UNIVERSITI PUTRA MALAYSIA

FREQUENCY RESPONSES OF TRANSFORMER WINDING DEFORMATIONS BASED ON FINITE ELEMENT MODELING UNDER TRANSIENT OVERVOLTAGE IMPULSES

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By

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Frequency Response Analysis (FRA) is one of the best approaches to detect the mechanical integrity of transformer windings. FRA can be measured on-site or simulated based on the transformer's design information. The calculations of Resistance (R), Inductance (L), Capacitance (C) and Conductance (G) parameters are essential to simulate the frequency responses based on transfer function and Multi-conductor Transmission Line (MTL) methods. These methods however could not provide detail conditions of the individual windings as well as the cause and effect of mechanical movements. The known causes such as the lightning strikes or switching events could lead to the amplification/attenuation of the overvoltages along the windings and subsequently result in abnormal voltage stresses. The electromagnetic fields could be generated and result in electromechanical effects which need to be classified. Hence, this project is carried out to address the stated issues. First, an alternative approach to extract transformer's winding RLCG parameters based on Finite Element Method (FEM) was proposed. The C and G were computed based on Fast Multipole Method (FMM) and Method of Moment (MoM) through quasi-electrostatics approach. The AC resistances and inductances were computed based on MoM through quasi-magnetostatics approach. Maxwell's equations were used to compute the DC resistances and inductances. Based on the FEM computed parameters, the frequency response of the winding was simulated through the Bode plot function. The simulated frequency response by FEM model was compared with the simulated frequency response based on the MTL model and the measured frequency response of HV winding for 33/11 kV transformer. Next, the resonant oscillations of HV layer and disc types windings for 11/0.415 kV and 33/11 kV transformers under different cases of lightning and switching impulses were analyzed. The impulse overvoltage were applied to the HV winding and the resonant oscillations were simulated for each of the layers and discs with consideration on different placement configurations of an electrostatic shield. The effects of different magnitudes of standard lightning impulse on the mechanical displacements and deformations of HV windings of an 11/0.415 kV transformer were also examined based on FEM. The resultant electromagnetic forces acting in axial and radial directions were computed and induced to the winding structure. It is found that the simulated frequency response by FEM model is quite close to measured frequency response at low and mid frequency regions based on Root Mean Square Error (RMSE) and Absolute Sum of Logarithmic Error (ASLE). The voltage stresses along the windings are more linear and the resonant oscillations are the lowest once a floating shield is placed between the HV and LV windings of the 11/0.415 kV and 33/11 kV transformers under different cases of lightning and switching impulses based on error of the slope (SEb). It is observed that the outer column supports of the winding structure for 11/0.415 kV transformer experiences apparent electromechanical stresses and radial buckling deformations are observed. The life and lightning overvoltage impulse withstand capability of the winding is estimated to be 1×10^6 impulse cycles which is lower than the design life of 1×10^9 for the copper conductors based on fatigue life and Von-Mises criterion.

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FREKUENSI SAMBUTAN UBAH BENTUK BELITAN PENGUBAH BERDASARKAN PERMODELAN UNSUR TERHINGGA DIBAWAH VOLTAN LAMPAU FANA DEDENYUT

Oleh

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Analisis Respons Frekuensi (FRA) adalah salah satu pendekatan terbaik untuk mengesan integriti mekanikal belitan pengubah. FRA dapat diukur di lokasi atau disimulasikan berdasarkan maklumat reka bentuk pengubah. Pengiraan parameter Rintangan (R), Aruhan (L), Kapasiti (C) and Kekonduksian (G) sangat penting untuk mensimulasikan tindak balas frekuensi berdasarkan fungsi pemindahan dan kaedah Jalur Penghantaran Multi-konduktor (MTL).Kaedah ini bagaimanapun tidak dapat memberikan keadaan terperinci bagi belitan individu serta sebab dan akibat pergerakan mekanikal.Sebab-sebab yang diketahui seperti kilat atau peristiwa pensuisan boleh menyebabkan penguatan / pelemahan lebih tegangan di sepanjang belitan dan seterusnya mengakibatkan tekanan tegangan yang tidak normal.Medan elektromagnetik dapat dihasilkan dan menghasilkan kesan elektromekanik yang perlu dikelaskan. Oleh itu, projek ini dijalankan untuk mengatasi masalah yang dinyatakan.Pertama, pendekatan alternatif untuk mengekstrak parameter RLCG belitan pengubah berdasarkan Kaedah Unsur Terhingga (FEM) dicadangkan. C dan G dihitung berdasarkan Kaedah Pelbagai Cepat (FMM) dan Kaedah Momen (MoM) melalui pendekatan kuasi-elektrostatik. Rintangan dan aruhan AC dihitung berdasarkan MoM melalui pendekatan kuasi-magnetostatik. Persamaan Maxwell digunakan untuk menghitung rintangan dan aruhan DC. Berdasarkan parameter dikira FEM, tindak balas frekuensi belitan disimulasikan melalui fungsi plot Bode. Tindak balas frekuensi simulasi oleh model FEM dibandingkan dengan tindak balas frekuensi simulasi

berdasarkan model MTL dan tindak balas frekuensi yang diukur dari belitan HV untuk transformer 33/11 kV. Seterusnya, ayunan resonan lapisan HV dan belitan jenis cakera untuk transformer 11/0.415 kV dan 33/11 kV di bawah kes berlainan kilat dan impuls pensuisan dianalisis. Impuls lebih tegangan dikenakan ke atas belitan HV dan ayunan resonan disimulasikan untuk setiap lapisan dan cakera dengan mempertimbangkan konfigurasi penempatan pelindung elektrostatik yang berbeza.Kesan pelbagai magnitud piawai kilat yang berbeza pada anjakan mekanik dan ubah bentuk belitan HV dari transformer 11 / 0.415 kV juga dikaji berdasarkan FEM. Daya elektromagnetik yang terhasil yang bertindak dalam arah paksi dan radial dihitung dan diinduksi ke struktur belitan. Didapati bahawa tindak balas frekuensi yang disimulasikan oleh model FEM cukup dekat dengan tindak balas frekuensi yang diukur pada kawasan frekuensi rendah dan pertengahan berdasarkan Root Mean Square Error (RMSE) dan Total Absolute of Logarithmic Error (ASLE).Tekanan tegangan di sepanjang belitan lebih linear dan ayunan resonan adalah yang paling rendah apabila perisai terapung diletakkan di antara belitan HV dan LV dari transformer 11/0.415 kV dan 33/11 kV di bawah kes berlainan kilat dan impuls pensuisan berdasarkan ralat cerun (SEb).Telah diperhatikan bahawa sokongan tiang luar struktur belitan untuk transformer 11/0.415 kV mengalami tekanan elektromekanik yang jelas dan ubah bentuk lengkungan radial diperhatikan. Jangka hayat dan ketahanan impuls lebih tegangan kilat belitan dianggarkan 1×10^6 kitaran impuls yang lebih rendah daripada 1×10^9 hayat reka bentuk untuk konduktor tembaga berdasarkan jangka hayat keletihan dan kriteria Von-Mises.

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LIST OF ABBREVIATIONS

FRA	Frequency Response Analysis
RLC	Resistance, Inductance and Capacitance
MTL	Multi-Conductor Transmission Line
FEM	Finite Element Model
HV	High Voltage
LV	Low Voltage
SLI	Standard lightning Impulse
CLI	Chopped Switching Impulse
SSI	Standard Switching Impulse
OSI	Oscillating Switching Impulse
MoM	Method of Moments
SEE	Slope Error of Estimate
SEb	Error of Slope
CIGRE	International Council on Large Electric Systems
EMF	Electromagnetic Force
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
TF	Transfer Function
VFTO	Very Fast Transient Overvoltages
ASLE	Absolute Sum of Logarithmic Error
RMSE	Root Mean Square Error

VFTS	Very Fast Transient Surges
ML	Medium Voltage
PSD	Power Spectral Density
FFT	Fast Fourier Transform
MMF	Magnetomotive Forces
S-N	Stress-Cycle
EM	Electromagnetic
SD	Standard Deviation
FMM	Fast Multipole Method
EMI	Electromagnetic Interference
CC	Correlation Coefficient
KCC	Kendall's tau correlation coefficient
BIL	Basic Lightning Impulse Insulation Level
HF	High Frequency

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, the demands for energy are increasing and interruption in any of the components in the electrical power system network can be costly. Transformers form an integral part of either the transmission or distribution network. The reliability of transformers has a crucial role on maintaining the continuity of the electrical power delivery. Condition monitoring of transformers is essential to ensure any issues can be detected early and thus reduce the probability of failures in-service.

There are several parameters of transformers that can be monitored which include thermal, chemical, electrical and mechanical properties. Mechanical properties are known as one of the critical parameters for transformers whereby it could lead to sudden failures if no mitigation is carried out. Frequency Response Analysis (FRA) is known as one of the common approaches to analyze the mechanical integrities of transformer windings. It can be used to detect any movements or deformations in the windings. FRA analyzes the windings by representing the physical geometries of the windings as resistance (R), inductance (L) and capacitance (C) elements. Damages in transformer windings could change the RLC elements, which in turn lead to different responses along the frequency spectrums.

Generally, the winding parameters are dependent upon the number of turns in the winding, size of the conductor and insulation thickness. Transfer function method is among the conventional numerical approaches that can be used to analyze FRA [1], [2]. This method has also been used to analyze various types of deformations in transformer windings which include the radial deformation, axial displacement, axial bending and disc space variation [3]–[5]. Other numerical approaches that have been used to carry out FRA on transformers windings are Multi-Conductor Transmission Line (MTL) method and lumped circuit modeling [6]–[8]. These numerical methods however have their own limitations especially on giving detail conditions of the individual windings. Furthermore, the study of winding deformation causes are still limited and require further investigation.

1.2 Problem Statement

The numerical methods have limitations especially on determining the faults causes and its corresponding detail mechanical windings damages. The FRA is the most utilized condition monitoring technique to determine the physical health of the winding structure. MTL, TF, lumped circuit and duality-based models were commonly used for simulation of transformer winding to simulate the frequency response. However, these methods could not accurately represent the actual winding due to the simplifications during the modeling stage. Finite Element Modeling (FEM) could provide much clear insight into the FRA of transformer windings as compared to existing numerical methods. The FEM model usually applies magnetostatic and electrostatic solvers to determine the inductance and capacitance matrices based on Maxwell's equations [9]–[11]. Eddy current solver is typically used to calculate the frequency-dependent resistances of the winding model [12]. The parameter calculation of the detailed 3D model of the winding requires longer simulation time [13]. However, accurate modeling of the transformer winding structure by optimizing the required computational power is still a challenge. Nevertheless, there is no specific technique entirely based on FEM available to simulate FRA. Therefore, an alternative FEM computation method is required to reduce the simulation time and at the same time maintain the reliability of the outputs.

Switching and lightning surges are among the faults that could possibly cause the deformation of transformers windings [7], [14]–[16]. Once the windings are subjected to external voltage surge impulses, voltage stresses can initiate and propagate in the winding insulations and result in the degradation process [17]. The repeated exposure of the overvoltage surges could accelerate the degradation of the insulation which in turn could lead to failures of windings in transformers [18], [19]. The effect of oscillatory impulse is more severe than lightning, chopped lightning and switching impulses [20]. However, further analyses on this phenomena are limited especially on the overvoltages distribution along windings and its corresponding mitigation approaches. Several approaches have been proposed to mitigate the overvoltage issues on transformers by the placement of surge arrestors, arcing gaps and shielded overhead Medium Voltage (MV)/LV lines. However, there is no much focus on improving the withstand capability of transformers under the lightning and switching surges has been considered. The placement of the electrostatic shield as recommended by IEC 60076-3 and IEC 60076-4 at predetermined locations in the winding geometry could mitigate the effect of the transient voltages and improve the linearity of the voltage distributions [24–30]. An electrostatic shield can be used to increase the series capacitance which in turn could increase the uniformity of the voltage and dielectric stress distributions in the windings. Currently, the study on the shield placements' impact on the resonant surge distributions in the transformer windings are still lacking and needs further investigation. Hence it is a critical aspect of the research in order to evaluate this aspect to maintain the reliability of transformers.

In addition, failures could be mechanical in nature due to deformations in the transformer windings. As the lightning strike on the power line, the transformer winding could be subjected to resulting electromagnetic force. This condition could instigate apparent electromechanical effects on the winding structure. Monitoring the electromechanical effects through the electromagnetic forces in axial and radial directions assists to minimize the mechanical failure in transformer windings. Previous studies have computed the axial and radial forces under short circuit and inrush currents through analytical methods [26][27]. However, the study on the mechanical damages and the level of winding deformations under transient overvoltage impulses are still limited. To date, there are no clear guidelines especially to identify the severity levels of transformer winding deformations.

1.3 Research aim and objectives

The aim of this research is to evaluate the impact of transient overvoltage impulses on the frequency responses and electromechanical behaviors of transformer's winding deformations based on FEM approach. In order to achieve the above aim, several objectives have been identified.

1. To develop an approach to extract RLC parameters of the transformer windings based on FEM method for computation of FRA.
2. To investigate the overvoltage transients in transformer windings under standard/chopped lightning and standard/oscillating switching impulses and its mitigation through shield placements.
3. To examine the electromechanical effects on transformer windings under different magnitudes of lightning impulses based on FEM method.

1.4 Scope of Study

The present study considers various assumptions to achieve the individual objectives:

1. For the first objective, a Dyn11 transformer used in the study has the power and voltage ratings of 30 MVA and 33/11 kV of which only one phase of the HV winding is considered for the FEM simulation. The FEM model of the distribution transformer used for validation considers eight discs with six conductors and thirty turns of the total ninty-six discs of the HV winding for the RLC parameters extraction due to the limitation of the high-speed computation capabilities. Therefore, the eight discs with the computed RLC parameters were stacked twelve times in series to form the complete HV winding of one phase. The FRA test circuit simulated by Ansys Simplorer is based on end-to-end short circuit configuration.

2. For the second objective, the first of the two transformer case studies considered is a Dyn11 transformer with power and voltage ratings of 160 kVA and 11/0.415 kV with layered helical HV winding and foil LV winding. The second transformer is a Dyn11 transformer consists of disc HV winding and layered helical LV winding with power and voltage ratings of 33/11 kV and 30 MVA. The study considers the individual HV conductor specifications for the calculation of initial voltage distribution. The allowance considered in the actual height of the HV winding could not be considered for the purpose of validation due to the lack of information on the distribution of allowance in the winding geometry. The shield used in the mitigation of overvoltage surges in the windings is aluminium conductor of thickness 0.075 mm. The eddy current loss was neglected for both transformers under study since the calculated value of eddy current loss were found to be low as compared to the calculated total loss. The mutual coupling between HV and LV windings was not considered in the transient voltage study.

3. For the third objective, the HV winding in 11/0.415 kV distribution transformer is considered for the electromechanical analysis under the lightning impulses. It is due to the transformers are tested in laboratories under standard lightning impulses as part of the routine acceptance tests to establish a minimum level as per IEEE Std C57.98-2011. A Dyn11 transformer with power and voltage ratings of 160 kVA

and 11/0.415 kV with layered helical HV winding is considered in the study.

1.5 Contribution of the research

The details of the contributions of this research study are as follows:

1. The current study applies FEM entirely to extract the RLC parameters for FRA simulation. Besides, an alternative FEM approach based on Ansys Q3D was introduced to obtain the RLC parameters which is much faster than the FEM method based on Ansys Maxwell. The 3-D model can be modeled close to the actual geometry to study the various types of structural deformations in the transformer windings.

2. The study on the overvoltage surge distribution mitigation for two different types of transformers could assist the design engineers to identify the optimized location of electrostatic shield placement to minimize the adverse effect of voltage stresses on the winding conductors.

3. The FEM simulation can be applied as an alternative non-invasive technique to monitor the electromagnetic force, location, type of the damage and estimates the remaining life of the winding due to overvoltage impulses. This information provide the field engineers with much insight especially on the root cause assessment.

1.6 Organization of the report

The report is organized in five chapters to achieve the objectives mentioned. The chapter one provides the general background of the current research. The problem statement, objectives of the study and the assumptions are discussed briefly.

The chapter two begins with the review of the previous works that discuss the different methods of calculation of RLC parameters of the transformer winding and subsequent generation of FRA response. Then the previous conducted studies on the overvoltage surges existing in the power system and their adverse effects along the winding layers are discussed. In addition, the methods to mitigate the voltage stress along the windings are explained. Finally at the end of chapter two, the concept of the electromechanical effect on the transformer windings generated due to electromagnetic forces is discussed based on previous studies.

In chapter three, the methodology to approach the research objectives are explained in detail. At first, the novel method that is introduced to calculate the RLC parameters is presented. The subsequent simulation of FRA response is explained in detail. Then, the analytical model to study the overvoltage surge behavior of two different transformer cases are analyzed. The procedure to investigate the appropriate location of shield placement is explained. Finally, the procedure to calculate the electromagnetic forces generated due to various magnitudes of impulse surges and the resultant deformation of the winding structure are discussed in detail.

The chapter four discusses the results of the research study. First, the FRA response simulated based on MoM and FEM based on Ansys Q3D is compared with the measured response and the response simulated based on MTL method. Then, the overvoltage surge behavior of SLI, CLI, SSI and OSI impulses on the HV winding of a 11/0.415 kV and 33/11 KV transformers are presented. The optimized location of shield placement is simulated and is compared based on the results of Error of Slope (SEb). Finally, the structural deformation due to various magnitudes of SLI are presented for the HV winding of 11/0.415 kV transformer. Besides, the results of fatigue life estimation and the classification of the deformations are discussed.

Finally the chapter five summarizes the conclusion of the research study along with the recommendations of the future works.

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LIST OF PUBLICATIONS

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