TRANSFORMER T-JOINT OPTIMIZATION USING PARTICLE SWARM OPTIMIZATION AND HEMISPHERE-SHAPE DESIGN OF THE CORE

OMAR SHARAF AL-DEEN YEHYA

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By

OMAR SHARAF AL-DEEN YEHYA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

This thesis is dedicated to my parents
For their endless love, support and encouragement

And

To my beloved family (my wife and my children)
Especially my wife who leads me through the valley of the darkness with light of hope and support
Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

TRANSFORMER T-JOINT OPTIMIZATION USING PARTICLE SWARM OPTIMIZATION AND HEMISPHERE-SHAPE DESIGN OF THE CORE

By

OMAR SHARAF AL-DEEN YEHYA

August 2017

Chairman : Professor Mohd Zainal Abidin Ab. Kadir, PhD, PEng
Faculty : Engineering

Transformers are considered as a key in the transmission and distribution of electrical energy. The increases for electricity have encouraged the manufacturers to produce huge numbers of transformers for different sizes and ratings to work on the electric grid in order to meet market demands. The electrical power engineering and transformer experts seek to achieve the best economic and practical operation of electrical power system transformers, which include minimizing losses that are generated inside the transformers. The losses in transformers can be significantly reduced, especially in the core by improving the performance of the joint design. Several factors and parameters contribute to core losses such as shape of joint, gaps in between the joint parts, thickness of laminations, overlapping, orientation and number of laminations per stack.

In this study, an intelligent algorithm was carried out using the particle swarm optimization technique (PSO) to propose the optimum design of T-joints for the core in three-phase distribution transformers. This technique was applied to design a new geometry of joint to get the minimum losses and to reduce the temperature in three-phase transformers. The smart algorithm proposed in this study presents the following advantages: (i) the correlation between the angles of the T-joint and gaps, (ii) the core loss profiles with temperature were considered, and (iii) the system was examined under different operational conditions.

The transformer was simulated on the basis of real dimensions obtained from the transformer manufacture’s data. Furthermore, a 3D finite element analysis software model for transformer coupling with particle swarm optimization (PSO) technique was used and is validated by corresponding experiments. The simulation results have been validated with the manufacturer’s data of transformer rated at 1000 KVA.
Practically, good agreements were obtained between the simulation results and the experimental data. The important parameters in the core joint design were emphasized through a comparison of the losses in various types of T-joint designs. The core losses, total losses were reduced for the new proposed model.

The core and oil temperature underwent a good reduction as compared with the conventional T-joint designs. The core losses in the proposed design reduced more than 11% and 7% when using material M5 and M4 respectively. While more than 25% of the core loss reduction occurred when using material M6. The total owing cost for energy saving for different materials in the different T-joint designs indicated a life cycle, saving of RM 1297 for the M5 material and RM 1971 for the M6 material per transformer when compared to a conventional T-joint design of the same rating. Moreover, the proposed intelligent algorithm in this work can improve the transformer core design as well as can be applied to various power and distribution transformers.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

OPTIMISASI PENGUBAH T-JOINT MENGGUNAKAN TEKNIK PENGOPTIMUMAN KELOMPOK ZARAH (PSO) DAN REKA BENTUK TERAS SEPARA SFERA

Oleh

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Di dalam kajian ini, suatu algoritma pintar telah dijalankan dengan menggunakan teknik pengoptimuman sekelompok zarah (PSO) bagi mencadangkan reka bentuk optimum sambungan-T untuk teras dalam pengubah pengedaran tiga-fasa. Teknik ini telah digunakan untuk mereka bentuk geometri baru sambungan untuk mendapatkan kerugian minimum (tanpa-beban dan dengan beban) dan untuk mengurangkan suhu minyak di dalam pengubah tiga-fasa. Algoritma pintar yang dicadangkan di dalam kajian ini membentangkan kelebihan berikut: (i) korelasi antara sudut sambungan-T dan jurang, (ii) profil kerugian teras dengan suhu telah dipertimbangkan, dan (iii) sistem itu diperiksa di bawah keadaan operasi berbeza (dengan beban dan tanpa-beban).
Pengubah itu disimulasi berdasarkan dimensi sebenar yang diperolehi daripada data pengilang pengubah. Untuk mencapai sasaran ini, suatu model perisian analisis berunsur 3D untuk gandingan pengubah dengan teknik pengoptimuman sekelompok zarah (PSO) digunakan dan disahkan oleh eksperimen yang sepadan. Selain itu, tiga jenis bahan-bahan teras yang penting telah digunakan untuk model-model yang dicadangkan. Alat perisian yang telah digunakan di dalam kajian ini adalah Ansys Workbench, dan juga untuk pra dan pasca pemprosesan termasuk antara muka dengan MATLAB. Keputusan simulasinya telah disahkan dengan data pengilang bagi pengubah pengedaran tiga-kaki tiga-fasa berkadar 1000 KVA dan persetujuan yang agak baik telah diperolehi antara simulasi dan kerja eksperimen. Parameter penting di dalam reka bentuk sambungan teras telah diberi penekanan melalui perbandingan antara kerugian dalam pelbagai reka bentuk sambungan-T. Menurut keputusan simulasinya dan eksperimen, kerugian teras dan jumlah kerugian telah dikurangkan untuk model baru yang dicadangkan.

Teras dan suhu minyak menjalani pengurangan yang baik berbanding dengan reka bentuk sambungan-T konvensional. Keputusan simulasinya menunjukkan bahawa kerugian teras dalam reka bentuk yang dicadangkan dikurangkan lebih daripada 11% dan 7% apabila menggunakan bahan M5 dan M4 masing-masing. Manakala lebih daripada 25% daripada pengurangan kerugian teras telah diwujudkan oleh penggunaan bahan M6. Jumlah kos terhutang untuk penjimatan tenaga bagi bahan-bahan yang berbeza dalam reka bentuk sambungan-T yang berbeza menunjukkan penjimatan sepanjang kitaran hidup sebanyak RM 1297 untuk bahan M5 dan RM 1971 untuk bahan M6 bagi setiap pengubah berbanding reka bentuk sambungan-T konvensional yang sama kadarnya. Selain itu, algoritma pintar dalam kajian ini boleh meningkatkan reka bentuk teras pengubah dan juga boleh digunakan untuk pelbagai pengubah kuasa dan pengagihan dengan kadar yang berbeza.
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I certify that a Thesis Examination Committee has met on 21 August 2017 to conduct the final examination of Omar Sharaf Al-Deen Yehya on his thesis entitled "Transformer T-Joint Optimization using Particle Swarm Optimization and Hemisphere-Shape Design of the Core" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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<tr>
<td>A</td>
<td>core cross-section area</td>
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<tr>
<td>B</td>
<td>Magnetic Flux density</td>
</tr>
<tr>
<td>B&lt;br&gt;&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Maximum flux density</td>
</tr>
<tr>
<td>BIL</td>
<td>Impulse insulation level</td>
</tr>
<tr>
<td>C</td>
<td>Temperature</td>
</tr>
<tr>
<td>c&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Cognitive</td>
</tr>
<tr>
<td>c&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Acceleration factors</td>
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<tr>
<td>CRGO</td>
<td>Cold-Rolled Grain-Oriented Silicon Steel</td>
</tr>
<tr>
<td>D</td>
<td>Diameter of core transformer</td>
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<tr>
<td>E</td>
<td>Electric field intensity</td>
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<tr>
<td>F</td>
<td>frequency</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<tr>
<td>g</td>
<td>Velocity</td>
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<tr>
<td>Hi-B</td>
<td>High-permeability, cold rolled grain oriented</td>
</tr>
<tr>
<td>HRGO</td>
<td>Hot rolled grain oriented</td>
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<tr>
<td>HV</td>
<td>High-voltage</td>
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<tr>
<td>H</td>
<td>Magnetic field intensity</td>
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<tr>
<td>I</td>
<td>Current</td>
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<tr>
<td>J</td>
<td>Current density</td>
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<tr>
<td>K&lt;sub&gt;e&lt;/sub&gt;</td>
<td>Co-efficient of eddy current</td>
</tr>
<tr>
<td>K&lt;sub&gt;h&lt;/sub&gt;</td>
<td>Hysteresis or Steinmetz’s constant</td>
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<tr>
<td>L</td>
<td>length of flux path</td>
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<td>LV</td>
<td>Low voltage</td>
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<td>Symbol</td>
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<td>M4</td>
<td>Core material grade M4</td>
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<td>Core material grade M6</td>
</tr>
<tr>
<td>N1</td>
<td>Number of primary windings</td>
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<td>N2</td>
<td>Number of secondary windings</td>
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<td>p</td>
<td>Position</td>
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<tr>
<td>PSO</td>
<td>Particle Swarm Optimization</td>
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<tr>
<td>R</td>
<td>Resistance</td>
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<td>Ř</td>
<td>Reluctance</td>
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<tr>
<td>SASI</td>
<td>Swanson as Swanson Analysis Systems</td>
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<td>TOC</td>
<td>Total owning cost</td>
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<td>V1</td>
<td>Primary voltage</td>
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<td>V2</td>
<td>Secondary voltage</td>
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<td>w</td>
<td>Initial inertia weights</td>
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<td>µ</td>
<td>Permeability of the material</td>
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<td>µ₀</td>
<td>Permeability of the air</td>
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<tr>
<td>µᵣ</td>
<td>Relative permeability of steel</td>
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<tr>
<td>α₁</td>
<td>Angle of the T-joint</td>
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<td>γ</td>
<td>Conductivity</td>
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<td>Φ</td>
<td>Magnetic flux</td>
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CHAPTER 1

INTRODUCTION

1.1 Background

Three-phase are essential components in electrical power systems which transfer electrical energy from the power plants to the loads. Distribution transformers have intrinsically high efficiencies in comparison with other electrical equipment, especially as they are in constant operation and have a comparatively long lifespan. They are utilised in great numbers to enable and provide electricity distribution to the customers and end users (Lutchman, 2012). A huge number of distribution transformers have been working steadily and continuously in electrical network grids.

Nevertheless, the efficiency of transformers is not 100% as there are electrical losses associated with them. Although transformer efficiency during operation at full load is very high, but the losses are always present even with no load. In spite of operating with high efficiencies, the loss issue still attracts the attention of researchers. The power efficiency in transformers has been often greater than 98 % at its highest level (Ilo et al., 2000). The core loss represents about 70 % of the total losses of the transformer whereas the operating efficiency is 93.38 %.

In twenty five European Union countries (EU-25) and generally around the world, there is anxiety about the no-load losses that should be minimized as much as possible (Targosz and Topalis 2007).

Moreover, there are three important solutions to reduction the losses in transformer. One of them is to use better material. Another way is to improve the cooling medium and methods. The third one is to improve the distribution of flux by changing the geometry of the core design. For the first one, the economic factor is present here which means, can get a good performance for transformer if used high quality core materials but the cost is very high. In the recent years, cost of cold-rolled grain-oriented steel (CRGO) increase. Silicon iron for cores of transformers is supplied by a few factories which are quite renowned for this material. Major manufacturers are Posco of Korea, Nippon and Kawasaki of Japan, and manufacturers from East Europe, Russia and American continental nations.

The most prevalent CRGO electrical steel utilised is M5 which was at RM5.60 per/kg in January 2004; the cost in December 2005 was about RM17.04 per/kg, a price upsurge of 304 %. Figure 1.1 shows the average cold-rolled grain-orientated (CRGO) steel price graph which reveals that the highest price level was from February 2005 to December 2005 for each of the CRGO grades (Daut and Uthman...
For the second solution which can be used to reduction the losses in transformer is related to the cooling technique, but for this solution, the economic factor is very high because should be known about the heat distribution inside the core, windings and oil.

Furthermore, more information about oil properties and which type of oil should be used in the different rated of transformers. Therefore, as a result, any saving or minor increase in efficacy can amount to considerable savings over the lifetime of the transformer (Leonardo, 2010).

![Figure 1.1: Price of CRGO material (Daut and Uthman 2006)](image)

For the third solution (related to the geometry of joints) which effect to the losses profiles because any change of the core design has effect to the performance of the core. The central limb is linked to the base yoke and the top yoke and this joint is known as a T-joint. The T-joint is regarded as the spine of the transformer core since it affords a mechanical support for the core and a large amount of the magnetic flux is routed through the T-joint connection. Efficiency of any type of transformer depends on numerous factors, one of these factors is the joint design of the core (corner and T-joints). The relationship between the losses profiles with different geometries of the core T-joint is very complex. The core of a transformer is built from assembled numerous packages which have different thicknesses. The semicircular yokes tend to be joint with circular limbs so the features of a core joint are considered to be a complex 3D system. In a transformer, core losses and the behaviour of the magnetic flux are crucial for its design (Høidalen et al., 2016; Lotfi and Rahimpour 2013). As a very rough guide, increasing the flux density by 1 %
causes an increase in losses by about 2% (Pfützner et al., 2014). On the other word, most of the losses inside the transformers followed by a rise of temperature which means any reduce of losses, the temperature reduces and vice versa. Hence there is an urgent need to find a suitable way in the design of the transformer core to reduce the losses.

1.2 Problem Statement

The majority of these researches have focused on flux behaviour and localize losses in the T-joint area. However, there are many subjects in this matter has not been addressed in the previous studies. Currently, power transformer core joints generally use 45° mitred overlap joints (Bengtsson et al., 1989). Moreover, for laboratory studies, most of researcher have used few laminations to build the core of transformer to measure the localize losses and flux but this method does not give a real impression of the behaviour of core. From all the investigation in the literature, it is obvious that the main problem in the core design, it is coming from the joints. Although the above has been researched, so far there have been very few studies suggesting a new shape of T-joint design to reduce core loss and to achieve efficient flux behaviour in the core transformer. Thus, it is essential to find the optimum design of T-joint for core in three-phase transformer. There are many significant points which can be highlighted from previous studies and the research gaps brought to light as follows:

1. There is a lack of technique and justification to evaluate the T-joint parts and most studies are based on trial and error methods, whereas the angle should be evaluated based on the transformer conditions by considering other parameters at the same time.
2. No significant available concerning the correlation between T-joint angles, length of flux path (L) and the gaps in the joint area.
3. Lack of consideration on the T-joint design and the gaps between the joints under different load conditions as most studies consider only the no load condition whereas by increasing I, then B increased and losses increased.
4. No significant study focused on both aspects of the design of the core parameters in the presence of oil and considered the thermal profiles at the same time as the losses. This is significant because the gaps in the joints inside the transformer are filled using oil and the thermal behaviour of the oil is therefore very significant, especially in the ageing of a newly designed transformer.
5. The correlation between the joint design with the gaps and temperature profiles has not been addressed in previous studies.

1.3 Research Objectives

The main aim of this study is to propose a new model of the T-joint in a distribution transformer in order to improve the behaviour of the core and reduction the losses within the transformer. To attain this objective, it is essential to conduct several tasks in the area of transformer core prototyping, materials, measurement, and analysing
the correlation among them. Furthermore, the model must have the ability to be applied using finite element methods by using ANSYS Software. Distribution transformers have complex three-dimensional geometry with nonlinear materials in the core. This makes it necessary to use powerful and accurate numerical methods like the finite element method to analyze and understand its behavior. The overall gains from this study will have significance both for the end users and for the producers of transformers and related materials.

The key objectives and expected tasks and accomplishments of the current study were achieved under the below specific goals:

1. **To present** a new T-joint design of transformer core using proposed PSO base intelligent algorithm by considering on the power loss reduction under different load conditions.
2. **To develop** a new T-joint design called (hemisphere) for the transformer core.
3. **To evaluate** the proposed designs under different core materials and loads and also comparison between the electrical and economical indices of proposed designs and conventional ones from industry.

1.4 **Scope and Limitations**

In this study, the influence of redesign the form of T-joint to the losses and thermal profiles in three-phase transformer was studied in the different operation conditions. To achieve this target, the current study involved many points but the main ones can be summarized as follows:

1. Studying the effect of changing the design of T-joint shape to the performance of the core for three phase transformer via using different core materials.
2. In this study, intelligent algorithm proposed to find the optimum dimensions of T-joint parameters.
3. Using the commercial ANSYS Software to build all the 3D proposed models for transformer core.
4. Proposed a new T-joint model which called hemisphere that gives a good performance as compare with the conventional models.

1.5 **Research Contributions**

The contributions of this study can be brief as follows:

1- New information of the core design of three phase transformer under different types of materials and geometries.
2- Using an intelligent algorithm to determine the optimum design T-joint geometers by considering the important parameters which effect to the design.
3- The current proposed model (hemisphere) T-joint design is different from previous models in the literature in terms of form and content.
4- The relationship between the power loss and the oil temperature was considered.
5- The effect of changing the form of the T-joint design for a core transformer was presented to demonstration the relationship between the shapes of the design with the losses.

1.6 Organization of the Thesis

In order to accomplish the targeted objectives mentioned earlier, the thesis consists of five chapters and each is elaborated with further details below:

**Chapter One** provides an overview of this thesis and this chapter also discusses a briefly the research problem, objectives, scope and limitations of the study, research contributions and also discussed.

**Chapter Two** presents a literature review is given concerning the losses in transformers as well as a concise theory of transformers and their structures. There are different transformer variants and designs. In this chapter emphasis on the core-type of power transformers. All the selected past research and references were discussed briefly in this chapter.

**Chapter Three** discusses the details of methodology for the new algorithm, transformer parameters and graphs. A brief explanation is given of the algorithm which is proposed in this project. In addition, this chapter includes a description of the configuration of the transformer core design which is incorporated into this work that allows the study of losses and thermal profile of the transformer. Further, the modelling of a power transformer is discussed, including models of the transformer core and the windings. A discussion is also given concerning the finite element method (FEM) with a description of the Ansys software model for a three-phase transformer.

**Chapter Four** presents the simulation results of the three-phase transformer and an analysis of the developed model is discussed. It covers the new design modelling of the T-joint design in the different core materials.

**Chapter Five** concludes with emphasis on the final discussion and a summary of the conclusions. Possible future works are discussed in brief in this research area.
REFERENCES


