PREMATURE FAILURE DETECTION OF DISTRIBUTION TRANSFORMER WITH UNBALANCED HARMONIC LOADS USING HOTSPOT TEMPERATURE ANALYSIS

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ABSTRACT

Harmonics distortion is the most prominent power quality problem in an electrical power distribution network that interrupts a good quality of electric power to be drawn in the network. Additionally, the major impact of harmonics distortion is the risk of the distribution transformer failure due to the elevation of power losses and hotspot temperature (HST) in its three-phase low voltage (LV) winding cables. The major challenge is to identify the exact location and point where the premature failure could occur on the three-phase cables. This research proposes an HST mathematical expression to detect a premature failure at the three-phase LV winding along with the transformer loading. As most transformer failure cases were rooted in heat losses that require meticulous analysis, the best accuracy numerical method as Finite Element Method (FEM) is selected to analyse the HST of the thermal distribution transformer model. The HST is simulated by considering the three-phase unbalanced harmonic loads from three different group levels of THDI and under five different insulation temperature classes system. The simulation outputs are then verified with HST results from the HST mathematical model based on IEEE C57.110-2018 standard. Further analysis of the simulation results has been done to propose the HST mathematical expression, which will be assessed on the three-phase LV winding cables to detect premature failure. At the end of this research, it is found that the individual harmonic currents from the 7th until 19th order are the prominent harmonic orders that had exceeded the limit of MS 1555 (IEC 61000-3-4) standard. Other than that, based on the proposed HST mathematical expression, it is found out that if the transformer is being loaded with loading over 0.9 pu, the premature failure is expected to occur promptly in the group of THDI peak-level, prominently at 180, 200 and 220 insulation temperature classes. As for the lifetime expectancy of the distribution transformer, if the transformer is loaded with loading at 0.9 pu and above, the lifetime is approximated to drop by the minimum at 14.5% and maximum at 56% from its expectancy lifetime. Plus, it is also concluded that the possibility of the lifetime reduction to be happened at the premature failure point at average of 93.5%, 85.4% and 78% of the THDI peak-level, THDI average-level and THDI low-level correspondingly. Hence, the findings have successfully shown the proposed method's effectiveness in vividly viewing the distribution transformer's current condition. Upon the early detection of the premature failure on the three-phase cables, the execution of the proposed HST mathematical expression is also able to identify the exact location and point where the premature failure shall happen. Thus, it outright protects the distribution transformer from any unwanted breakdown, next preserves its best performance and lifetime expectancy.

ABSTRAK

Gangguan harmonik ialah masalah utama di dalam rangkaian elektrik kuasa, yang mana ianya mengaggu kualiti kuasa yang terbaik untuk mengalir di dalam rangkaian tersebut. Tambahan lagi, kesan utama gangguan harmonik ini ialah risiko kegagalan pada alat pengubah agihan yang berpunca daripada peningkatan dalam kehilangan kuasa dan suhu titik panas *(HST)* di atas kabel voltan rendah *(LV)* tiga fasanya. Cabaran utama adalah untuk mengenal pasti lokasi dan titik tepat di mana berkemungkinan terjadi kegagalan pramatang pada kabel tiga fasa. Kajian ini mencadangkan ekpresi matematik *HST* untuk mengesan kemunculan kegagalan pramatang pada kabel *LV* tiga fasa di sepanjang muatan alat pengubah agihan. Sebagaimana kebanyakkan kes - kes kegagalan pengubah berpunca daripada kehilangan haba yang memerlukan analisis yang teliti, keadah numerikal yang tepat seperti *Finite Element Method (FEM)* dipilih untuk menganalisa suhu titik panas *(HST)* pada model termal pengubah agihan. *HST* disimulasi dengan mengambilkira keadaan muatan harmonik tidak seimbang tiga fasa yang diperoleh daripada tiga kumpulan aras gangguan arus harmonik *(THDI)* dan pada lima sistem kelas penebat suhu yang berbeza. Hasil keputusan daripada simulasi tersebut kemudiannya diverifikasi dengan hasil keputusan *HST* yang diperoleh daripada model matematik *HST* berdasarkan kepada piawaian di dalam IEEE C57.110-2018. Tambahan analisis kepada keputusan simulasi tersebut dilakukan bagi mengemukakan ekpresi matematik *HST* di mana akan ditaksir pada kabel *LV* tiga fasa untuk mengesan kegagalan pramatang pada alat pengubah agihan. Di akhir kajian ini, telah didapati arus harmonik individu yang bermula dari jujukan susunan 7^{th} sehingga 19^{th} adalah merupakan jujukan yang paling ketara dalam melepasi batas piawai MS 1555 (IEC 61000-3-4). Selain daripada itu, berdasarkan kepada ekspresi matematik *HST* yang dikemukakan, sekiranya muatan pengubah melebihi 0.9 p.u, kegagalan pramatang dianggar akan berlaku pada kumpulan aras THDI tertinggi *(THDI peak-level)* , terutamanya dalam sistem kelas penebat suhu 180, 200 dan 220. Bagi jangkaan hayat pengubah agihan pula, sekiranya muatan pengubah pada 0.9 p.u dan ke atas, jangkaan hayat dianggarkan akan menurun secara minimumnya sebanyak 14.5% dan maksimumnya sebanyak 56%. Tambahan, ianya juga boleh disimpulkan bahawa kemungkinan pengurangan jangka hayat pengubah terjadi pada ketika kegagalan pramatang berlaku adalah secara puratanya pada 93.5%, 85.4% dan 78% di dalam gangguan arus harmonik yang paling tinggi *(THDI peak-level)*, aras sederhana *(THDI average-level)* dan aras rendah *(THDI low-level)* masing - masing. Maka berdasarkan kepada penemuan - penemuan tersebut, ianya telah menunjukkan keberkesanan metodologi yang dicadangkan untuk memaparkan secara jelas keadaan semasa alat pengubah agihan tiga fasa. Di atas pengesanan awal kegagalan pramatang pada kabel tiga fasa, perlaksanaan ekpresi matematik *HST* yang dikemukakan ini juga dapat mengenal pasti lokasi dan titik tepat di mana kegagalan pramatang bakal berlaku. Maka ia serta merta dapat melindungi alat pengubah agihan tersebut daripada kerosakkan yang tidak diingini, seterusnya dapat memelihara prestasi terbaik dan jangkaan hayatnya

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Alternating Current
CPU	-	Central Processing Unit
DGA	-	Dissolve Gas Analysis
DP	-	Degree of Polymerization
EC	-	Eddy Current
EV	-	Electric Vehicle
FCM	-	Fuzzy C-Means
FEM	-	Finite Element Method
HST	-	Hotspot Temperature
LV	-	Low Voltage
MQ	-	Family of Gas Sensor
PCC	-	Point of Common Coupling
PEV	-	Plug-In Electric Vehicle
PQ	-	Power Quality
PSO	-	Particle Swarm Optimization
PV	-	Photovoltaic
RBF	-	Radial Basis Function
RMS	-	Root Mean Square
T1	-	Transformer 1
T2	-	Transformer 2
TDD	-	Total Demand Distortion
THD	-	Total Harmonic Distortion
THDV	-	Total Harmonic Distortion Voltage
THDI	-	Total Harmonic Distortion Current
WHF	-	Two Dimensional

LIST OF SYMBOLS

F_{HL}	-	Harmonic Loss Factor
F_{HLec}	-	Harmonic Loss Factor for Eddy Current
F_{HLosl}	-	Harmonic Loss Factor for Other Stray Part
$FHL_{ec} P_{ec}$	-	Corrected Real Eddy Current Power Load Loss
β	-	Real Load Factor
P_{NL}	-	No Load Losses
P_{LL}	-	Load Losses
P_T	-	Total Power Losses
$P_{LL\,(pu)}$	-	Per Unit Value of Load Losses
$P_{LL\,rated\,(pu)}$	-	Rated Per Unit Value of Load Losses
$P_{LL\,rated}$	-	Rated Load Losses
$P_{I^2Rrated}$	-	Rated Ohmic Losses
$P_{tosl\,rated}$	-	Rated Total Other Stray Losses
$P_{osl\,rated}$	-	Rated Other Stray Losses
$P_{ec\,rated}$	-	Rated Eddy Current Losses
P_{I_2}	-	Power Loss at Secondary Side of Transformer
K	-	Constant gain
I_1	-	Current at Primary Side of Transformer
I_2	-	Current at Secondary Side of Transformer
R_1	-	Resistance at Primary Side of Transformer
R_2	-	Resistance at Secondary Side of Transformer
h	-	Harmonic order
I_h	-	Harmonic Current
μ_r	-	Relative permeability
σ	-	Electrical conductivity
C_p	-	Heat capacity at constant pressure
ε	-	Relative permittivity
ρ	-	Density
k	-	Thermal conductivity
ɣ	-	Ratio of specific heat

b.c	-	Boundary Condition
n	-	Boundaries Vector
q	-	Conductive Heat Flux
q_0	-	Convection Heat Flux
T	-	Temperature
T_0	-	Initial Temperature
Q	-	Heat Source
Q_{ted}	-	Thermo Elastic Damping
Q_e	-	Electromagnetic Heat Source
P_0	-	Power Losses
V	-	Volume
d_z	-	Thickness of the Geometry
u	-	Thermal Heat Coefficient
$\Theta_{HS-rated}$	-	Rated Hotspot Temperature
θ_{HS}	-	Hottest-spot Winding Temperature
θ_a	-	Ambient Temperature
$\Delta\theta_{HS,r}$	-	Rated Hottest-Spot Temperature Rise Over Ambient
$\Delta\theta_{HS}$	-	Hottest-Spot Temperature Rise Over Ambient
Θ_{HS-130}	-	HST at 130 insulation temperature class
Θ_{HS-150}	-	HST at 150 insulation temperature class
Θ_{HS-180}	-	HST at 180 insulation temperature class
Θ_{HS-200}	-	HST at 200 insulation temperature class
Θ_{HS-220}	-	HST at 220 insulation temperature class
$\Theta_{HSpre-130}$	-	HST of premature failure at 130 insulation temperature class
$\Theta_{HSpre-150}$	-	HST of premature failure at 150 insulation temperature class
$\Theta_{HSpre-180}$	-	HST of premature failure at 180 insulation temperature class
$\Theta_{HSpre-200}$	-	HST of premature failure at 200 insulation temperature class
$\Theta_{HSpre-220}$	-	HST of premature failure at 220 insulation temperature class
L	-	Per Unit Load
m	-	Empirical Constant
t_{Life}	-	Expected Lifetime of Transformer
exp	-	Base of Natural Logarithms

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research background

Ever since the evolution of the power electronics technologies to replace the conventional alternating current (AC) electrical system, Malaysia as a developing country is not exceptional in utilizing those technologies to improve its system towards the country's development. Upon that matter, good quality of the electricity power is expected to be drawn along the distribution networks. Unfortunately, the ideal state of the power could not be ideally obtained due to the undesired power quality event such as the harmonics. Harmonics distortion is the most prominent power quality problem in electrical power distribution networks. International standard bodies such as the Institute of Electrical and Electronics Engineers, IEEE defined harmonics as the frequency components that are integer multiples of the fundamental line frequency.

The harmonics mainly originated from the nonlinear loads in the electrical distribution equipment which the frequency variations are mainly involved. The nonlinear load is defined as a load where the steady-state wave shape does not follow the wave shape of the applied voltage [1]. Other than the distorted power sinusoidal wave shape, the problems that might be happened due to the nonlinear harmonics loads include the elevation of the power losses and overheated the distribution transformer, poor power factor condition that causes users to pay the penalty fee, disturbance in the smoothness of massive production at industrial sites and many other bothersome issues within the network.

Based on the above problems, other crucial aspects are the electrical equipment's safety and lifetime. This hence mainly refers to the distribution transformer. In any electrical system network, a distribution transformer is a vital component of the distribution system, which enable the utility provider to deliver power to its customers. It supplies voltage throughout the four wires cables to the electricity consumer, which usually requires high demand. Thus, making the distribution transformer the most expensive equipment in the electricity delivery system. Upon that matters, it is vital to ensure the durability and lifetime expectancy of the distribution transformer and its best performance to be preserved. In order to do this, it is best to explicit the possible root cause of any probability failure in the transformer at the earlier stage to avoid the massive loss due to the breakdown of the transformer. In [2], the author stated that the top ranking in the distribution transformer failure cases was caused by the transformer's excessive heat. The statement is strongly supported by the group of previous works that most agreed that the heat is the primary source of the failure in the distribution transformer [3–16]. Other than that, the authors also came to the mutual finding that most failures are happened at the low voltage side winding (LV) of the transformer compared to the core or other parts in the transformer. Elsewhere, the failure is said to frequently happen due to the degradation of the winding's insulation [17-28]. Nevertheless, the harmonics were not much being appointed or focused as the source of the excessive heat in that particular works.

Despite that, the impacts of the harmonics towards the distribution transformer are being highlighted in the numerous previous works, with most having emphasized the impact from the harmonic currents and having neglected the harmonic voltages due to its insignificance in the analysis [29-37]. The harmonic currents are said to be the root in the induction of the additional power losses and elevation in the average temperature rise and hotspot temperature of the transformer's LV winding. This is highly supported in [37], where the author had clarified that the harmonic currents had caused the 17% increment in the temperature rise at the LV winding and only caused the 3% increment at the HV winding. However, from the mentioned past works, another drawback is that less attention was paid to the actual condition of the unbalanced harmonics loads. Only a few authors opted to illustrate the impacts from the view of unbalanced harmonics loads condition [38-46]. Without illustrating the actual operation of the LV network, in which the current in each phase is expected to be imbalanced as the supply depends on the load needs, the accuracy of the results can then be disputed. Thus, to get a precise outcome of any research problem, this unbalanced condition shall be considered and analysed thoroughly without exception.

Other than the actual harmonics loads condition, the behaviour of the harmonics loads also needs to be carefully observed, as it can indicate any possibility of premature failure at the transformer. Additionally, the behaviour shall cover the order of the harmonics (h_{th}), the individual spectrum of the harmonics (I_h) in which finally brought to the generation of the harmonics distortion level produced during the operation of the network, which is also known as total harmonic distortion (THD). On the topic to preserve the performance and the lifetime of the transformer, abundance methods are being proposed to observe and understand the behaviour of the harmonics loads in the transformer [47-59] and their contributions to the temperature rise and HST that may cause failure inside the transformer [60-67]. However, based on their results, the ambiguities were still there because not many authors came with the exact classification of the harmonic behaviour, especially on the THD that represents the several loads' distortion condition from the consumer. This is by means, the harmonic behaviour towards the power losses and hotspot temperature of the transformer should be determined and analysed according to the specific loads status and the actual operation timing of the loads which either the loads are generating low, intermediate or high harmonic distortion at that particular time. From this exact classification, the particular condition of the premature failure of the transformer shall be achieved.

The final part is the premature failure condition of the transformer due to the unbalanced harmonics loads. This is vital since prevention is indeed better than cure. It is highly recommended to protect the transformer at the earlier stage of any premature failure before the failure worsens until the unwanted massive breakdown becomes unavoidable. Since last 2011 up to the year 2020, many published research papers related upon endeavour in detecting and analysing the premature failure of the transformer. There are broad methods, including the model simulation covering numerical and analytical analysis [68-72], power quality collected data assessment [73-77], laboratory testing, and maintenance activities [78-81]. However, despite the advantages in each finding, there are still rooms for improvement that can be made in the analysis. First of all, only limited papers had put the influence of the harmonic range or harmonic classification into the premature failure of the transformer. Secondly, none of the specific location on the winding was declared whenever they had traced any sign of the premature failure from their output results. This has made their methods impractical when there is a high necessity to trace the suspected problem from a specific view. This is important to avoid waste in cost and energy to replace the whole transformer unit with the new one. Secondly, there is a high necessity in choosing the most efficient technique to obtain the most accurate result. Based on studies, researchers have agreed that the Finite Element Method (FEM) from the numerical analysis is the most accurate, efficient, reliable and relevant up to recently to solve any simple and even complex problem in any condition compared to other methods [82-85]. Aside from the previously mentioned papers, this can also be seen in numerous published papers that are prominently related to the solution of the problems in transformer [86-91]. Last but not least is lacking in using the international standard as the reference for the premature failure condition. This is by means, other than using the formulation guide in the standard, the limit stated in the standard also can be beneficial as a benchmark of any evaluation analysis work.

Hence, it comes to the consideration in this research to utilize the FEM and combine it with the selected international standard limit as the reference of the premature failure condition of the transformer. The designed thermal transformer model using FEM is expected to generate the value of hotspot temperature (HST) in the LV winding of the three-phase transformer under unbalanced harmonics conditions throughout the simulation. Then the HST value is compared to the standard limit to check the compliance of the HST towards the limit. As for the limit compliance reference, the best reference to be referred to in harmonics behaviour towards heating the transformer is the guide solution from the well-established and trustworthy IEEE standard. For every type of temperature, the related standard such as IEEE Std. C57.134-2013 [92] and IEEE Std. C57.96-2013 [93] have already provided the guidelines and set the limit to be the reference for any study related to the distribution transformer's temperature. In the actual practice of the distribution transformer, if any temperature value exceeds the limit, the transformer is said to be in a risky state and need to be alert for any failure or tripped. This fact can hence be beneficial in clarifying the premature failure condition of the distribution transformer due to the harmonics.

In order to validate the results proposed in this thesis, the HST results from both thermal distribution transformer modelling using FEM [94] and HST mathematical modelling using IEEE Std C57.110-2018 standard [95] are compared. The modelling using the IEEE standard can be done because, in the mentioned standard, the committee had established the hotspot temperature (HST) calculation concerning the non-sinusoidal load currents for both liquid immersed-type and dry-type of power and distribution transformer.

Thus the main focus of this research is to propose an early detection of premature failure expression at the distribution transformer by improving the analysis of power losses concerning the unbalanced harmonic loads towards the hot spot temperature of the transformer. Hence, the percentage of the harmonic current loads that contribute to the final hot spot temperature is classified and presented. Also, for any hotspot temperature that has exceeded the standard limit, the percentage of that particular unbalanced harmonic current loads towards the hotspot is expressed as an indication of the early detection of premature distribution transformer failure.

1.2 Problem statement

Generally, the harmonic current loads gradually impact the ideal performance of the distribution transformer when they increase the power losses and HST, which lead to the possible failure inside the winding of the distribution transformer. Hence, some of the related problems to be solved in this thesis are listed as follows:

i. The excessive unbalanced harmonic loads currents elevate the total power losses and increase the hotspot temperature in the LV winding. This can cause damage and breakdown of the distribution transformer if no preventive measure has been taken at the earlier stage [37]. In the network operation between commercial loads and voltage supply, lack of attention had been given to the relationship between the unbalanced harmonics loads to the power losses and hotspot temperature of the transformer to observe any premature failure that could be occurred in the transformer [43].

ii. The harmonics current distortion (THDI) is often treated as the distortion percentage, which is calculated from one whole day instead of particularly measured at a specific real-time within the day in observing its impact towards the distribution transformer's LV winding. When considering the power losses and hotspot temperature of the winding in the distribution transformer, no harmonic current distortion from specific hours is highlighted in the previous in order to explicitly recognize its behaviour towards the premature failure of the winding [63]. Additionally, most of the previous works cited in this research focused on the higher value of THDI instead of paying attention to the lower value to analyse its impact on the distribution transformer [64-66]. Hence, this brought to the hypothesis that the failure's causes upon the harmonic distortion can only be known once the distribution transformers are either already damaged or its expectancy lifetime had dramatically dropped, as the premature failure in the distribution transformer could not be traced at an earlier stage.

iii. The existing methods to detect the premature failure of distribution transformers remain ambiguous in the findings. This upon lacking in utilizing the mathematical function to vividly express the final findings for a better understanding of the proposed solution [70], [73], [75], [77]. Plus, when dealing with failure in the distribution transformer, it is also important to perform the real lifetime of the transformer in order to observe the impact of the failure on the lifetime expectancy of the transformer. Thus, with the comprehensive expression of the findings, the analysis of the real lifetime estimation of the transformer shall be improved.

1.3 Research objectives

Based on the previously mentioned problems in Section 1.2, here are the listed three main objectives to be implemented for this research to reflect those arisen problems accordingly.

i. To propose an improved analysis in power losses of distribution transformer to detect the premature failure of the transformer by considering the relationship between unbalanced harmonic current from the loads towards power losses and HST of the transformer.

ii. To enhance the examination of the HST behaviour on the LV windings by employing the power losses under different THDI levels onto the FEM thermal distribution transformer model to identify the premature failure condition of the LV windings under such particular circumstances.

iii. To develop a new HST mathematical expression for premature failure condition assessment based on HST upon per unit loadings, which to be assessed on the LV windings and evaluate the real lifetime estimation of the distribution transformer.

1.4 Research scopes

In accountability to implement the abovementioned objectives in Section 1.3, the following scopes are hence shall be covered in this research.

i. All harmonic data are measured and collected for one week with 10 minutes intervals using a power quality data logger at the substations interconnected to commercial buildings.

ii. The measured and collected harmonic data for this research mainly comes from the detected problematic transformer at a substation that supply electricity to commercial load building.

iii. The harmonic data for this research is extracted and assembled according to three different hours within the load operation of the selected day. The three different hours are named as the peak hour, average hour and low hour.

iv. The harmonic current orders that being considered for this research are the odd harmonics orders, which start from 1st until 19th (I_1 until I_{19}).

v. The THDI value being analysed for the research finding ranges between 12% to 22%.

vi. The computation of the HST value is intended on the specified LV winding of the distribution transformer model.

vii. The applications of Power analyse software, COMSOL Finite Element Method software, MATLAB software and Microsoft Excel are used to simulate the power flow harmonics analysis throughout the model of the distribution transformer.

viii. FEM thermal distribution transformer model in COMSOL is developed to classify the condition of the hotspot temperature of the LV winding due to the unbalanced harmonic current loads.

ix. The premature failure condition of the distribution transformer is determined by referring to the maximum hottest spot temperature loading above rating standard limits in [93].

x. The results are validated by comparing with the HST obtained from the IEEE HST mathematical model, which is modelled using the guidelines from [95].

1.5 Research contributions

Prior to the statements and explanations from the previous sections above, here come the lists of contributions that shall be gained throughout the findings in this research.

i. The final finding in this research summarized the HST condition of the LV winding by considering the possibility of different levels of the THDI that might occur in the network.

ii. The proposed method had considered the unbalanced current loads due to the harmonic to be the adding value for this research. The finding in this research is hence convincible to be the reference to the early detection of a premature failure of the distribution transformer. Additionally, the generated premature failure expression allows to observe and analyse the insulation deterioration condition of the LV winding from each phase to decide the suitable counter measure regarding the condition. This hence will ease the diagnostic action on the transformer and replace the tedious, laborious and yet costly repair and maintenance for the whole one unit of the transformer.

iii. The analysis in this research covered the whole types of insulation temperature classes that might be used in designing a distribution transformer for the low voltage network.

iv. The lifetime analysis of the transformer under nonlinear loads is improved by the implementation of the proposed method from this thesis. Not limited only to observing the impact of the THDI on the lifetime, the proposed method provides a coherent view of the real condition inside the transformer that contributes to the impact.

v. The application of FEM as the acknowledged efficient numerical method and the regulation of the aforementioned standards has improved the reliability, robustness, result accuracy, practicality, and cost effective, which benefitted to achieve the objectives from this research.

1.6 Thesis outlines

This thesis is organized into five chapters. The introduction in Chapter 1 is comprised of research background, problem statements, research objectives, research scopes, research contributions and thesis outline. The literature review in Chapter 2 reviews previous related research works dominantly on harmonics and its impact on the transformer. Several selected publications are presented rigorously to expose the effectiveness and research gaps that are beneficial in the development of the proposed premature failure determination in distribution transformers. Chapter 3 explains the entire sequences in this research, including the harmonics data measurement and assembly from the site, designation and simulation of the distribution transformer, derivation of the premature failure function, and estimation of the real distribution transformer's lifetime. The designed distribution transformer model, which is verified based on remodelling the similar research problem using guidelines from the selected international standards, are also presented in this chapter. The results and discussion in Chapter 4 report the data collection, simulation results, discussions and validations of the HST behaviour under the unbalanced harmonic influence, the proposed HST at premature failure condition of the transformer and affected expectancy lifetime of the transformer. Ultimately, the conclusion in Chapter 5 summarizes the entire works in this thesis and proposes several recommendations that can be implemented in the future.

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