A Novel Method to Enhance the Core Design of Power Transformers Using Particle Swarm Optimization (PSO) Technique

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Abstract **- The reduction of losses in a power transformer is a significant topic in a power transmission grids, with the design of the core being one of the important factors related to the losses. In this study, an intelligent algorithm is developed using Particle Swarm Optimization (PSO) technique to find the optimum core design. Using a smart algorithm we consider a novel method to reduce the losses. To achieve this target, a nonlinear B-H curve with a 3D Finite-Element Method (FEM) is used to simulate the proposed model of core coupling with the PSO technique. Steady state analysis is considered in the simulation and the losses of the core and windings were considered a heat source inside the transformer. The results show core losses are reduced by 11 % and 5 % was achieved by the proposed model compared with the 90° butt-lap and 45° mitred designs respectively. The results were validated against the manufacturer's experimental measurements. Our proposed optimization techniques can be used to improve performance of electrical power transformers and can be applied to various transformers of different sizes and power rating.**

Keywords - Particle swarm optimization (PSO); power transformer; core losses; joint design; finite elements (FM)

I. Introduction

Power transformers are thought to be one of the most important components of a power system and their efficiency can reach up to 98% [1]. In the EU-25 group of countries, core loss accounts for almost 70 % of the total transformer losses while the operating (or energy) efficiency can be as high as 93.38 %. There is worldwide concern about core losses which should ideally be reduced [2]. In electrical transformers, losses are an important factor in thermal designs and electromagnetic analyses [3], [4]. In recent decades there has been great and rapid change in the manufacture of electrical transformers [5]–[10]. Although there has been extensive research into improved techniques in transformer structures such as in the automotive, aeronautical and electrical industries, the applications of these techniques in electrical engineering remain limited.

Previous comprehensive studies on the behaviour of the geometry of the T-joint have mainly assessed the performance under a no-load condition. However, the behaviour of the T-joint is depending on many factors such as gaps, shape of joints, overlapping distance, materials [11]–[15] and etc. Most of the previous studies have considered only a part of the core design under no-load conditions while it is known that the load has a direct effect on the values of flux distribution and consequently the loss distribution. Moreover, the thermal distribution of the core and oil transformer has been taken into account in this work because these matters not addressed has been done in most of the previous research.

In this paper a smart algorithm has been proposed in order to reach the optimum design of a new T-joint to reduce the losses. The simulation model was designed as a full-size geometry core for a 1 MVA three-phase distributing transformer. The main apparatus consisted of a real model core of three-phase transformer assembled with three limbs three-legs which has a rating of 11 / 0.433 KV.

In order to validate this work, real data from the transformer manufacturer has been used to simulate the core with windings in T-joint cut as a butt-lap 90° and a 45° mitred arrangement assembled from grain orientated silicon steel (CRGO) grades M5 material.

II. Current Core Joints Designs in Transformers

In order to place the windings in a suitable place inside the core, the top yoke must be open so that the windings can be installed on the central arm. Afterwards, the electromagnetic circuit is closed by returning the yoke to its normal place in the core. For this reason, joints appear in the core of a transformer. The different types of T-joint design that have been examined in numerous previous works [16], [17] namely 90°butt-lap and mitred 45°T-joint designs that have also been investigated in many previous research studies. However, the fundamental relationship between magnetic flux density (B) and flux is:

$$B = \text{Ø}/A \tag{1}$$

Where:
B = flux density in tesla (weber / square meter)
Ø = core flux in lines
A= core cross-section area
The magnetic flux density in the core is determined by the voltage per turn:

$$E = \frac{V}{N} = 4.44 \times f \times B_m \times A \quad (2)$$

The diameter of the core must be optimized during designing of transformer core, considering both the aspects. As approximate rough rule, increase 1% of B causes increase a 2% of the losses [18]. It is appearing clearly from this short introduction in above, the flux density (B) play the essential factor for the losses in transformer. Moreover, according to what has been mentioned in the literature, joints shape considers one of the key which able to changing the direction and the value of flux density (B) inside the transformer. Rotating and circulating flux appear in the area of the joint as a result of stacking the flux in the joints because of the gaps between the laminations. Most of the hot spot areas can found in the area of the joints, which gives an indication that the losses have increased in this area as compared with other areas in the core. Furthermore, additional losses occur in the joint area as a result of changing the flux path direction by about 90° to follow the rolling direction of the material. Nevertheless, from a research view which is in touch with core performance, there are some significant issues which should be highlighted to gain a good knowledge to attempt to understanding the core behaviour.

There are numerous substantial points and gaps that can be highlighted in the former studies. Some of the hypotheses in the previous studies do not address some significant points. The research gaps in the existing literature can be summarised as:

- No mathematical equation can give the values of these angles for T-joint design.
- There is no standard that can be considered as a reference to design the optimum joint geometry shapes.
- The issue of the correlation between the T-joint angle designs with the gaps in the joint area has not been addressed. However, in this paper, by using a smart algorithm, the correlation between the design of the angle and the gaps will be considered.
- No significant study has been done on the design of the T-joint and gaps under different load conditions as most previous studies have only considered the no load condition. In this paper the T-joint parameters have been designed by considering the load effects on the transformer performance using a proposed intelligent algorithm.
- No significant study has been done concerning the design of the T-joint parameters in the presence of oil and considering the thermal profiles at the same time with the losses. The joint gaps inside a transformer are filled using oil and the thermal behaviour of the oil is very important especially with respect to the ageing of a new designed transformer. In this study the no-load, load losses and thermal profiles under different load conditions are considered.

III. PARTICLE SWARM OPTIMIZATION (PSO)

An algorithm can be defined as a process or set of rules to be followed in calculations or other problem-solving operations, especially by a computer. As an introduction, a swarm can be thought of as similar to the behaviour of a flock of birds, a group of ants, a school of fish, etc., which formed the field of study during the early days. Such collective motion of insects and birds is known to as "swarm behaviour." Later on biologists and computer scientists in the field of artificial life studied the modelling of biological swarms to analyse the interaction among the social animals, to achieve simulation goals, and to evolve them. Recently the interest of engineers in this field is increasing rapidly since the resulting swarm intelligence (SI) is applicable in optimisation problems in various fields such as telecommunication systems, robotics, electrical power systems, consumer appliances, traffic patterns in transportation systems, military applications, and many more [8].

Particle Swarm Optimisation (PSO) is a swarm intelligence based algorithm to find a solution to an optimisation problem in a search space, or model, and predict social behaviour in the presence of objectives as well as sharing many similarities with evolutionary computation techniques [19]. Furthermore, each particle of the PSO flies in the search area with a velocity based on its own previous ideal solution. Fig.1 displays the particle position and velocity updates for a two dimensional parameter space. The velocity comprises three main vectors [20].

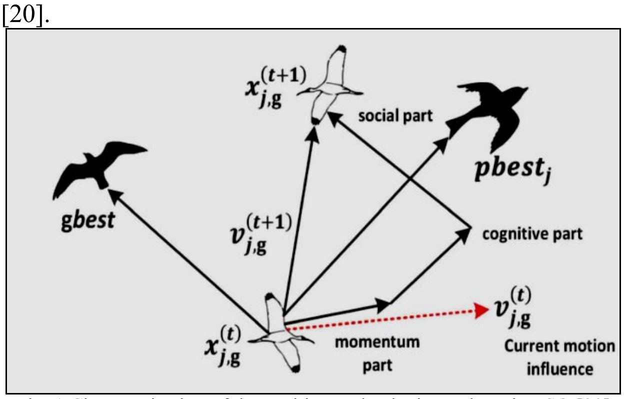

Fig. 1 Characterisation of the position and velocity updates in PSO [20]

IV. MODELLING OF TRANSFORMER

The dimensions of the core, width, length, depth, windings and oil area were used in the simulation. The relevant data for the B-H and P-B curves were obtained from the data supplied by the manufacturer [21]. The

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parameters that have an effect on the T-joint design such as angles and gaps were considered in the proposed model in this algorithm, as well as losses and temperature. The main purpose of taking real data was to reach the optimum design for the T-joint in a core transformer that can be applied in the production process and to be closer to reality. Table 1 presents the electrical parameters of the transformer which was used in the 3D finite-element analysis software.

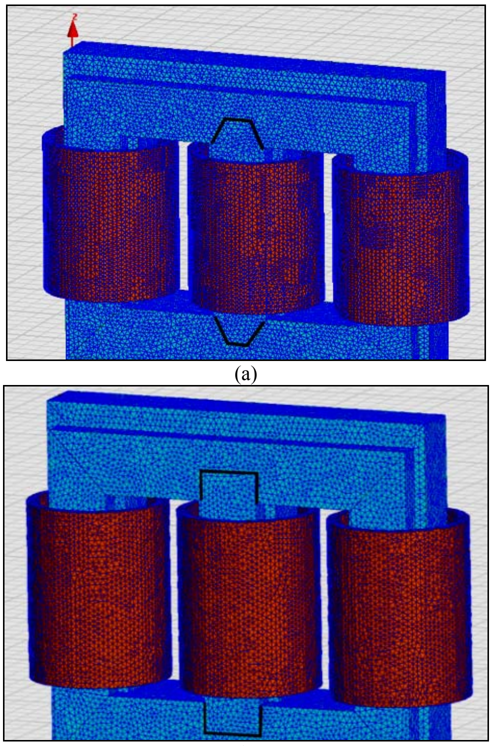
TABLE 1 ELECTRICAL PARAMETERS OF THE STUDIED TRANSFORMER

Parameters	Value	Unit
Rated capacity	1000	KVA
Rated frequency	50	Hz
Voltage ration	11/0.433	KV
no-load loss	1496	Watt
Material Grade (CRGO)	M5	------
Flux density	1.584	Tesla
Cooling type	ONAN	------
Core and winding weight	1185	Kg

Furthermore, to compare the results between the proposed model with the conventional designs, two types of T-joint designs were applied, namely, 90° butt-lap and 45° mitred T-joint designs with 45° outer corners. Due to the slight thickness of the core laminations, it is difficult to analyse the 3-D magnetic field in each separate thin core sheet. To avert this modelling annoyance, the core frame was assumed to be a solid part [22]. The simulation for the 3D design was accomplished using ANSYS software according to a sketch of the geometry model for a three-phase transformer. The specific parameters for the oil transformer were taken from [23] to provide realistic data in this simulation.

Moreover, the optimum nodes of the mesh number depend on the geometry of the sample under the run and the accuracy which is needed. In this study high resolution meshing was assigned to the problematic regions of all the different T-joint designs in the core transformer. Furthermore, the number of primary windings was set to provide a magnetic flux density of around 1.56 T in the core of transformer. Nevertheless, there were many affected areas in the joints, so to cover all these regions a specific mesh was proposed for the core, windings and oil. This mesh required several million elements, which needed much time and a huge amount of computing power. Many levels of mesh resolution were considered for the core geometry to increase the accuracy of the results.

The typical mesh generated during the running of the simulation contains about 3053658 elements, consisting of 856441 elements for the core, 1497862 for the oil, 466915 for the windings. Fig. 6 illustrates the mesh analysis for the proposed design and a conventional T-joint as a 90° butt-lap and a 45° mitred design. The same numbers of mesh nodes and analysis were made for all models in order for the results to be comparative and correct for all operating conditions.



(a)

(b)

Fig. 2 3D Model mesh analysis in ANSYS Software (a)proposed design (b) 90° butt-lap design

V. METHODOLOGY AND CORE JOINT DESIGN

The angles in the butt-lap design are right angles, each of them 90° because the shape of this joint is rectangular and the distance between the joints (L) involves the width of the limb of transformer as shown in Fig. 3. While in the 45° mitred design all of the angles are acute because the shape of this joint is triangular and the value of angles α_1 and α_2 is 45° while α_3 is 90°.

However, between the 90° angle in the butt-lap and the 45° in the mitred design there is a wide range in the value of the angles. All these angles are dependent on (L) which represents the extent of changing the angles in the T-joint area in the middle limb. Because of this wide range of angles, it is possible to generate many shapes and geometries of T-joints.

However, in fact this is not considered practical or economic. Due to this, a smart algorithm is proposed to find the optimum design angles of the T-joint which depends on many factors. There are many angles ($\alpha 1$, $\alpha 2$, …, αn) which can generate many shapes of T-joint which called hexagon shape.

The main parameters which are related to the joint design in the T-section part of a core are the angles between the yokes and the middle limb. Furthermore, the distance between the angles (L) and the gaps play a part. In general, there are four angles ($\alpha 1= \alpha 2$), ($\alpha 3= \alpha 4$) as appears in Fig 4. The value of angle (αn) has been changed between 45°

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mitered design and 90° butt-lap as reported in the literature as well as the width of the gaps changed between 0.5 to 1.5 mm. These values were considered as an initial condition to run the algorithm in the proposed model and the sequence of the simulation run depended on the link between all these variables to the software.

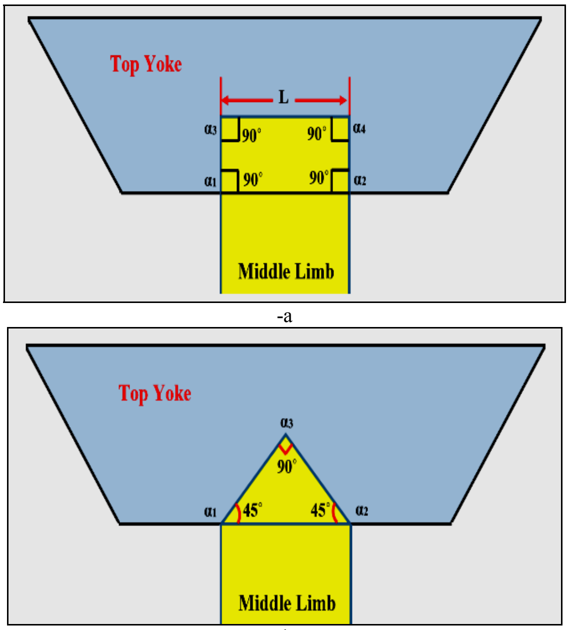

Fig. 3 Description of T-joint designs (a) 90° butt-lap (b) 45° mitred

The implementation of PSO, numerous parameters required to be identified, such as c_1 and c_2 (cognitive and acceleration factors, respectively), initial inertia weights (w), swarm size and stop criteria. Then, definition of the parameters models such as (α_1, α_2, α_3, α_4, and gap) are given in the early stage in PSO. After this stage, the initial swarm is generated, this step is still under running in several loops until reach to the maximum iterations. The output of this stage given the objective function which should be the minimum objective function. If not reach this target of the minimum objective function, a new populations start to run until reach the minimum objective function as illustrates in Fig 5.

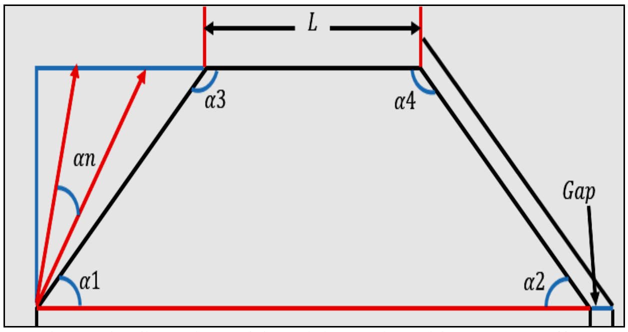

Fig. 4. The dimensions of the T-joint section with parameter effect

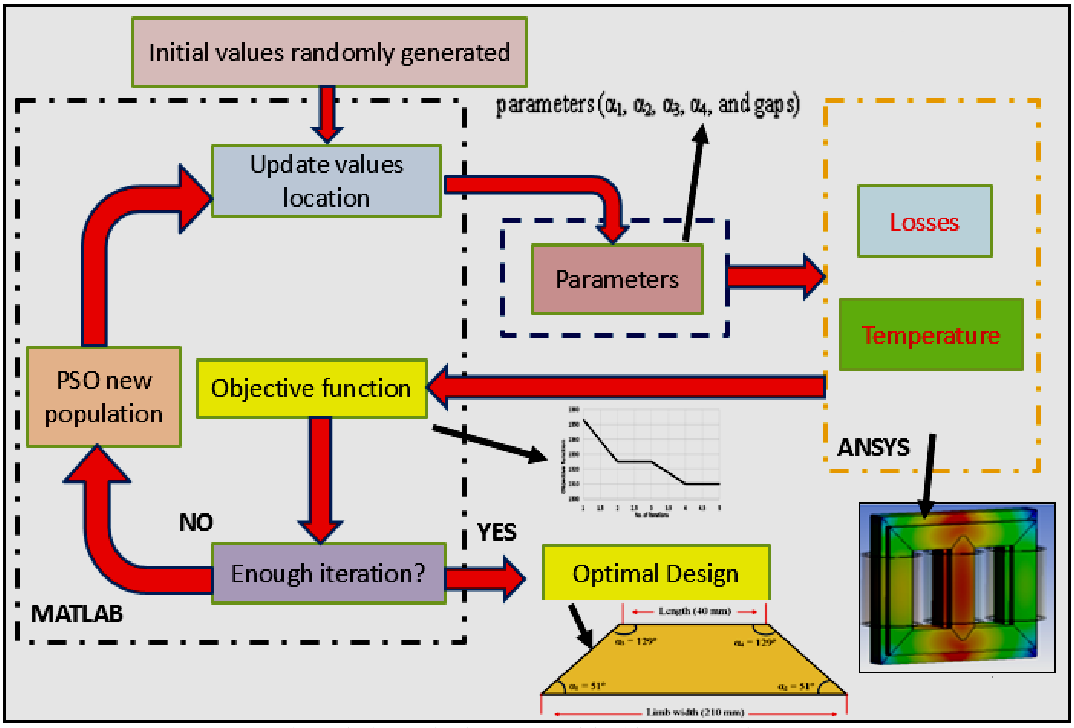

Fig. 5 The interaction between Mat lab with ANSYS software

However, when α_n was changed, the losses and temperature profiles changed as well. At the first, the propose algorithm generated the first iteration of angles depending on the information which has been provided from the literature about the range of angles and gaps. A sinusoidal voltage was applied to the windings after assigning all the materials in the transformer geometry to calculation no-load losses. The same procedures were applied for the different percentage of load by changing the load current from minimum until full load.

In the early stage of analysis, the interaction between Mat lab code for PSO and the ANSYS software appears. By taking the first generation results from the PSO, immediately, it is created a new joint design according to the angles, gap and length (L) that has been obtained. In the same stage of analysis, the losses, core and oil temperature are simulated in the ANSYS software. The output results from the ANSYS simulation in the different load condition consider the input conditions for the proposed algorithm.

After complete the iterations the output from the proposed method give us the best solution for the angles, gaps with length(L).

The main advantages of this smart algorithm are:

1) The realistic scenario between load variations with temperature profile has been examined.

2) The correlation between important parameters which affect the T-joint design has been considered.

3) In this method, reference was made to the importance of the issue of the gaps between the joints.

4) By finding the optimum design of T-joint, it may be possible to increase the lifespan of the transformers.

5) The proposed algorithm can support a wide range of distribution transformers with different rates.

6) This method will also help designers to determine suitable models for core designs.

Fig. 6 illustrates the technical perspective on the diagram of the strategy developed to obtain the appropriate design of the joint, with the variables and relevant factors being taken into consideration.

VI. RESULTS AND DISCUSSION

The data collection from the simulation results was divided into two groups, one of them related to the losses profile and the second one for thermal profile. Furthermore, the losses will be presented in two categories, namely, core losses and total losses. The core losses depend on many factors such as type of material, type of stacking the core (joint design). As a result of the simulation as shown in Fig. 7, the minimum value of the core losses was obtained by the proposed model, while the core losses were higher in the other designs.

The simulation of the transformer was run using steady state analysis. As shown, the reduction of the core losses is encouraging to continue in this area of search. The core losses were decreased in the proposed design by around 11 % as compared to the 90° butt-lap design and 5 % as compared with the 45° mitred T-joint design. Improve the design core make the flow of the flux inside the core better than the previous designs, especially at the joints area.

The normal behaviour of a transformer when the load is increased will definitely see the losses increased. However, different percentages of the load levels have been used to generate the results. All these results were compared with the conventional T-joint design (90° butt-lap and 45° mitred) against the proposed design. The total losses of the transformer (core, winding and stray losses) are considered as the main source of the losses in a three-phase transformer.

The differences are clear, and furthermore, the total losses in the full load of butt-lap design are 8534 watts while the total losses for the mitred T-joint design are 7943 watts. If a comparison is made between these losses with the optimum design of T-joint which obtained from the smart algorithm, the reduction of total losses is around 11 % and 5 % respectively.

Ones of these matters is the energy management in the power transmission grids. The reduction of the core and total losses lead to many advantages. Firstly, reducing the losses means increase the efficiency for the transformer and the end increase the efficiency for all the power transmission grids. Secondly, decrease the losses lead to increase the power deliver to the consumers which means increase in revenues of for electric power producing countries. Moreover, by using this proposed algorithm can cover different ratings of power and distribution transformers. It is clear the no-load and load losses in different levels of the load for propose model were decreased as compare with conventional T-joint design.

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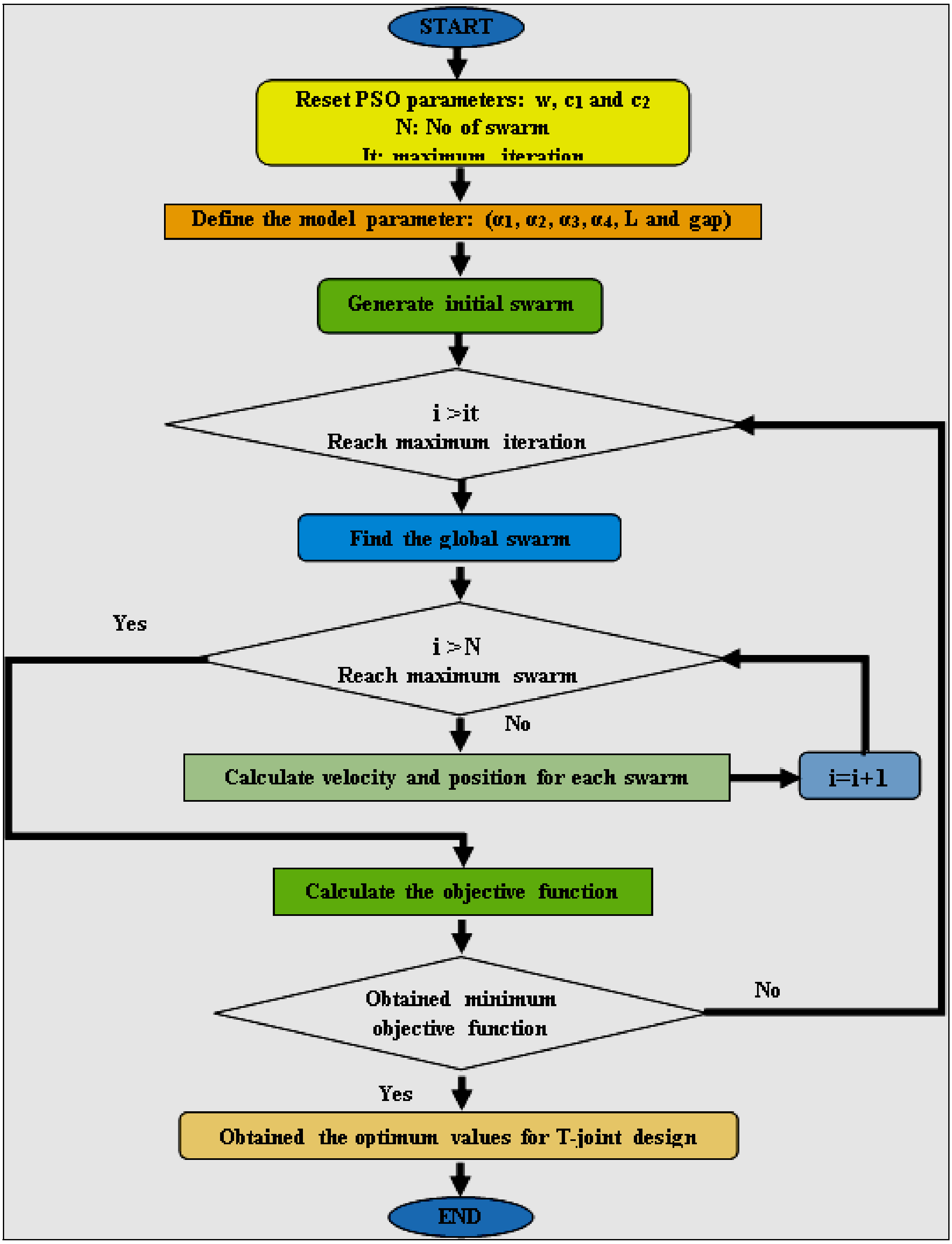
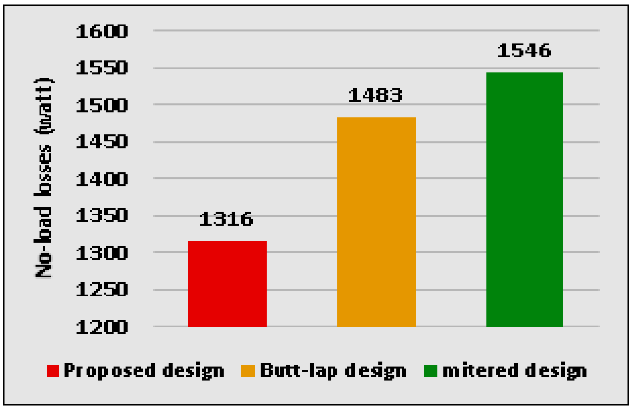
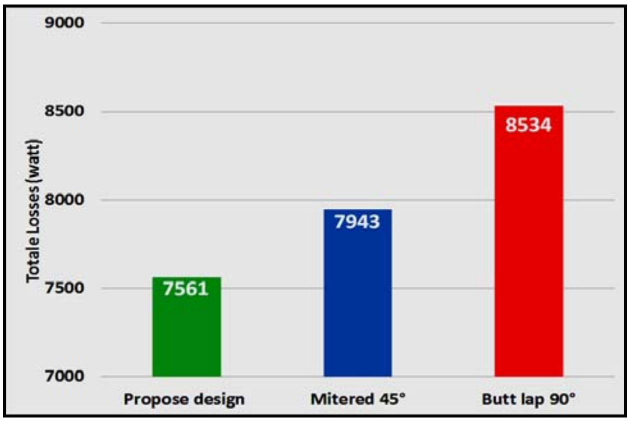


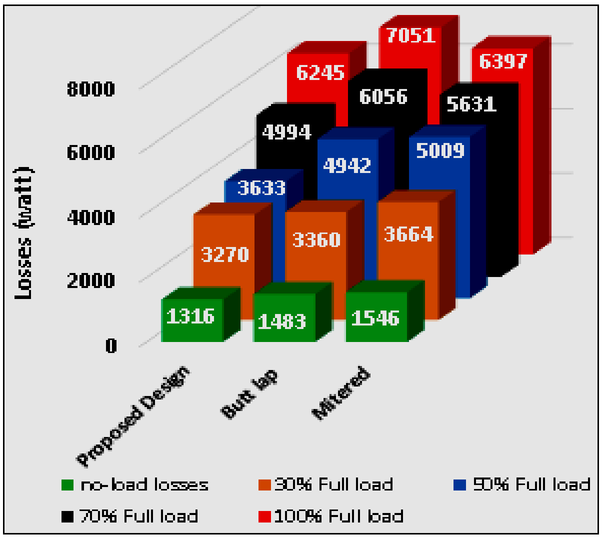
Fig 6. Technique perspective on the methodology



a.



b.



c.

Fig. 7 The losses profiles (a) Core losses in different types of T-joint designs (b) Total losses for different types of T-joint designs at full load (c) Losses in different loads

However, in the natural case for running a transformer, the core and windings are immersed in oil to reduce the temperature. The losses of the core and windings were considered a heat source inside the transformer. Actually, simulating running the transformer immersed in oil is closer to reality. Fig. 8 demonstrates the distribution of the core and windings temperature for the different T-joint designs when the transformer works on the full load. In the real, the temperature of the windings is higher than the core temperature. The reason of that, the current movement in the windings depending on the load and the value of the losses is coming from the current cross the resistance.

The same scenario has been done for the 45° mitered T-joint design and the core with windings temperature were measured. In case of full load, the oil temperature was measured between the distances from the point which is very nearest from core to the point near to wall of the tank. Because of, most of the behaviour for oil temperature is confined in this area. This means that all these points were sandwiched between the core and the tank.

The reduction of the temperature for different loads is clearly observed in these results. This matter could open a door to a new subject of study in future that useful to control the temperature profile inside the transformer. Reduction of the losses in the propose model lead to decrease the core temperature. As a result, the oil temperature inside the transformer reduced. However, the distribution of the oil temperature under different loads for different T-joint designs obtained from the simulation is present in Table II.

The highest value of the oil temperature appeared for the butt-lap design at 99 °C while the propose design for the T-joint as proposed by the algorithm indicated an oil temperature of 92 °C. In other words, the relation between the core and the oil temperature with the age of the transformer is interdependent between them. This issue leads to opening the possibility of an impetrate case study which is related to the age of transformers.

TABLE II. DISTRIBUTION OF THE OIL TEMPERATURE FOR THE DIFFERENT LOADS FOR DIFFERENT T-JOINT DESIGNS

Types of T-joint design	The Oil temperature ˚C in the different increment of the load			
	30%	50%	70%	100%
Proposed model	51	58	75.9	92.4
Butt-lap design	52.4	59.2	77.93	99
mitered design	54	59.5	78.7	94

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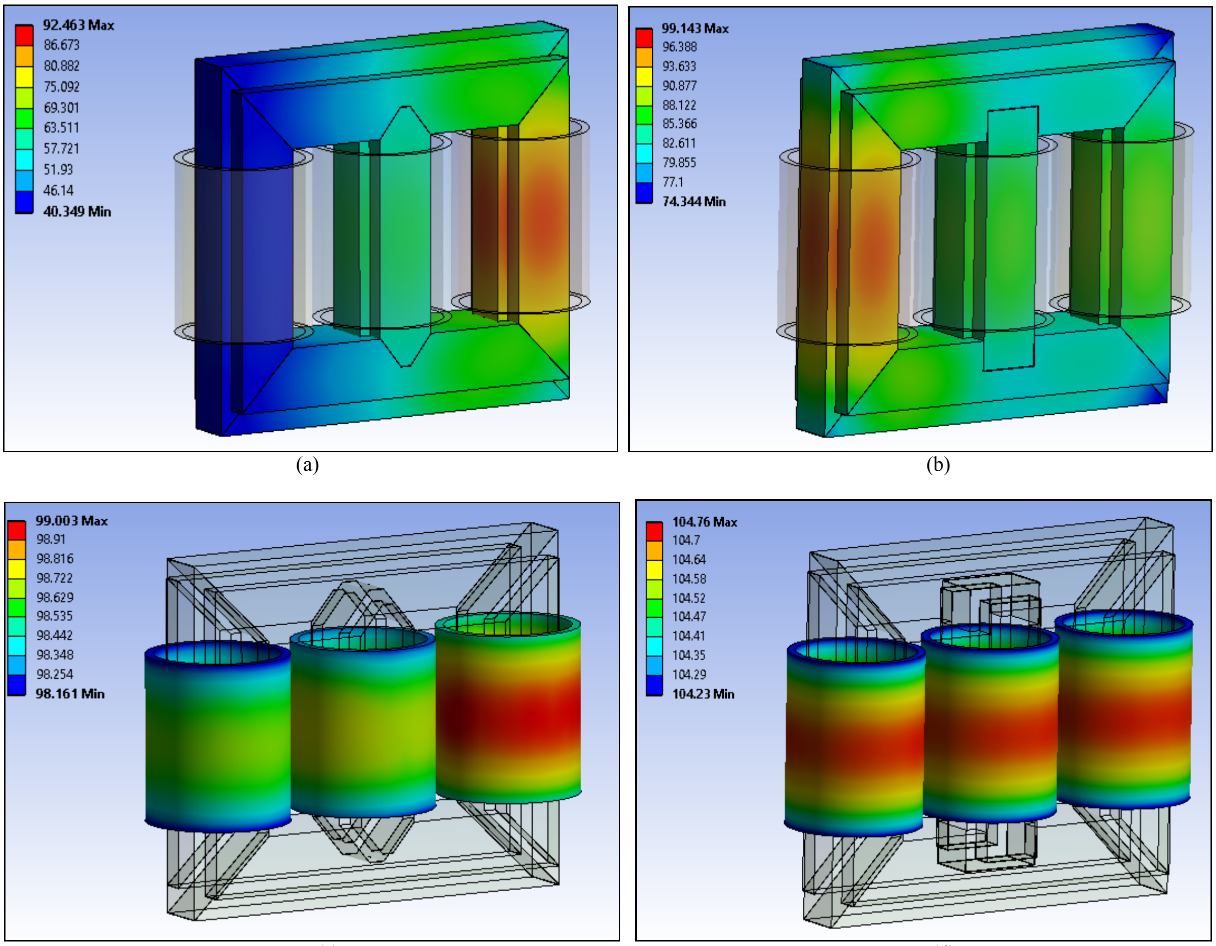

(a) (b) (c) (d)

Fig. 8. The core and windings temperature on the full load for different designs of T-joints (a) proposed design (b) butt-lap core(c) windings in proposed design (d) windings in butt-lap

VII. VALIDATION OF THE RESULTS

In order to validate the results for this work, the authors compared the results in two ways. The first way, is compare the results with the experimental measurement in the manufacturer (no-load, full load and total losses) cases for a three-phase transformer. Fig. 9 shows the experimental work for transformer type butt-lap T-joint design.

From the manufacturer's measurement, the total loss in the core with windings is approximately 9079 watts. Meanwhile, the total loss from the optimum T-joint design is 7561 watts. The losses are reduced by 16 %. Further, the no-load losses in the new proposed design are 1316 watts while in the experimental measurement the no load losses are 1496 watts. Which means more than 12% the core losses were reduced. Moreover, to provide a clear comparison between the simulation results and the experimental results, Table III illustrates the simulation results for the proposed model, conventional designs and experimental measurement in the manufacturer.

Fig. 9. The experimental test for transformer type butt-lap T-joint design

TABLE III. COMPARISON BETWEEN THE PROPOSED MODEL WITH ACTUAL MEASUREMENT IN THE MANUFACTORY

Source of data	**Core Losses watt**	**Total losses watt**
Experimental measurement tin the factory	1496	9079
Simulation model for butt-lap design	1483	8534
Simulation model for mitred design	1546	7943
Proposed model	1316	7561

The thermal limits of the transformer used in this work are within the range of some of previous studies [24]–[26] because it is crucial to know whether the results of the models in this study on the range or not . Also the guidelines, such as those provided by the IEEE standard C57.91-1995[27], the maximum oil temperature of 110 °C and winding temperature of 120 °C are imposed according to the comparative aging degree of the insulation in the transformer. These values take into consideration the maximum limits for the oil and windings. The transformer temperature has to always be lower than these limits. However, by finding the optimum design of the core transformer, this leads to reducing the power losses and reduces the temperature for the core and oil. In addition, this method useful to manage the power and energy consumed inside the transformer.

This gives cause to say that the intelligent algorithm used in this study might help to increase the lifetime of the transformer which is a significant target of most designers of transformers. Consequently, the present research work can be very useful for the design and manufacturing of transformers.

VIII. CONCLUSION

In this paper an intelligent algorithm has been proposed to find the optimum T-joint design for the core in a three-phase distribution transformer. The results obtained from this algorithm have highlighted several essential and important issues which are closely related to reducing the losses in transformers and thus reducing losses in the electrical power grids. The results present the ability of the PSO technique to assess electrical engineering problems. This indicates that PSO could be used as an effective tool to detect optimal solutions to decrease the losses in electrical machines, including power and distribution transformers with different parameters. The simulation results showed the total losses were reduced from 8534 watts 7561 watts respectively when comparing the T-joint in the optimum design with the conventional (butt-lap and proposed design). While 7943 watts, the total losses for 45° mitred T-joint designs. The temperature of the core and oil has been presented and these were found within normal standard limits. The verification of the results was compared with the results from the experimental measurement from the manufacturer. Reduction of these losses and the temperature could possibly increase the lifetime of the transformer, which is considered the main objective of most transformer designers. This algorithm can be applied to various transformer types with different rates, power capacities, and distributions, as well as different oil materials.

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