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3D Methodology for the Overheating Assessment on Power Transformers Structural Parts

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Abstract

On power transformer structural parts the main design criterion is the limit temperature rise caused by leakage field due to the high current leads. Previous works found in the literature focus their results on the consequences of electromagnetic leakage flux in terms of stray power losses. The calculation of stray losses is, of course, also important to guarantee the total losses. However, the drawback of such computational proposals is that the direct measurement of stray losses is not achievable in the vast majority of cases and, therefore, they are difficult to validate. For this reason, this dissertation proposes to compute the consequences of leakage flux not only in terms of losses but also in terms of temperature distribution. The objective is to offer a practical tool to compute the temperature distribution and to localize the hot spot areas on metallic structural parts heated by electromagnetic induction.

A three-dimensional methodology for the overheating hazard assessment based on electromagnetic analytical formulation linked with thermal finite element method is presented. The proposed methodology is carefully focused on those cases where the electromagnetic wave penetration depth compared to the big machine dimensions is a key issue. Thus, stray losses into the thin skin depth penetration can be readily calculated with the analytical model, based on Poynting's Vector formulation. Then, the temperature distribution is computed by means of 3D FE thermal analysis, where the penetration depth sets the volume thickness where losses are introduced.

Moreover, the material data required for computation might be inaccurate as they are taken from catalogues or the literature and boundary conditions of heat exchange are difficult to determine from theory or measurements. An attempt to identify these parameters by means of multi-objective deterministic and non-deterministic optimization algorithms is proposed ensuring thus the accuracy of obtained results.

An experimental work is presented, and numerical results are discussed and compared to measurements. Test are carried out for transformer cover plate and tank wall over a wide range of currents and varying also other design parameters, i.e. plate thickness, distance between conductors or including amagnetic material, in order to validate the computational methodology.

To stress the potentiality of the tool, some practical applications are presented, which include the overheating analysis on complex 3D structural parts, the design of amagnetic inserts on three-phase transformer cover plates and the evaluation of the overheating hazard due to zero sequence flux on tank walls taking into account the influence of the tertiary stabilizing windings.

List of Publications

X. M. Lopez-Fernandez, P. Penabad-Duran, and J. Turowski, "Three-dimensional methodology for the overheating hazard assessment on transformer covers," *Industry Applications, IEEE Transactions on*, vol. 48, pp. 1549-1555, Sept.-Oct. 2012.

X. M. Lopez-Fernandez, P. Penabad-Duran, J. Turowski, and P. M. Ribeiro, "Non linear heating hazard assessment on transformer covers and tank walls," *Przeglad Elektrotechniczny* (Electrical Review), vol. 88, no. 7b, pp. 28-31, 2012.

P. Penabad-Duran, X. M. Lopez-Fernandez, J. Turowski, and P. M. Ribeiro, "3D heating hazard assessment on transformer covers. Arrangement decisions," *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 31, no. 2, pp. 703-7015, 2012.

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P. Penabad-Duran and X. M. Lopez-Fernandez, "Part A: Introduction to FEM Analysis," in *ARWtr FEM Tutorial. Finite Element Method applied to design and analysis in power transformers* (Xose M. Lopez-Fernandez, editor & publisher), Santiago de Compostela, Spain, 2010, ISBN:978- 84-614-3527-2.

P. Penabad-Duran, X. M. Lopez-Fernandez, C. Alvarez-Mariño, "Transformer Tertiary Stabilizing Windings: Part I: Apparent Power Rating," XXth *International Conference on Electrical Machines* (ICEM2012), Marseille, France, pp. 2362-2368, Sept. 2012.

P. Penabad-Duran, C. Alvarez-Mariño, X. M. Lopez-Fernandez, "Transformer Tertiary Stabilizing Windings: Part II: Overheating hazard on tank walls," XXth *International Conference on Electrical Machines* (ICEM2012), Marseille, France, pp. 2369-2374, Sept. 2012.

P. Penabad-Duran, P. Di Barba, X. M. Lopez-Fernandez and J. Turowski, "Electromagnetic and Thermal Parameter Identification Method for Best Prediction of Temperature Distribution on Transformer Tank Covers," Accepted to be presented in: XVIth *International Symposium on Electromagnetic Fields* (ISEF2013), Ohrid, Macedonia, September 12-14, 2013.

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Resumen - Spanish Summary

Metodología 3D para el análisis de sobrecalentamiento en elementos estructurales de transformadores de potencia

Existen un gran número de técnicas de simulación disponibles en electromagnetismo para asistir al diseño de dispositivos electromagnéticos, en particular, de transformadores de potencia. Sin embargo, se necesitan satisfacer las necesidades de los clientes cada vez más exigentes y ser cada vez más competitivos en términos de costes de fabricación, alta eficiencia, fiabilidad o peso. Además con el desarrollo de nuevas tecnologías y materiales, se hace especialmente crítico analizar cada diseño propuesto con el máximo detalle, para que se puedan conseguir soluciones óptimas. Por tanto, el desarrollo de técnicas novedosas y métodos emergentes para aplicaciones de simulación multifísica hacen que sea un área de investigación muy amplia y próspera, dentro de la cual se enmarca esta tesis doctoral.

El trabajo de investigación aquí presentado, se ha realizado en el marco de ayudas a la investigación 2009 concedidas por la Universidad de Vigo, dentro del "Programa específico para la formación predoctoral en áreas con especial dificultad para contratar doctores".

Introducción

En máquinas y equipos eléctricos de gran potencia los conductores con intensidades elevadas que pasan cerca de paredes metálicas o atraviesan las paredes de la carcasa, son elementos térmicamente peligrosos y fuente adicional de pérdidas. En el caso particular de los transformadores de potencia, la fiabilidad, los puntos calientes y el mantenimiento dependen de los efectos térmicos producidos por la distribución del flujo electromagnético.

Los métodos de diseño de las partes activas, el núcleo y los devanados, están bien establecidos. Por el contrario, el diseño de componentes inactivas como los elementos estructurales no es tan directo y se requiere un estudio minucioso. El control y la minimización del sobrecalentamiento en los pasatapas de los transformadores juegan un papel importante y decisivo en el comportamiento del transformador. Sus consecuencias más significativas son el ahorro de energía y reducir el peligro de los apagones, que causan elevados costes a las distribuidoras y clientes, debido a que los transformadores son un unos de los elementos más importantes de las redes eléctricas.

This is a PhD thesis summary, written in Spanish to meet requirements from the University of Vigo.

Por tanto, la predicción y localización de las pérdidas por dispersión y puntos calientes y sus consecuencias se vuelven una cuestión vital para los fabricantes. Normalmente, estos efectos se minimizan aumentando la distancia entre los conductores y la pared o colocando apantallamientos electromagnéticos y en el caso de los pasatapas se utiliza acero amagnético. Este es un fenómeno muy conocido, pero los fabricantes y diseñadores cada vez están más sensibilizados con este problema debido a una serie de factores: el aumento de potencia de los transformadores, elevado coste de los materiales y la reducción del tamaño del transformador, impuestos por un mercado cada vez más competitivo.

Motivación

Las referencias encontradas en la literatura centran sus resultados en las consecuencias del flujo electromagnético de dispersión en términos de pérdidas. Sin embargo, el inconveniente de esas propuestas es que no es posible la medida directa de la distribución de pérdidas en la mayoría de los casos, y por tanto son difíciles de validar. Por otro lado, es una realidad que la temperatura superficial se puede medir y monitorizar fácilmente a través de sensores disponibles en el mercado.

Aunque el cálculo de pérdidas por dispersión en transformadores de potencia es también importante para garantizar las pérdidas totales, el incremento de temperatura local debido a altos valores de densidad de flujo son más importantes. Uno de los principales factores que influye en el envejecimiento de los transformadores es la temperatura y la distribución de la densidad de pérdidas puede dar lugar a valores de temperatura peligrosos si los materiales no se seleccionan de manera adecuada. Además, el principal criterio de diseño de pasatapas y otros elementos estructurales es el incremento de temperatura causado por la exposición a campos magnéticos generados por corrientes elevadas de hasta varios kA. Las normas que se aplican establecen unos valores de temperatura límite de hasta 140 °C para todas las partes metálicas, y comprobar este requerimiento en los diseños se hace esencial.

En este escenario surge la necesidad de una herramienta práctica capaz de evaluar la temperatura de manera precisa y establecer criterios claros para identificar el peligro de sobrecalentamiento en transformadores. Esta herramienta sólo se puede considerar utilizando un análisis 3D magneto-térmico, donde el cálculo de temperatura permite verificar indirectamente el cálculo del flujo de dispersión y las pérdidas. Esto resulta de una gran importancia práctica, puesto que así se puede validar la temperatura de manera experimental y localizar los puntos calientes.

Los problemas que conllevan el uso de materiales magnéticos siempre están caracterizados por la pequeña profundidad de penetración del campo dentro del metal, pero además aparecen complicaciones adicionales debido a su característica no lineal y saturación. Existen paquetes de software comerciales basados en el Método de Elementos Finitos (MEF), muy utilizados en el mercado, pero en esos casos, incluso los cálculos 2D se hacen complicados, y requieren gran cantidad de tiempo computacional y memoria. Esto se debe a que se necesita una discretización muy fina para calcular las pérdidas dentro de la pequeña profundidad de penetración del flujo electromagnético, que es de aproximadamente 1 mm, comparado con las dimensiones de varios metros del volumen del transformador. Además la solución de problemas 3D de corrientes inducidas con MEF requiere un conocimiento profundo de la formulación para garantizar las condiciones de contorno adecuadas, estabilidad de cálculo, minimizar el número de variables o la habilidad para tratar discontinuidades en las propiedades de los materiales.

Por tanto se puede concluir que los complejos modelos 3D no son adecuados todavía para implementar en la etapa de diseño de transformadores de potencia ya que el modelado y resolución demandan mucho tiempo y esfuerzo comparado con los tiempos de mercado, además de usuarios expertos. Además, si se requieren resultados fiables, se necesita precisión en el cálculo de las pérdidas y temperatura. Por otro lado, se pueden obtener fórmulas sencillas a través de métodos analíticos, que permiten un cálculo más rápido para determinar las pérdidas, y tienen la ventaja de que su resultado se puede incorporar en otros programas que calculan, por ejemplo, la temperatura resultante.

Objetivos y contribución

Los fabricantes y diseñadores de transformadores requieren métodos de cálculo rápidos, específicos y fáciles de utilizar para acelerar los procesos de diseño. Los métodos de cálculo analíticos, combinados con datos experimentales u otros métodos proporcionan modelos eficientes para una representación precisa de determinadas características del trasformador. En esta dirección, el trabajo de investigación que se presenta en esta tesis describe el desarrollo del herramientas de cálculo de pérdidas y temperatura aplicadas al diseño de pasatapas, tapas y paredes del tanque del transformador.

Otros trabajos que encuentran en la literatura, se refieren al sobrecalentamiento en elementos estructurales en términos de densidad de pérdidas o intensidad de campo magnético, que son difíciles de validar experimentalmente. Por el contrario, las consecuencias del flujo de dispersión en términos de distribución de temperatura son fáciles de validar y por esta razón la metodología propuesta se centra en el cálculo de la temperatura.

Por tanto, se presenta una metodología 3D que combina una formulación analítica para el cálculo electromagnético con el análisis térmico por el MEF para evaluar el peligro de sobrecalentamiento en elementos estructurales de transformadores. Así, se solventan las dificultades del cálculo de pérdidas en la profundidad de penetración, mientas que el análisis 3D MEF térmico permite comprobar experimentalmente los resultados obtenidos. Se presentan además una serie de experimentos que permiten validar la metodología de cálculo propuesta, en los que se evalúan los efectos térmicos inducidos en chapas de acero por conductores de alta intensidad.

La precisión en el cálculo de pérdidas es necesaria para estimar el incremento de temperatura y diseñar métodos para eliminar y controlar sus efectos más peligrosos. Por tanto, en este trabajo de investigación se profundiza en la implementación de una formulación analítica considerando el comportamiento no lineal de la profundidad de penetración. Este comportamiento permite un mejor entendimiento del fenómeno electromagnético y permite además establecer la profundidad del volumen en el que se localizan las pérdidas en el modelo térmico.

Por último, un aspecto importante en la metodología propuesta es garantizar la precisión del los resultados para otras condiciones de carga o distinto número de conductores. Esto se consigue incluyendo un proceso de optimización que identifica los parámetros de entrada adecuados para los cálculos electromagnético y térmico. La calibración del modelo se basa en datos experimentales, y se incluye la sensibilidad del modelo a posibles errores en la medida.

Metodología de cálculo

La metodología de cálculo propuesta en esta tesis doctoral, empieza con el modelo analítico electromagnético que permite calcular las pérdidas debidas al flujo de dispersión. Después de introducir parámetros geométricos, propiedades de los materiales y el valor de la fuente de intensidad, se obtiene la representación del campo magnético aplicando la ley de Biot-Savart. El siguiente paso es el cálculo de la distribución de pérdidas disipadas debido a la presencia de conductores con corrientes elevadas integrando la formulación analítica del teorema de Poynting.

Los aspectos físicos y matemáticos relacionados con el modelo electromagnético se explican en detalle. Se demuestra como aplicando el Vector Poynting en un modelo que consta de un conductor con intensidad elevada posicionado cerca de una superficie metálica permeable se puede calcular cómo la energía electromagnética fluye en el sistema, la transferencia de energía y la disipación de pérdidas en forma de calor.

Se comienza con la formulación de las ecuaciones de onda electromagnéticas dentro del un conductor, a partir de las ecuaciones de Maxwell. Cuando una onda electromagnética incide en un metal conductor, se propaga un pequeña distancia que es la llamada profundidad de penetración δ. Además, a partir de la relación entre los valores superficiales del campo eléctrico y magnético se define el valor de la impedancia superficial $\mathbf{Z}_s$ que tiene valores de Ohmios (Ω).

El teorema de Poynting es el teorema principal de conservación de energía para campos electromagnéticos y permite identificar todas las fuentes de energía en un determinado volumen. La formulación del Vector Poynting se obtiene a partir de las ecuaciones de Maxwell e indica la dirección y densidad de potencia en un punto determinado del sistema. Por tanto es posible representar como se propaga el flujo de energía en el espacio a través de ondas electromagnéticas dentro y fuera de los conductores, y como esta se transforma en pérdidas dentro del conductor.

Por tanto a partir de la formulación del Vector Poynting e integrando en la superficie a calcular se pueden obtener las pérdidas por dispersión, siendo conocida la distribución de campo magnético en la superficie del metal. Si se han de tener en cuenta además la característica no lineal del acero e histéresis, se deben aplicar factores de linealización que dependen del material y del tipo de superficie estudiada. En esta tesis se explica en detalle el origen de estos factores, y su interpretación física. Se destaca el comportamiento no lineal de la permeabilidad magnética en la superficie del metal y su comportamiento no lineal dentro del propio metal. También se debe considerar el factor de apantallamiento, que depende de la relación entre el espesor del metal y la longitud de onda del campo, que pueden dar lugar a fenómenos de reflexión y consecuente disminución de las pérdidas.

Finalmente, se describe la formulación analítica en términos de impedancia superficial y profundidad de penetración no lineal. Esta formulación permiten combinar el comportamiento en la zona lineal y saturación a través de una función de peso que tiene en cuenta el grado de saturación del material. Así es posible introducir de manera sencilla el comportamiento no lineal y la saturación de materiales ferromagnéticos en el modelo analítico.

Se incluye en la descripción de la metodología computacional también la formulación analítica del campo magnético para los dos tipos de excitación que aparecen en el transformador: tangencial y normal. La excitación tangencial aparece en la tapa y pasatapas del transformador, donde los conductores atraviesan la chapa metálica, y la excitación normal se debe a conductores que pasan paralelos a las paredes del tanque.

Por otro lado, a partir de la solución analítica, la potencia disipada se introduce dentro de la región de la impedancia superficial en el modelo térmico, como fuentes de calor. Además la profundidad de penetración no lineal obtenida a partir de la representación analítica permite establecer en el modelo térmico la profundidad exacta de regiones en las que se ubican dichas fuentes de calor. Aplicando las condiciones de contorno adecuadas se calcula la distribución de temperatura en régimen estacionario, conectando de esta manera los dos modelos.

Ensayos de laboratorio

Con el objetivo de ilustrar la capacidad de la metodología de cálculo presentada en esta tesis como una herramienta práctica para el análisis de puntos calientes en elementos estructurales del transformador se realizan una serie de ensayos experimentales. Este estudio ha sido realizado gracias a la colaboración de Efacec Energía S. A. Power Transformers. Los ensayos están diseñados para determinar las áreas que alcanzan un mayor incremento de temperatura en chapas de acero utilizadas en pasatapas, tapas y paredes del tanque, como consecuencia de la presencia de conductores con intensidades elevadas.

Se toman medidas de temperatura en régimen estacionario en varios tipos de ensayos. Por un lado se hacen ensayos tipo tapa, en los que una chapa de acero posicionada en horizontal sobre un soporte es atravesada por uno o varios conductores. Por otro lado se hacen ensayos tipo pared, en los que uno o varios conductores pasan paralelos a una chapa de acero colocada en posición vertical. Por último se hacen ensayos en pasatapas con forma redonda y cuadrada atravesados por un conductor.

Se tienen en cuenta varios parámetros de diseño a la hora de realizar los ensayos, como la magnitud y fase de la corriente (desde 200 A a 2.5 kA), distancia entre conductores, la distancia entre los conductores y la chapa de acero, el número de conductores y su disposición (en vertical u horizontal), el espesor de las chapas de acero y los materiales.

Los ensayos se realizan en aire de manera que se obtiene condiciones de refrigeración más severas que las que realmente tienen lugar con el aceite del transformador. Pero una vez que haya validado el método de cálculo las condiciones de contorno se pueden cambiar por factores correspondientes a condiciones reales.

Identificación de parámetros de cálculo

Una vez establecida la metodología de cálculo se ha encontrado la dificultad de determinar datos de propiedades de los materiales y condiciones de contorno a partir de catálogos o en la literatura que sean realmente fiables. En la metodología de cálculo propuesta estas incertidumbres se evitan introduciendo un método de identificación de parámetros, es decir se calibran los modelos de cálculo. Su objetivo es identificar y ajustar los parámetros de entrada electromagnéticos y térmicos para la simulación, de manera que los resultados se ajustan a las mediciones de temperatura tomadas como referencia. Una vez que los parámetros de entrada han sido identificados, la distribución de temperatura se puede calcular, por ejemplo, para otros valores de carga o distinto número de conductores. Este trabajo se ha realizado durante una estancia de investigación en la Universidad de Pavia, Italia, bajo la supervisión del Prof. Paolo Di Barba, beneficiándonos de su experiencia en problemas inversos y optimización en electricidad y magnetismo.

Se describe una técnica para la identificación de estos parámetros basada en algoritmos de optimización mono-objetivo y multi-objetivo. Además se detallan una serie de estudios claves como la influencia relativa de cada parámetro en la distribución de temperatura final, o la sensibilidad del modelo a posibles errores introducidos en la medida.

El proceso de solución del problema inverso comienza con la implementación de un algoritmo de optimización mono-objetivo para identificar los parámetros de entrada óptimos para la simulación. El siguiente paso es determinar la sensibilidad de dicha solución. Para ello se introduce una perturbación en los parámetros de entrada del modelo y se determina cuanto afecta a la salida. Se ha comprobado, que existen soluciones que son menos sensibles a estas perturbaciones, es decir, menos sensibles a errores introducidos en la medida. Por tanto este conjunto de soluciones (frente de Pareto) se identifican a través de algoritmos de optimización multi-objetivo. Se aplican un algoritmo determinístico y otro no determinístico, GATT y NSGA-II respectivamente. No obstante, existen en la literatura una gran variedad de algoritmos que se pueden utilizar para automatizar el proceso de calibración.

A través de la optimización multi-objectivo se obtienen una serie de soluciones que se pueden seleccionar dependiendo de los requerimientos de precisión y sensibilidad de cada modelo. Además se ha comprobado que con los dos algoritmos se consigue la identificación de soluciones bien distribuidas en el frente, pero el GATT requiere más tiempo de cálculo y correr el algoritmo varias veces variando la solución inicial y discretizando las direcciones de búsqueda para centrarse en la región de interés.

Resultados y conclusiones

Teniendo identificados los parámetros de entrada óptimos, finalmente se presentan una serie de casos de estudio para analizar en detalle el comportamiento no lineal en el modelo analítico. A través del modelo de profundidad de penetración no lineal que se describe en esta tesis, se representan resultados de un amplio rango de corrientes destacando el comportamiento según se trabaje en la zona lineal o de saturación de la curva del acero.

También se presentan una serie de resultados de simulaciones térmicas tanto para uno o dos conductores y se validan con medidas obtenidas en forma de termografías a través de los ensayos, donde realmente se demuestra el potencial de esta metodología. Se compara la distribución de temperatura entre simulaciones y ensayos a la hora de evaluar la influencia del espesor de la chapa, y también el uso de materiales amagnéticos. De esta manera, indirectamente se valida también el cálculo de las pérdidas. Además en el caso de las paredes del tanque la metodología de cálculo se extiende al uso de modelos en 2D, en los que también se validan los resultados de la distribución de temperatura con termografías.

Para destacar la potencialidad de esta herramienta de cálculo, se presentan aplicaciones prácticas que incluyen el cálculo de temperatura en elementos estructurales 3D más complejos y que combinan distintos materiales, el diseño de injertos amagnéticos en tapas planas de tanque de transformadores trifásicos y la evaluación del peligro de sobrecalentamiento en paredes del tanque debido a la presencia del flujo de secuencia cero, teniendo en cuenta si el devanado de estabilización está o no conectado.

Futuras líneas de trabajo implicarían el uso de la herramienta de cálculo en el ámbito industrial, validando casos prácticos, con valores de corriente mucho más elevados, con distinto número de conductores y distintos desfases.

Chapter 1

Introduction

In field simulation there are a large number of techniques available to assist in the design of electromagnetic devices, and in particular of power transformers. Commercial software packages offer efficient modeling and modern simulation tools and the vast literature available on the subject covers various aspects of field simulations in the context of optimum design and performance prediction of the studied device [1]. Nevertheless, designers of modern transformers need to satisfy customers and be competitive in terms e.g. of low manufacturing and operating costs, high efficiency, reliability or minimum weight. Moreover, new types of technologies and new materials are being developed and investigated. Thus, it becomes increasingly critical to analyze any proposed design in considerable detail, so that an optimum solution might be achieved. Emerging new techniques and methods for multi-physics applications [2], also in the area of multiobjective optimization [3] make it to be a prosperous area of research.

1.1 Background

In the recent years the power industry is faced with an important challenge to keep design and development cost at a minimum and at the same time they need to design power transformers with energy efficient criteria. Methods for design of active parts, core and windings, are well established. Contrarily the design of inactive components such as the structural parts, is still not straightforward and requires careful treatment [4].

Losses produced on structural parts of large power transformers are due to both, leakage flux from windings and high current leads passing near conducting parts of the tank walls, including also low voltage bushing terminations. In addition, high current leads passing close to conducting plates and housing walls of large power equipment are thermally hazardous elements of construction [5]. Therefore, they not only reduce the efficiency of transformers, but also give rise to local high temperatures, more important in terms of safety and reliability. Hot spots, reliability and maintenance closely depend on the thermal effects produced by the distribution of electromagnetic leakage flux [6] and they shorten transformers service life [7]. Specially, low voltage bushing terminations are areas of high risk and hot spots are more likely to develop since the cooling effect of transformer oil is negligible and eddy current densities are very high. The excessive overheating in those components could be dangerous at overloading, which is not uncommon nowadays [6].

The subject of tank wall losses near the low voltage bushings in power and distribution transformers has received little attention. The minimization and control of the consequent overheating in bushing plates and other structural parts play a decisive role in transformer performance. Their significant consequences are energy savings and reduce the risk of shutdowns. They involve high cost to utilities and customers as transformers are one of the most expensive components in electric system networks [5]. This means that the accurate prediction and localization of stray losses and their thermal consequences become a vital issue for manufacturers. Usually these losses are mitigated by moving the conductors farther away from the wall [8] or by placing a shield of high conductivity and low permeability on the tank wall near the high current conductors [9]. In the case of bushing turrets and tank cover plates, they are usually made of stainless steel [10].

This is a well know phenomenon but manufacturers and designers are nowadays more concerned about this problem due to the combination of factors: the increasing of power rating in power transformers, the high cost of materials, and the reduction of the overall size of the transformer imposed by a more and more competitive market [11]. Efforts made on efficient design of transformers, not only focus on loss reduction, but also on manufacturing costs reduction and the present study is part of such effort.

1.2 Motivation

References and previous works found in the literature [12], [13], focus their results on the consequences of electromagnetic leakage flux in terms of stray power losses [14], [15]. The drawback found by authors of such computational proposals is that the direct measurement of stray losses is not achievable in the vast majority of cases, and therefore they are difficult to validate. Meanwhile it is a fact that the surface temperature can be easily monitored nowadays by means of temperature sensors available at the market.

Although stray losses computation in large rating transformers is, of course, also important to guarantee the total losses, the local temperature rise due to high values of incident flux density is more important. One of the fundamental criteria which influences the transformer ageing and the degree of loading is the transformers temperature. The loss density distribution may attain levels leading to hazardous local temperature rise if the material and design are not selected properly. Besides, the main design criterion of the bushing adapters in large transformers is the limit of the temperature rise caused by the exposure of the adapters to the magnetic field generated by high current leads carrying several kA. The applicable standards used for the design of power transformers specify a temperature limit of 140 °C for all metallic parts of the transformer because above this temperature gas formation starts developing in the oil, with its consequent insulation damage [16], [17]. Many papers are devoted to accurately calculate transformer oil and windings temperature [18], but only in recent years some attention has been paid the temperature calculation on structural parts starts [10], [19], [20]. To proof a design against this requirement becomes essential.

In this scenario, there arises the need for a practical tool capable of assessing the temperature distribution accurately and establish clear criteria to identify overheating hazard in transformers. Such tool can be correctly considered only by using a coupled 3D magneto-thermal analysis [21], [22] where the temperature calculation indirectly permits to verify the underlying leakage field and stray losses calculation. It is of great practical importance for transformer designers since the temperature can be validated experimentally and overheated points can be localized.

Problems involving magnetic materials are almost always characterized by small penetration depths but in addition there are further complications due to the non-linear material characteristics and saturation of ferromagnetic materials [23], [24], [25]. Any calculation of the electromagnetic field or losses due to eddy currents in ferromagnetic bodies is complicated by the fact that the permeability of the material depends on the magnetic field itself. In such cases, even two dimensional problems could place unreasonable demands on the computational time and storage.

In the recent years, some authors invested efforts to demonstrate that the 3D Finite Element Method (FEM) is capable of routinely providing a solution to a large, complex real-world problem and can hence be incorporated in the design cycle of large transformers [25], [26], [27], [28]. However, solving a 3D FEM eddy current problem is not straightforward and requires advanced knowledge on the formulations, particularly in the case of a multiply connected problems, such as the tank cover. Additionally, from industrial perspective computing transformer losses on its structural parts from a 3D model taking into account non-linear material properties and complex geometries is not the most adequate from a practical point of view due to its non-affordable computational time [29]. Often authors advise to perform a separate study with different solvers and formulations to compute stray losses due to windings or high currents leads on certain structural parts of transformers such are the tank walls and bushing adapters [30].

Thus, it can be concluded that full 3D models are still not suitable to implement on the design stage of power transformers. Modeling and solving still demand much time and effort in the scale of a rapid response in market time, and it does require experienced users. Moreover, for the computation of the stray losses and resulting temperature from the electromagnetic induction heating, such accurate model must be taken into account if calculations are to be reliable [30], [31]. On the other hand, simple formulae can be obtained by means of analytical methods, which provided with a deep experience and understanding of the phenomenon permit quicker and easier determination of losses. Their correctness can easily be proved by measurements made on a model, and their accuracy can be improved by correction factors determined experimentally of from other empirical data [17]. Analytic methods can not only help one to quickly assess the effect on losses of e.g. repositioning the bus bars or using shields of different materials, but also make possible to incorporate such loss calculations in other computer programs which calculate, for example, the plate temperature rise resulting from these losses [8].

1.3 Objectives

The complexity of transformer design demands reliable and rigorous solution methods. Since complicated methods are impractical for day-to-day use, solutions using simpler methods but giving sufficiently accurate answers are in constant demand by designers. Transformer developers need rapid, easy to use and specialized software tools for specific features on transformer analysis to speed up their processes [30]. Such are experimental methods, combining data provided by measurements with analytical or other methods, in order to provide efficient models for the accurate representation of certain transformer characteristics [32].

In this direction, the work presented in this thesis reports the development stray loss and temperature computation tools applied to the design of transformer tank covers, bushing adapters and tank walls of power transformers.

References found in the literature refer to overheating and hot spots only in terms of magnetic field strength or stray loss density distribution. However, in practice stray loss densities are difficult to measure and those methods might result inaccurate. For that reason, the temperature computation is the novelty addressed in this research, where the specific objectives are:

- To present a computational methodology based on an electromagnetic analytical formulation linked with a 3D FE thermal analysis. Thus, the problems to compute the stray power losses into the thin skin depth penetration are overcome analytically. Meanwhile, the 3D FE thermal analysis easily allows checking experimentally the obtained results.

- To include a non-linear penetration depth formulation for the calculation of stray loss on magnetic steel components. It provides more insight into non-linear electromagnetic and thermal behavior. Obtained results also yield an improvement on the thermal model, allowing to adequately locate the heat sources within the penetration depth thickness.

- To implement a calibration process to guarantee the accuracy of computed results. It is done based on measurements and including optimization algorithms which identify the adequate value of electromagnetic and thermal parameters involved in the computation. An exhaustive investigation on the influence of parameters and sensitivity to measurement error is also addressed.

- To validate experimentally the obtained results. A series of experiments are presented in order to validate the proposed methodology, where the influence of several design factors on thermal effects caused by high current leads on steel plates is evaluated.

- To demonstrate the practicality of the proposed computational methodology. Some practical applications are included proving the development of efficient models with low computational cost and runtime which provide accurate results and are suitable to be included in the design stage or large power transformers.

1.4 Outline of the Thesis

This dissertation revolves around the concept of stray losses and its unwanted effects in terms of temperature rise. The study presented here is based on an analytical electromagnetic analysis, which allows to evaluate the stray loss densities on various structural parts of the transformer, and a steady state FE thermal analysis for the computation of the consequent temperature distribution. The presented work is structured as follows:

Chapter 2 presents a review of the literature focusing on eddy currents, stray fields and losses computation methods. The advantages and drawbacks of each of them when applied to the analysis of power transformers are given. Moreover, an exhaustive discussion on previous works related the analysis of leakage fields and consequent stray losses caused by high current leads and windings is presented.

In Chapter 3 a computational methodology for the calculation of the overheating hazard in transformer tank and low voltage bushing terminations is described. Physical and mathematical principles in which the electromagnetic analytical formulation is based are rigorously reported. The FE thermal formulation and computational models are also described.

Chapter 4 presents an experimental setup for temperature measurements in steel cover plates, tank walls and bushing turrets of power transformers. The experimental work presented in this chapter serves on one hand to describe a parameter identification method and on the other hand to validate the computational results.

In Chapter 5 a parameter identification method is described for best prediction of temperature distribution in the transformer structural parts. It is done by means of the implementation of optimization algorithms from which the adequate input parameters for the simulation are obtained. Sensitivity to measurement error is introduced by means of multi-objective optimization, where deterministic and non-deterministic algorithms are used for the sake of comparison. The efficiency of the algorithms and the selection of the most suitable for the parameter identification problem is reported.

In Chapter 6 computational results from applying the proposed methodology are discussed. The electromagnetic and thermal non-linear behavior on transformer covers are analyzed in detail, allowing thus a better understanding and more insight into the phenomenon an required analysis. Computed temperature distribution is compared with thermal imaging from measurements where the accuracy of the computational model is enhanced.

In Chapter 7 practical applications applying the proposed computational methodology are given, stressing its potentiality on further analysis on structural parts of power transformers. Thus, the overheating hazard is evaluated in 3D complex structures, such is the transformer tank cover with bushing turrets. In addition, a practical tool is presented for the arrangement of amagnetic inserts in order to control and reduce the overheating hazard on flat three-phase transformer covers. The methodology is also applied to evaluate the overheating hazard on transformer tank walls due to zero-sequence flux with and without tertiary stabilizing winding.

Finally in Chapter 8 overall conclusions and future lines of work are given.

Chapter 8

Conclusions and Future Work

A 3D methodology has been proposed as a practical tool to evaluate overheating hazard on transformer structural parts taking into account electromagnetic skin depth penetration. Stray losses are computed by means of an electromagnetic analytical approach based on Poynting's Vector. A thermal FE analysis, where calculated losses are introduced as heat sources, computes the space temperature distribution. The presented computational methodology has been applied to several study cases, where the main contributions and conclusions are given in the following sections, including also future lines of research.

8.1 Contribution and Conclusions

Computational Methodology

This research work pays special attention to the particular case of transformer cover plates being more representative. Then the computational methodology is applied to tank walls and other structural parts.

For the computation of the temperature on transformer covers, there arises the need to develop accurate and reliable methods to characterize the induced thermal field taking into account the non-linear magnetic material characteristic.

A non-linear penetration depth magneto-thermal model and its physical aspects are rigorously described and used for the magnetic field computation providing thus more insight of the problem performance when taking into account saturation.

The described model allows to analyze the electromagnetic behavior in detail from weak to strong fields over steel transformer cover plates.

Particularly, the novelty of the model stressed in this dissertation lies in that it clearly defines the non-linear penetration depth of electromagnetic field inside metal in (3.112), which is crucial in the FE thermal model to set the volume regions where stray losses are introduced as heat sources.

Temperature Measurements

In order to evaluate the overheating hazard due to high current leads an experimental work is described. Several tests are carried out, where steel plates used in transformer structural parts are heated by electromagnetic induction. The temperature is measured over metal surface by means of several sensors, and also by means of thermal imaging.

Tangential and normal field excitation are applied to the steel plates, i.e. the case of transformer cover plate and the tank wall.

Several design parameters are taken into account as e.g. number of conductors and distance between them, distance to the tank wall, amagnetic inserts, or the plate thickness.

Temperature measurements serve on one hand, to validate the temperature results, but on the other hand to calibrate the numerical models.

Calibration Process

A calibration process of computational models is highlighted in the methodology proposed in this dissertation. This process ensures the reliability of results by identifying material properties and boundary condition data which might be inaccurate as they are usually taken from characteristic sheets or from the literature. The calibration process also avoids uncertainties due to that the numerical results also depend on the kind of mathematical solver used for the computation. Thus, a parameter identification technique is described based on multiobjective optimization algorithms, where sensitivity to measurement error is taken into account.

The analytical-numerical approach does provide models with low computational effort and runtime so that the optimization process is successfully implemented.

A set of Pareto-optimal solutions is obtained with Goal Attainment Method (GATT) and Non-dominated Sorting Genetic Algorithm (NSGA-II) for the sake of comparison. Results from GATT and NSGA-II are compared showing good agreement along the tradeoff surface.

The solution from SO optimization is also compared to MO solution stressing the consistency of results, as SO optimization represents a particular solution from the front.

From the MO optimization can be easily obtained the set of parameters chosen for computation according to desired criteria on accuracy and sensitivity to measurement error. The parameter identification taking into account sensitivity to measurement error yields a significant improvement on the accuracy of obtained results.

Experimental Validation

The validation of the computational methodology focus firstly on transformer covers, where induced heating is due to tangential field excitation. Once the identification of the adequate input parameters is done, the presented methodology is applicable to any load condition and any number of conductors.

Temperature results computed from non-linear penetration depth model are compared with measurements for several current values, for one current carrying conductor and single phase currents according to the performed tests. Good agreement between simulation results and experiments has been achieved, which demonstrate the crucial influence of the non-linear penetration depth on the temperature computation.

The results are validated experimentally by comparing 3D numerical results with measurements from thermal images. It confirms that the novelty of the present dissertation of computing the temperature to localize the hot spots on transformer covers represents one step ahead compared with those proposals existing in the literature, where results are available only in terms of power losses.

Moreover, the accuracy on the temperature distribution for the wide range studied cases indirectly validates the power loss computation.

The results illustrate how overheating clearly appears at commercial rated currents in single-phase and three-phase transformer flat tank cover plates.

Amagnetic Inserts

Means of preventing overheating hazard on transformer tank covers are evaluated, such considering amagnetic inserts in the metal plates, where the influence of metal thickness must be taken into account and screening coefficients must be introduced in the computational methodology.

The calibration process has been successfully implemented to identify unknown material properties. In particular, stainless steel has been found to be slightly magnetic. Model-calculated values are compared with measurements showing that good agreement is achieved for one conductor and single-phase currents through the cover plate.

A practical tool for the design of amagnetic inserts in three-phase flat transformer covers is also presented to be included into the computational methodology, so that cost-effective designs might be achieved.

Tank wall

The proposed 3D methodology is extended to the case of tank wall where the problem might be solved by means of 2D models. FE thermal simulations are compared with measurements validating the obtained results at one current carrying conductor and single-phase currents.

It has been proven that the overheating due to normal field excitation is not as hazardous as the overheating due to tangential field at tested current values.

A practical application is presented, where the tank wall overheating due to the presence of zero-sequence flux is evaluated. The influence of having connected a Tertiary Stabilizing Winding (TSW) is also taken into account in three-phase three-column transformers. Results show that overheating due to zero-sequence flux clearly arises if no TSW is connected.

Complex 3D Structures

The proposed computational methodology is applied to complex 3D structures such are e.g. bushing turrets. Measurements are compared with numerical results, for round and square structure shapes and different materials showing good agreement with each other.

A three-phase system with bushing turrets and flat base is included, considering various combinations of mild steel with stainless steel.

It represents the capability of the models for being implemented in the design stage of large power transformers, with drastic reduction of computation time due to the introduction of the electromagnetic analytical model.

8.2 Future Work

One of the main components of power transformers besides the core and the winding is the tank and therefore its effective and reliable design is crucial. The work presented in this dissertation represents a significant contribution in this area, however it must be continued. Thus, future lines of research would include:

- Further investigation on electromagnetic screening coefficients and screening effectiveness. Thickness of metal plates and screens or double-layer walls combining different materials, e.g. including copper screen, and their experimental testing must be considered.
- Development of models including several configurations of conductors arrangement and phase angles, creating complex problems which should be solved as rapidly as possible.
- Testing different cooling conditions such as oil or forced air convection.
- Testing the implemented models and the proposed computational methodology in real transformers, where the influence of several sources of field might be present.
- Implementation of cost-effective and optimum shape design of structural components. It requires the application of optimization algorithms taking into account design and geometric parameters and possibly a cost function. Including e.g. to automate the design of amagnetic inserts, presented in Chapter 7, considering maximum permitted temperature and total loss values together with material cost.

As first design approach the deep knowledge and understanding of the phenomena occurring in the structure is essential, obtained from parametric investigation and validated with tests. However, this research must be extended in several directions to guarantee the complete development of the presented computational methodology and tools.

a	Distance between conductors, distance to tank wall
a_p	Linearization coefficient for non-linear permeability on active power losses
a_q	Linearization coefficient for non-linear permeability on reactive power losses
b	Distance from conductor to x-axis
c_1, c_2	Distance to tank wall, coefficients for analytical approximation of BH curve
d	Plate thickness
d_i	Euclidean distance
f	Frequency, weighting function, objective function
f_1	Accuracy
f_2	Sensitivity
h	Magnetic field instantaneous value, height
h_c	Convective heat exchange coefficient
i	Current instantaneous value
j	Imaginary number, $\sqrt{-1}$
k	Attenuation constant in solid metal, constant coefficient for weighting factor
k_s	Coefficient of wall finite dimensions
k_t	Thermal conductivity
n	Normal direction
n_f	Number of objective functions
n_p	Population size
n_s	Number of sensors
n_Q	Image coefficient
n_v	Number of variables
p	Active power density, loss density
p_σ	Joule loss density
$\mathbf{q_k}$	Heat flux density
q	Reactive power density
t	Time
w_e	Stored electric energy
w_m	Stored magnetic energy
x	Design variable
x, y, z	Components of Cartesian coordinate system
x_p	Stray losses correction factor
$\mathcal{F}$	Magnetomotive force
Γ	Propagation constant
Ω	Domain
Φ	Magnetic scalar potential, Magnetic flux
$\Re$	Magnetic reluctance
$\Re e$	Complex real operator

α	Attenuation constant
β	Phase constant
δ	Field penetration depth
ε	Dielectric permitivity, relative error
ϵ	Radiation heat exchange coefficient or emissivity
λ	Wave length, attain factor
μ	Magnetic permeability
σ	Electric conductivity
σ_r	Stephan-Boltzmann constant
θ	Position angle of cylindrical coordinate system
ω	Angular frequency, search directions
ρ	Electric charge density
$\prec_n$	Crowded comparison operator
ζ	Screening coefficient

Acronyms

3D	Three-dimensional
2D	Two-dimensional
EMF	Electromotive Force
BEM	Boundary Element Method
FDM	Finite Difference Method
FE(M)	Finite Element (Method)
GATT	Goal Attainment Method
HD	Highest Deviation
HV	High Voltage
IBC	Impedance Boundary Condition
IE	Initial Estimation
IEM	Integral Equation Method
IR	Infrared
LV	Low Voltage
MD	Mean Deviation
MO	Multi-Objective
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
PD	Penetration Depth
RNM	Reluctance Network Method
RRN	Reluctance Resistance Network
RTD	Resistance Temperature Detector
SI	Surface Impedance
SO	Single-Objective
TSW	Tertiary Stabilizing Winding

Subscripts

0	Vacuum, initial estimate, zero-sequence
a	amagnetic
abs	Absolute
av	Average
e	Element
h	Hole
i, j, k	Nodal values
im	Imaginary part
L	Linear
l	Lower
m	Maximum
max	Maximum
nl	Non-linear
$perm$	Permitted value
r	Relative, radius, radial component
re	Real part
ref	Reference value
rms	Root mean square
s	Surface, sensor
$subs$	Substitution
sup	Support
Sat	Saturation
U, V, W	Components of a three-phase system
u	Upper
v	Volume
θ	Tangential component
0	Vacuum, initial estimate

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