer, input data. Percentage impedance is the vector sum of percentage reactance and percentage resistance and is represented as:

$$Z(\%) = \sqrt{(X\%)^2 + (R\%)^2} \quad (39)$$

As per International Electro-technical Commission (IEC) standard percentage of short circuit impedance at rated current for the rated power up to 630kVA distribution transformers is 4%. For a distribution transformer with two windings when the percentage of short circuit impedance value is <10% tolerance of ±10% of the declared value is allowed.

Efficiency: The insulation layer of press paper between the windings is designed to have certain withstanding capabilities. The efficiency at rated load and unity power factor is calculated:

$$\%\eta = \frac{KVA}{KVA + NLL\,in\,KW + LL\,in\,KW} \times 100\% \quad (40)$$

$$\eta_{min} \le \eta_{transformer} \quad (41)$$

Implementation of brute force search algorithm for the distribution transformer design optimization: In this section, the actual implementation of the program for the design process is developed using the mathematical model of the transformer design. The section lists the steps of the implemented program and will briefly explain it starting from the data entry depending on the transformer characteristics until the final step which is the calculation of the total losses of the transformer design.

Brute force search algorithm: A brute force search algorithm is a general problem-solving technique that computes all possible candidates for the solution and checks whether each candidate satisfies the problem's statement. The algorithm is simple to implement and it will always find a solution if it exists, The method is also used when the simplicity of implementation is more important than speed. A Brute force search algorithm is a guaranteed way to find the correct solutions to a problem because it tests every possible candidate as an answer. A brute force search algorithm is selected due to its wide applicability, simplicity and to yield reasonable results. Its weakness is its time complexities grow exponentially with problem size[6].

Input data: The data entry stage of the program is the first step in which the required transformer characteristics are set, most of these characteristics are provided by the customer and the manufacturer only sets the standards to be used which could differ from one manufacturer to another[7].

Below are lists for the data entry for a three-phase core type oil immersed three phase distribution transformer with a primary connection of delta and secondary connection star having M4 grade core material of 0.27 mm thick:

- Transformer rating in kilo volt ampere (kVA) = 315
- Primary voltage in volts = 15000
- Secondary voltage in volts = 400
- Empirical value of K = 0.41
- Rated frequency in Hz = 50
- Core building factor = 1.15
- Magnetic flux density in Tesla = 1.7
- T_{LV-ins} in mm = 0.02
- T_{duct} in mm = 1
- $Gap_{HVlimb-Phases}$ in mm = 38
- RB_{LVCoil} in mm = 15
- $Gap_{Core-LV}$ in mm = 10
- Gap_{HV-LV} in mm = 10
- RB_{HVCoil} in mm = 38

Table 3: Design variables lower and upper bounds

Design variables	Lower bound	Upper bound
Secondary number of turns	27	37
Core radius	83	113
Primary wire diameter	1.7	2.7
Secondary foil width	271	367
Secondary foil thickness	2.1	2.9
Secondary number of cooling ducts	1	2
Primary number of cooling ducts	1	2
Turns per HV layer	62	86
Primary number of layers	15	21

Table 4: Design constraints for 315 kVA distribution transformer

Design constraints	Values
Maximum allowed load loss in W	<4600
Maximum allowed no load loss in W	<800
Guaranteed percentage of impedance in %	$3.6\leq Z\leq 4.4$
Efficiency in %	≥98

Lower and upper bounds: The lower and upper bounds are fixed for the available and manufactured range for the design variables. For this research, based on practical manufacturability and availability, the design variable's lower and upper bounds are selected by taking ±15% values of the design variables used by the transformer manufacturer EPEI. Table 3 displays the lower and upper bounds of the design variables[8].

Transformer design constraints: Every design has to comply with a set of constraints according to standards to ensure a proper and safe operation of the transformer. Table 4 lists the constraints used for the design of the 315 kVA transformer.

Process of design optimization: Next is the optimization process that takes place looking for an optimal transformer design. The process starts at the lower bound initial values and searches within the range of the upper and lower bounds using the specified non-linear inequality constraints.

Total losses calculation: After the optimal design variables are obtained, the no-load loss and load loss for the distribution transformer to be designed are calculated. Finally, a total loss is calculated by the summation of the no-load loss and load loss[9].

RESULTS AND DISCUSSION

The results of the design variables from the analytically designed transformer and optimal transformer design variables found using the Brute force search algorithm (BFSA) are shown in Table 5.

The design output shows that the design variables using the analytical method are different from that of using the Brute force search algorithm (Table 6).

Regarding the losses on the existing distribution transformers, a 730 W no-load loss and a 3300 W load loss were reported, this is confirmed by the manufacturer Ethiopian Power Engineering Industry by taking a sample test value of delivered 315 kVA distribution transformer to the customer. The designed transformer using the Brute force search algorithm has a no-load loss of 702.24 W and a load loss of 1,985.32 W. The calculated percentage of short circuit impedance value 3.61% is acceptable as it is in the range of (3.6-4.4%) as stated on IEC 60076-1.

Further, the optimally designed transformer has an efficiency of 99.15% which is higher than the transformer designed analytically.

Table 5: Comparison of design variables

Design variables	Analytical	BFSA
Secondary number of turns	32	30
Core radius	98	92
Primary wire diameter	2.1	2.5
Secondary foil width	319	271
Secondary foil thickness	2.5	2.5
Secondary number of cooling ducts	2	1
Primary number of cooling ducts	2	1
Turns per HV layer	74	62
Primary number of layers	18	15

Table 6: Comparison of losses, percentage of impedance and efficiency

Parameters	Analytical	BFSA	Standard
No load loss(W)	730	702.24	<800
Load loss(W)	3300	1985.32	<4600
Impedance (%)	3.80	3.61	$3.6\leq Z\leq 4.4$
Efficiency (%)	98.73	99.15	≥98

CONCLUSION

This study considers analysis and design which gives all the acceptable solutions, design dimensions and performance parameters of a loss minimized distribution transformer. This study presented the analytical and algorithm-based design results regarding the reduction of distribution transformer losses. From the optimal design output, the no-load loss is 702.24 W and the load loss is 1,985.32 W. The results from the optimization algorithm show that the design reduces the total losses on the existing distribution transformer selected for the study from 4,030-2,687.56 W by 1,342.44 W, thus, representing a percentage reduction of 33.31%. If this saving is applied to the existing 48, 315 kVA distribution transformers of the Jimma town route of the case study area, the saving will be 64,437.12 W. To put 64,437.12 W savings into context: 64,437.12 W is equivalent to 4,296 units of 15 W fluorescent light bulbs enough for 1,074 small houses (with 4 bulbs per house). In terms of energy saving, applying the design on the 48 distribution transformers can bring 564,469.17 kWh/year (1.34244k W*48*8760 h/year). Note that, this is the saving associated with replacing only 48, 315 kVA distribution transformer units. If the designed transformer is to be implemented on a larger scale across the electrical distribution networks of Ethiopia, the magnitude of savings would be huge[10].

RECOMMENDATIONS

This study work does not include the design of the body/tank of the transformer. Thus, it is recommended to be included in future work for complete transformer design. The design is new and has not been tested earlier in service, thus, it is further recommended if a proto-type transformer will be manufactured and the practical test would be made before undertaking commercial production.

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