MODELLING OF OIL IMPREGNATED PAPER TRANSFORMER BUSHING ON ELECTRIC FIELD AND HOT SPOT TEMPERATURE USING FINITE ELEMENT METHOD

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
AC	Alternating Current
AI	Artificial Intelligence
AIS	Air Insulated System
ANSI	American National Standards Institute
CAD	Computer Aided Design
DC	Direct Current
EF	Electric Field
EFVD	Electric Field and Voltage Distribution
FEM	Finite Element Method
GIS	Gas Insulates System
HST	Hot Spot Temperature
Hz	Hertz
IEC	International Electrotechnical Commission
IEEE	Institution of Electrical Electronic Engineer
IR	Industrial Revolution
MIS	Main Intake Substation
OIP	Oil Impregnated Paper
PDE	Partial Differential Equation
RBP	Resin Bonded Paper
RIP	Resin Impregnated Paper
SF6	Sulfur hexafluoride
TD	Temperature Distribution
VD	Voltage Distribution

LIST OF SYMBOLS

E_r	Radial stress
E_a	Axial stress
S_n	Spacing between each foil
r_n	Radius of the foil referred from the centre of conductor
L_n	Length of aluminum foil
b_{ln}	Length difference of aluminum foil at left side
b_{rn}	Length difference of aluminum foil at right side
N	Number of foils
n	Outermost foil
ε_r	Electric permittivity
ε_o	Vacuum permittivity
∇V	Voltage difference
C	Capacitance
E	Electric field
D	Electric displacement
ρ	Charge density
ε	Permittivity
k	Thermal conductivity
T	Temperature
C_P	Specific heat capacity
$q(r)$	Heat flux vector
J	Current density
P_1	Heat generated along the unit length of conductor
φ	Flux density
σ	Insulator heat conductivity
f	Frequency
$\mathrm{Tan}\,\delta$	Dissipation factor
P	Heat in the unit volume

Permodelan Sesendal Pengubah Kertas Diresapi Minyak Terhadap Medan Elektrik dan Suhu Titik Panas Menggunakan Kaedah Unsur Terhingga

ABSTRAK

Sesendal pengubah adalah bahagian yang paling lemah pada sebuah pengubah kuasa. Seringkali, kerosakan pada bahagian ini akan menyebabkan kegagalan kepada sistem elektrik secara keseluruhannya. Pencemaran dari kawasan perindustrian adalah salah satu punca yang boleh menyebabkan berlakunya peningkatan terhadap nilai agihan medan elektrik. Selain itu, peningkatan permintaan beban yang tinggi, boleh menyebabkan kenaikan suhu sesendal pengubah. Kajian ini tertumpu pada sesendal pengubah dengan kadar nominal 145 kV. Sesendal pengubah dalam bentuk 2D dibangunkan terlebih dahulu sebelum analisa taburan elektrik, voltan dan suhu dijalankan dengan menggunakan perisian kaedah unsur terhingga. Analisis taburan suhu diperlukan bagi mengenalpasti titik paling panas (TPP) pada sesendal pengubah ketika sedang beroperasi. Rekabentuk sesendal pengubah dilaksanakan menggunakan perisian terbantu komputer (PTK). Parameter untuk rekabentuk 2D diperolehi dari jurnal dan dari pengeluar sesendal pengubah. Terdapat tiga tahap pencemaran yang dipertimbangkan dalam kajian ini iaitu rendah, sederhana dan tinggi. Setelah itu, analisis kesan dari beberapa tahap pencemaran dan peningkatan beban terhadap pengubah sesendal dijalankan menggunkan perisian kaedah unsur terhingga. Setelah selesai rekabentuk menggunakan perisian PTK, sesendal pengubah dalam keadaan bersih dianalisis terlebih dahulu bagi memastikan integritinya dan keputusannya digunakan sebagai garis dasar. Seterusnya, dari analisa, membuktikan bahawa kehadiran pencemaran pada permukaan pengubah sesendal, taburan elektrik meningkat selaras dengan peningkatan tahap pencemaran. Pengubah sesendal yang telah di bangunkan di ujisahkan terlebih dahulu dengan beberapa penyelidik lain dari aspek taburan voltan dan medan elektriknya dan ia menghasilkan keputusan yang memuaskan. Nilai medan elektrik meningkat dengan peningkatan tahap pencemaran. Berdasarkan dari analisis, nilai tertinggi meningkat hingga 90% bagi peneduh pertama dan bagi peneduh 16 ke 18, nilai medan elektrik meningkat 22 %. Satu persamaan matematik telah di dicadangkan bagi nilai taburan voltan. Bagi analisis taburan suhu pula, apabila berlaku peningkatan beban melebihi tahap kadaran sesendal pengubah iaitu 2500 A, titik TPP akan bergerak dari kawasan minyak ke kawasan udara, iaitu pada bahagian porcelain. Nilai suhu TPP juga meningkat. Ini membuktikan bahawa, kerja-kerja penyelenggaraan secara berkala bagi membersihkan permukaan sesendal pengubah perlu sentiasa dijalankan. Peningkatan permintaan beban juga perlu di kawal supaya tidak melebihi kadar yang ditetapkan pada sesendal pengubah. Dalam tesis ini, sumbangan utama ialah menunjukkan secara visual bagaimana TPP bergerak dari kawasan minyak ke kawasan udara apabila permintaan beban ditingkatkan secara berperingkat. Kemudian, satu persamaan matematik bagi menghubungkan nilai TPP dan nilai arus telah dicadangkan dalam tesis ini.

Modelling Of Oil Impregnated Paper Transformer Bushing On Electric Field And Hot Spot Temperature Using Finite Element Method

ABSTRACT

A transformer bushing is the weakest part in a power transformer. Often, damage to this part will result in the failure of the electrical system as a whole. Pollution from industrial areas is one of the possible causes of the increase in the value of electric field distribution. In addition, high load demand can cause a temperature rise on the transformer bushing. This study focused on a transformer bushing with a nominal rate of 145 kV. The transformer in 2D form was first developed before analysis on electric, voltage, and temperature distributions carried out using finite element method software. Temperature distribution analysis is needed to identify the hottest point (HST) on the transformer bushing during operation. The transformer bushing design is implemented using a computer-aided design (CAD) software. The parameters for the 2D design are obtained from the journal and from the transformer bushing manufacturer. There are three levels of pollution considered in this study, namely low, medium, and high. Subsequently, the analysis of the effects of several levels of pollution and the increase in load on the transformer bushing was performed using finite element method software. Upon completion of the design using CAD software, the transformer bushing in clean condition is first analyzed to ensure its integrity and used as a baseline result. Further, from the analysis, it was found that the presence of pollution on the surface of the transformer bushing, the electric distribution increased in line with the increase in pollution level. The designed transformer bushing has been validated with several reseacher in term of its voltage distribution and electric field at several parts and it is found satisfactory. The electric field value has increased with the level of pollution. Based from analysis, with high level of pollution, the value of electric field at first shed has increase up to 90 % and the value has increased 22 % between shed number 16 to 18. In this thesis, a mathematical equation for voltage distribution has been propsosed. For analysis of temperature distribution, when the load increases beyond the rated current which is 2500 A, the HST point in the transformer bushing moves from the oil side to the air side area, which is on the porcelain side. The HST value also increased. This proves that regular maintenance work to clean the surface of the transformer bushing should always be carried out. Increased load demand also needs to be controlled so that it does not exceed the rated value of the transformer bushing. The movement of HST point from the oil to the air sides due to gradually increasing of load demand is presented. Then, the relationship between the HST point and the injected current to the transformer bushing is represented in the form of mathematical equation.

CHAPTER 1 : INTRODUCTION

1.1 Introduction

In leading and realizing the era of Industrial Revolution 4.0 (IR 4.0), reliance on efficient and reliable electrical systems is crucial (Nagy, Oláh, Erdei, Máté, & Popp, 2018). This is to ensure that electricity is provided to all enterprises, agriculture, public transport, health facilities in hospitals and to the public without any interruption. Sophisticated use of systems in the IR 4.0 era, such as the use of artificial intelligence (AI) on computers and robotic systems in the corporate sector (Tandon, 2020), would incur a significant cost and it must be protected and any electricity supply disruption resulting in significant damage and loss should be avoided. With the growth of human population also, the demand for electricity increased significantly with the projected demand increment of 24 % in 2040 (BP, 2019).

Conventional electrical system has also been transformed into a smart electric system in most countries such as America, Japan, Germany and many countries (Abolhosseini, Heshmati, & Altman, 2014). This is because, with the increasing awareness in environmental protection, the use of renewable energy is strongly encouraged in most countries (Abdmouleh, Alammari, & Gastli, 2015; Ahuja & Tatsutani, 2009). Renewable energy is the energy derived from available renewable sources. Examples of these renewable energies are solar, biomass, wind, mini hydro, tidal, geothermal heat and oceanic waves (Owusu & Asumadu-Sarkodie, 2016). The smart electric system or better known as the smart grid is an integration between renewable energy and conventional energy sources. It is anticipated that in the future, it is likely that the source of energy will be dominated by renewable energy (Bari, Jiang, Saad, & Jaekel, 2014; Rehmani, Reisslein, Rachedi, Erol-Kantarci, & Radenkovic, 2018; Renewable & Agency, 2013).

All of the dreams of tomorrow as discussed in previous paragraph must always depend on a reliable electrical system. The electrical system is made up of three main segments namely, generation, transmission and distribution. On the generating side, electricity is generated. The generated electricity will be stepped up first before being sent to the destination via the transmission line. After arriving at destinations such as industrial and residential areas, electricity will be stepped down according to consumer requirements.

Stepping up and stepping down of electricity is done by transformers. Transformers are among the most important and expensive part of the electrical system. Whether in conventional electricity generation or renewable energy, the use of transformers remains mandatory.

Transformer consists of several important parts such as winding core inside transformer, bushings used to hold for incoming line and connect it to winding transformer, breather as humidity indicator, oil tank and Buchholz relay for transformer protection (Kondkar, Bhosale, Jawale, & Salavkar, 2019). The constituents of a transformer structure is shown in Figure 1.1 (Ahmed, 2011). Transformers has a solid structure mainly contain oil as the main insulator.

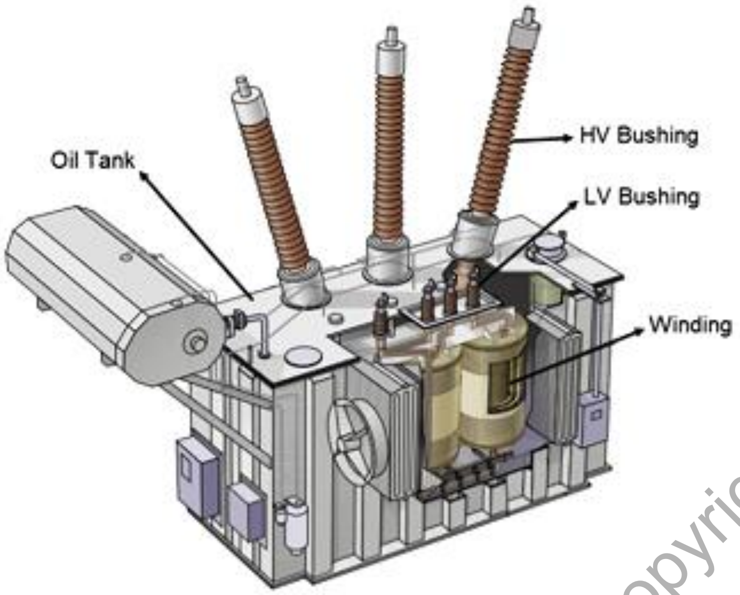

Figure 1.1 Basic components of transformer

However, there is one part that can be considered as the weakest in a transformer. That part is transformer bushing. Transformer bushings are required in connecting the external conductor to the internal windings of a transformer through the walls of the metal oil tank (Ahmed, 2011; Group, 2003; Harlow, 2004). The walls of the transformer housing are grounded, but need to be shielded from the incoming high voltage conductor. IEEE standard C57.19.00 describes a transformer bushing as "an insulating structure, including a through conductor or providing a central passage for such a conductor, with provision for mounting on a barrier, conducting or otherwise, for the purpose of insulating the conductor from the barrier and conducting current from one side of the barrier to the other (IEEE Standard Geneal Requirement and Test Procedure for Power Apparatus Bushing, 2005).

Briefly, high voltage bushing can be classified into three categories namely composite bushing, compound-filled bushing, condenser and non-condenser bushing

(Stirl, Skrzypek, Tenbohlen, & Vilaithong, 2014). Condenser type bushing can be classified as resin bonded paper (RBP), resin-impregnated paper (RIP) and oil-impregnated paper (OIP) (Anglhuber & Contreras, 2017). However, this thesis is essentially about OIP transformer bushings.

It has been reported that OIP bushing faults represent about 30 % in transformers catching fire and 10 % in bursting or exploding (Actis, Riccardo, & Vander, 2017). Insulation was the main factor of transformer bushing failure as reported by (Feilat & Metwally, 2013). This included overheating, cracking, oil leakage, damaged seal, overload current and broken lead. Refer to Figure 1.2 for percentage of each failure cases (AJ et al., 2018). Heat, oxidation, acidity, and moisture are the main factors responsible for insulation deterioration.

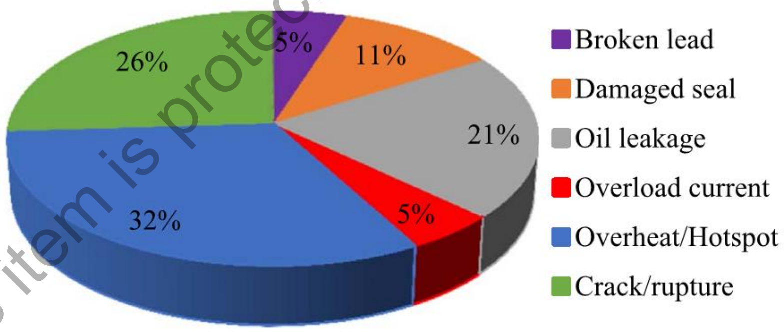

Figure 1.2 Causes of transformer bushing failure

In (Feilat & Metwally, 2013), reported transformer bushing having over heat or hotspot stress due to high loading condition. This situation leads to expansion of the bushing's multilayered insulation. On the other hand, during cooling, the multilayer insulation shrinks and this can create miniscule gaps. The phenomena allows moisture to penetrate into the bushing through leaky gaskets and other open parts (Qi et al., 2018).

Discharge activity caused degradation across the internal surface of bushing. Furthermore, environmental pollution lead to degradation of bushings and finally to failure.

1.2 Problem Statement

In Malaysia, some of main intake substations (MIS) are built in areas far from the settlements or in the countrysides. Therefore, for these MISs, its transformers are less prone to pollution. However, there are also MISs built near to the industrial areas. This is to cater the load specifically at industrial area. Depending on the type of industries, the level of pollution will be different. If the MIS is constructed in the areas requiring high voltage of 132 kV or 275 kV such as forcement plants, iron mills and quarries, certainly the transformers will be exposed to sand and cement dust.

Although transformer bushing models has been developed by other researchers in different country, however it is impossible to request it for further analysis. This may be due to a copyright or patent that prevents them from sharing their design with other researchers. Therefore, in this research, the OIP transformer bushing was successfully designed using CAD software and according to specifications and parameters that closely resemble the actual bushing.

Due to the presence of sand and cement dust of a certain quantity on the surface of the transformer bushing, there might be the occurrence of flashover. The presence of these dusts is caused by wind carrying the dust or air borne deposits from industrial exhausts. The dusted surface can be conductive. With the presence of rain even though drizzle, current leakage can occur by the dampened dust on the conductive parts. As the current density across the surface is not constant, differential drying of the surface occurs. This leads to the formation of the so called 'dry bands'. Voltage produced by dry bands is high, which can cause local spark over and scintillations. On the other hand, some conditions lead to a progressive development of the arc leading to a total flashover. As mentioned earlier the physical mechanisms leading to flashover are complex. For example, one has to consider the influence of the geometry of the insulator, the non-uniform surface pollution, the consequent growth of dry bands and scintillations which eventually leads to flashover.

Therefore, it is important for researchers to study and understand how the effects of pollution on transformer bushing surfaces can affect the electric field value and voltage distribution. With high pollution effects, flashovers can occur and can disrupt the power system of the area. In any event, if the effects of the pollution are not resolved, the flashover may occur, and eventually, the transformer bushing explodes and the transformer will fail to operate.

Increased demand for uncontrolled loads can also increase the transformer bushing temperature. The main concern is that, if the load demand continues to exceed the transformer bushing rating, the hotspot will also shifted. Hotspot is the hottest points in the transformer bushing during operation. The air side of transformer bushing is a weak part because it depends on porcelain which is a kind of ceramic. In any case, if the load increase is not controlled, the transformer bushing may explode and at the same time cause the transformer to fail.

Therefore, the purpose of this study is to address the concerns and implications of the case if the aforementioned problem is ignored. The results of this study can be used as inputs to power system providers in ensuing aspects of monitoring of the effects of pollution and increased unmanageable loads.

1.3 Objectives

The aim of the research is to investigate the performance of 145 kV oil impregnated paper (OIP) transformer bushing. As mentioned in the Sub-Chapter 1.2, pollution could degrade the performance of transformer bushing if the necessary action are not taken to maintain it for example cleaning the upper surface of bushing and unmanageable load demand could harm the transformer bushing. Thus, the objectives can be summarized as follows:

1. To design and analyze the performance of a 2D model of 145 kV OIP transformer bushing using Computer Aided Design (CAD) and Finite Element Method (FEM) softwares.
2. To evaluate the electric field and voltage distribution (EFVD) of transformer bushing under different levels of pollution specifically at the upper side of transformer bushing in electrostatic domain.
3. To evaluate the temperature distribution of transformer bushing at constant load and the hotspot location of transformer bushing with the effect of changing loads in stationary domain.
4. To propose mathematical equations for voltage distribution along creepage distances and the relation of hot spot with the values of injected currents.

1.4 Scope of Work

The overall scopes of research are as follows:

1. The proposed research starts with designing 2-dimension (2D) model of clean 145 kV oil impregnated paper (OIP) transformer bushing using computer aided design (CAD) software. Then, the analysis is performed by FEM software to obtain baseline results.
2. The design of 2D OIP transformer bushing is further expanded to include three different levels of pollution such as low, medium and high pollution at the top of surface. Then, the analysis is performed by FEM software for this difference cases.
3. The analysis of Electric Field (EF) and Voltage Distribution (VD) is carried out only for the upper side of transformer bushing and at the top surface of porcelain.
4. The temperature analysis is carried out to only clean transformer bushing.
5. Finally, the location of HST is determine with different level of load to investigate the location prior to changing of load demand. The analysis is carried out to clean transformer bushing.

1.5 Thesis Organization

This thesis is organized to have five main chapters consisting of introduction, literature review, research methodology, result and discussion and finally conclusion. Chapter 2 provides a review of transformer bushing background by focusing on the 145 kV oil impregnated paper transformer bushing.