High Voltage Stress Distribution Phenomena on Liquid and Solid Insulation Material Using Finite Element Method

Yanuar Z. Arief[1], Nor Asiah Muhamad[2], Mohd Hafiez Izzwan Saad[1], Syazwan Nazri[3], Siti Nur Anina Othman[3], and Mohd Fikri Hilmi Mohd Taib[3]

[1]Department of Electrical and Electronic, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), 94300 Kota Samarahan, Sarawak, Malaysia.

[2]School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM), 14300 Nibong Tebal, Penang, Malaysia

[3]Institute of High Voltage & High Current, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Malaysia.

ayzulardiansyah@unimas.my

***Abstract*—Electric field stress has been a major problem in high voltage phenomena that can lead to electrical degradation and thermal losses. Recent research found that with the development of existing liquid insulator (mineral oil, vegetative-based oils) and solid insulator (epoxy) will enhance the electrical, mechanical and thermal properties of high voltage insulation. This study investigates the properties of the electric field distribution, electrical potential and heat flow across the liquid insulating material (mineral oil, coconut oil, palm fatty acid ester oil and FR3) and solid insulating material (cross-linked polyethylene/XLPE, polyvinyl chloride (PVC), polymethyl methacrylate (PMMA) and epoxy) using finite element method (FEM). The aim of this study is to get a better understanding on the electric field distribution including heat transfer under high voltage stress for research purposes. The study was carried out using liquid test cell (according to IEC 60897) and solid test cell (according to CIGRE Method II). The result from this study will give a better understanding to interpret the phenomenon of electric field distribution, electrical potential and heat flow as the increase of the electrical stress.**

***Index Terms*—Electric Field Distribution; Finite Element Method; High Voltage Stress; Liquid and Solid Insulation Material.**

I. INTRODUCTION

The design of high voltage (HV) equipment requires full knowledge of the electric field distribution and ways to control such electric field. Understanding of the insulation failure modes requires some knowledge of the electric field concepts. For the case of solid and gas interface, the electric field is distorted at the boundary.

For AC applications, the dielectric material can get charged. It may be charging of insulator due to corona or other types of discharges giving rise to a surface charge density. It will enhance the total surface field on the gas side. Solid - gas, solid - vacuum, solid-liquid or solid-solid interface needs careful consideration. The higher value of the electric field may accelerate the degradation and lastly will damage the insulation. The application of controlled electric field consists of cable terminations, HV bushings, potential transformer and circuit breaker.

The electric field distribution can affect the partial discharge (PD) pattern. If the equipotential line of the electric field is compressed at a certain point in the insulator, as it slowly degrades the insulation and lastly leads to a complete breakdown of equipment. Then, electric stress values must be controlled to design the high voltage equipment.

There are many research works conducted to form a good insulating material that has a resistant to chemical, thermal, electrical degradation, and have good mechanical properties. A good insulating material will lower the cost of maintenance because such insulator can withstand for a longer period. Recent developments in the use of solid insulator as an excellent insulator with good characteristics have been reported. However, the concept of high voltage stress distribution in liquid and solid insulation material is not clearly understood. Thus, this research work will simulate the liquid and solid dielectric materials and analyze their electrical and thermal properties for research purposes according to experimental works on partial discharges research.

A. Liquid insulation

Transformer oil basically referred to the insulating oil in a power transformer. After undergoing subsequent treatment, transformer oil is formed through extraction from crude petroleum oil. Based on this, it is called mineral insulating oil or mineral oil. Transformer insulating oil has a highly refined mineral oil and excellent electrical insulating properties. Therefore, such properties will enable transformer oil to be stable in elevated temperature. Basically, transformer oil acts as an insulating material in the transformer. It serves as a cooling medium which helps to absorb the generated heat during core and winding and transfer it to the last surface of the transformer [1]. Mineral oil has been used as transformer oil since a long time ago. There are two ways to produce mineral oil which is crude petroleum and refining petroleum. Basically, petroleum oil is extracted from crude petroleum. Hydrocarbon is one of the contents in the mineral oil. We can get high quality of crude petroleum, when it undergoes refining process [1, 2]. Mineral oil is usually used in high voltage equipment and transformer it low viscosity and good insulating material properties. It also contributes to the excellent in transformer operation due to its low relative permittivity. Awareness of the importance of mineral oil has been spread around the world and gives the low cost however, due to its poor biodegradability, the environment will be in danger when there is any failure in transformer operation because it can contaminate soil and water when a serious spill occurred [3].

As a concern of environmental aspect, alternative transformer oil materials have been introduced, such as FR3, PFAE (palm fatty acid ester), and coconut oil. These alternative oils technically have a good potential to replace mineral oil in power transformer application based on physical, electrical, and electrical properties [4 – 7].

B. Solid insulation

Nowadays, many solid insulations are used to fulfil the requirement such as safety and cost management. One of the insulation that used solid insulator is the power cable. Power cables are greatly related to power transmission and distribution system. In cable installation, shielded power cable requires electric stress control when it terminated to avoid the failure of the cable. There are no standard or universal termination or joint. There are various types of termination and joints with advantages and disadvantage. Investigating their mode of construction will optimize the cable terminations [8-9]. Cables are electrically complicated. The basic components are the shielding, the conductor, and the electrical insulation or dielectric. There are different types of conductor and insulation. The types of the components are chosen based on the applications [10].

The insulation types of cables are Cross-linked Polyethylene (XLPE), Ethylene Propylene Rubber (EPR), Polyethylene (PE), Paper Insulated Lead Cable (PILC) and Polyvinyl Chloride (PVC) having specific physical, electrical and chemical properties [11-13]. Many researchers have investigated these materials as electrical insulation under high voltage stress [14-16]. This study investigates electric field distribution including heat transfer properties of these polymeric using finite element method under high voltage stress.

II. SIMULATION PROCEDURE

This work is divided into two parts which are, a study on liquid insulation and solid insulation form using specific test cell. Firstly, investigating the properties of liquid insulation (mineral oil, coconut oil, PFAE oil and FR3 oil) using breakdown voltage test cell - point to a plane electrode- (according to IEC 60897). The second part is to study solid insulation materials (XLPE, PVC, epoxy, and PMMA) properties using CIGRE Method II test cell. The detail whole simulation process is summarized in Figure 1.

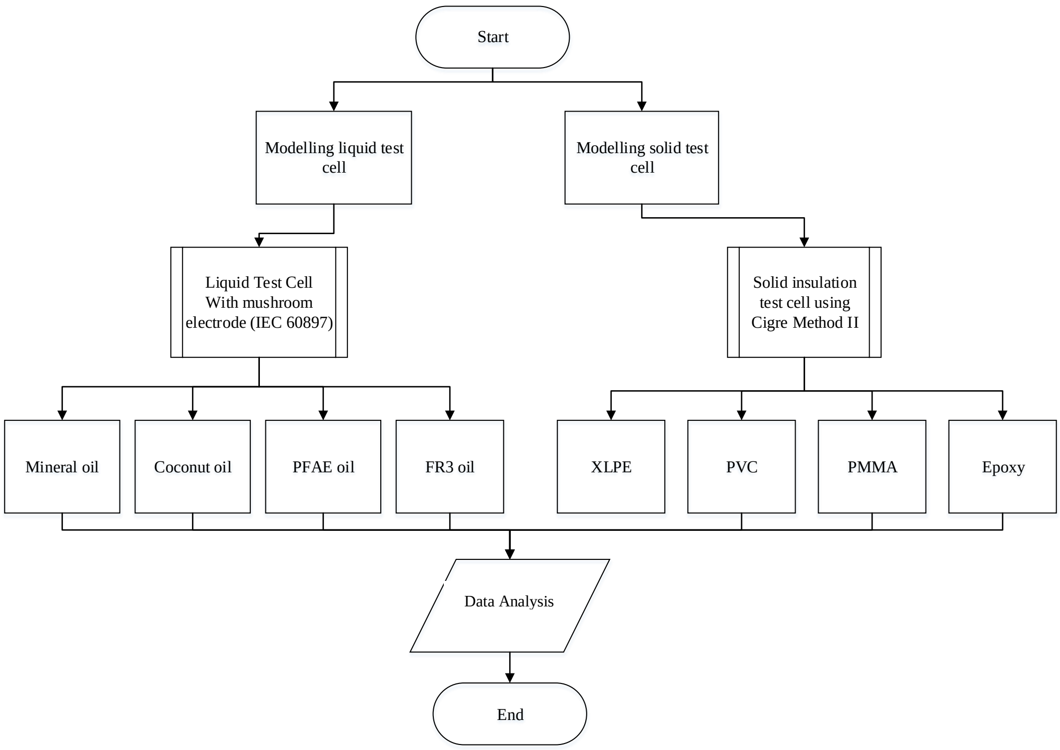


Figure 1: Flow chart of the simulation

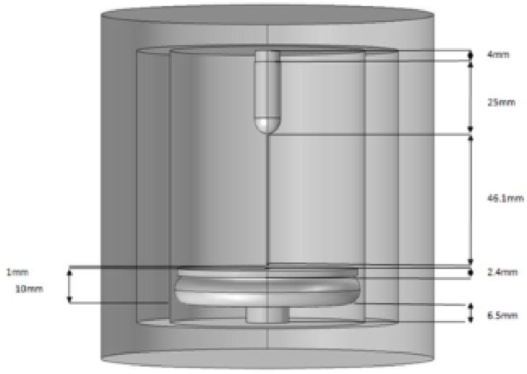
This computational simulation steps using finite element method (FEM) to investigate the electric field distribution of liquid and solid material. The simulation used 3D dimension. The injected voltage from 10kV, 20kV, 30kV, 40kV and 50kV, respectively.

A. Liquid breakdown test cell with point to plane electrode (IEC60897)

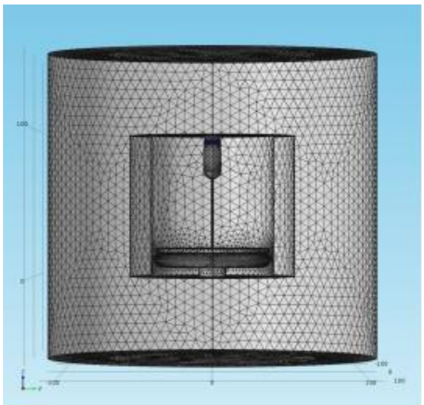
The electrical conductivity and relative permittivity of oil samples are shown in Table 1. This simulation used 3D dimension. The design of point to the plane electrode and mesh analysis of the electrode are shown in Figure 2. The diameter of the ground plate is 76mm. The simulation readings were taken from the middle of the ground electrode to the right side, which is about 38 mm because it is symmetrical.

Table 1
Properties of liquid insulation material

Properties	Mineral oil	Coconut oil	PFAE oil	FR3 oil
Electrical Conductivity (S/m)	2.17e-15	5.50e-12	1.41e-13	3.33e-14
Relative permittivity	2.200	3.525	2.900	3.200



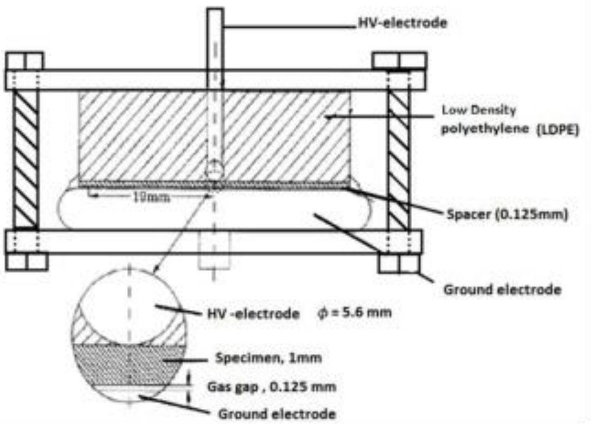
(a) Point to plane configuration



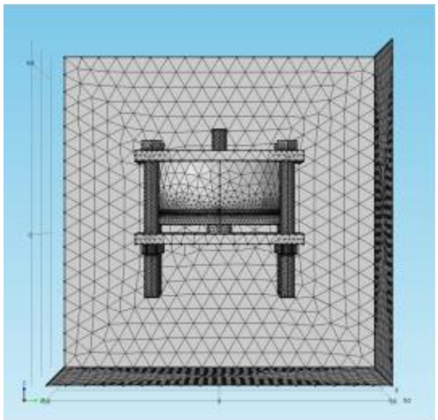
(b) Mesh analysis of point to plane electrode test cell
Figure 2: Test cell design for liquid insulation test: point to plane configuration

B. Solid Insulation Using CIGRE Method II Electrode Configuration

For solid insulation studies, the CIGRE Method II of electrode configuration was referred as the designed models which are shown in Figure 3(a). The Figure 3(b) shows the mesh analysis used in the test cell design for simulation measurement. The measured studies are taken from the middle point (above the specimen) of the plate to the left side as it is symmetrical with distance 19mm (shown in red line in Figure 11). Table 2 shows the properties of solid insulation used in this study.



(a) CIGRE Method II test cell [14]



(b) Mesh analysis of CIGRE Method II electrode configuration

Figure 3: Electrode configuration for solid insulation simulation

Table 2
Properties of solid insulation material

Properties	XLPE	PVC	Epoxy	PMMA
Electrical Conductivity (S/m)	1E-17	1E-16	1E-14	1E-15
Relative permittivity	2.3	2.9	3.6	3.0

III. Results and Discussion

A. Liquid Insulation Using Breakdown Test Cell with Point to Plane Electrode (IEC 60897)

The contour of electric field distribution results is shown in Figure 4. The reading was taken starting from the middle of the rod electrode to the right side of the test cell. This is due to the symmetrical shape of the model/test cell. Figure 5 shows an example of the electric field distribution result of PFAE oil at the cross-section of the point/rode electrode to the plane electrode of the test cell with injected voltage of 10kV to 50kV. It is clearly seen that electric field values increase as applied voltage increased. Moreover, the concentration of the electric field decreased as the distance from the electrode increased due to the rod electrode is the carrier of the voltage source for the system/test cell. The closer the location to the electrode carries the higher value of the electric field. The maximum electric field for every oil occurs at the point of 0.019mm from the rod electrode.

The maximum electric fields at injecting voltage of 50kV for all oils are shown in Figure 6. As can be seen from the figure, mineral oil has the minimum distribution of electric field compared to other oils. This reveals that mineral oil is the best oil in electric field distribution properties. The high electric field value tends to make breakdown occur easily. While Figure 7 shows the electric potential distribution result across the mineral oil. Similar patents are observed for other oils.

Figure 8 shows the typical thermal flow distribution results in the mineral oil. Basically, this model was set to be located on the room temperature condition which is at 20˚C. It was found that the value of heat flow decreased since the distance from the electrode increased. Figure 9 shows the maximum temperature of all oil samples. It was found that coconut oil has the highest temperature. Followed by mineral oil, FR3 oil and the last is PFAE oil. PFAE oil and FR3 oil carried low-temperature absorption as cooling system. There is only a slight difference between the materials. The temperature is quite the same as the environment temperature which is 20˚C.

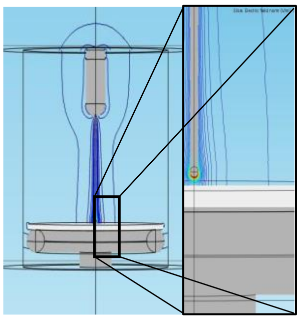


Figure 4: Contour of electric field

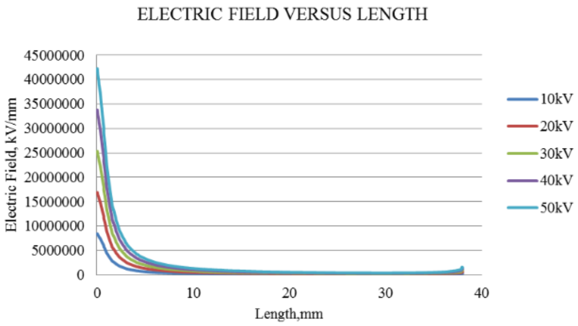


Figure 5: Electric field versus distance of PFAE oil

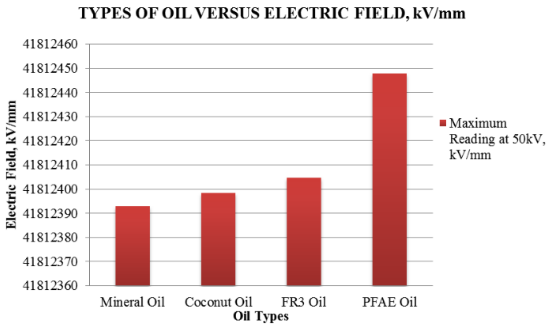


Figure 6: Maximum Reading for Electric Field at 50kV Injected Voltage

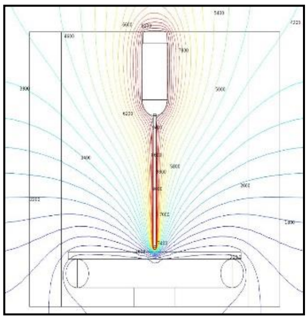


Figure 7: Electric potential across the mineral oil

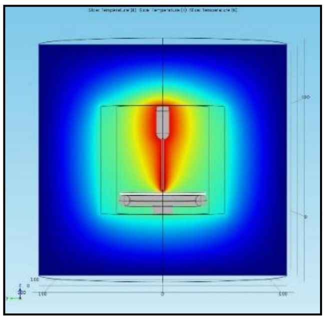


Figure 8: Temperature profile across the mineral oil

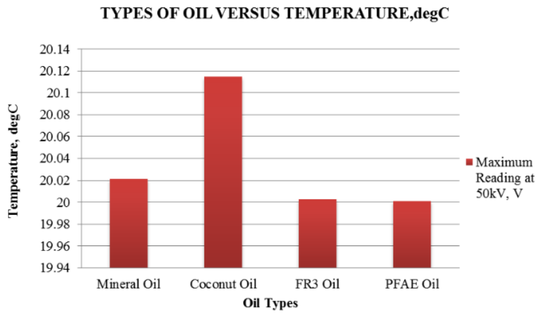


Figure 9: Maximum reading for temperature at 50 kV of injected voltage

B. *Solid Insulation Using CIGRE Method II Electrode Configuration*

The example of an electrical field distribution pattern on the CIGRE method II is shown in Figure 10. The Electric field measurement takes from middle of an electrode to the end of the electrode plate (19mm distance).

Figure 12 shows the relationship between electric field distribution and the distance from the center of rod electrode to the edge of epoxy resin with voltage injection of 10kV to 50kV. As can be seen from the figures, the electric field magnitude fluctuates as the distance from the terminal increase. Little hump produces at the end of the electrode due to the effect of curve electrode (boundary effect). A similar result was also observed for other insulation materials. Figure 13 shows the maximum electric field values of cross-linked polyethylene (XLPE), polyvinyl chloride (PVC), epoxy and polymethyl methacrylate (PMMA) at 50kV of voltage application. It is found that the highest value of electric field is PMMA material and the lowest value of electric field is XLPE. The electric field may lead to breakdown, treeing and flashover. This means cross-linked polyethylene was able to repel or block lot of electric field from flow through it compared to other three materials. Figure 14 shows the relationship between heat transfer and the distance from the center to the side of all insulation materials at 50kV of voltage application. This result shows that the epoxy has the lowest heat transfer followed by cross-linked polyethylene, polyvinyl chloride and polymethyl methacrylate in ascending order.

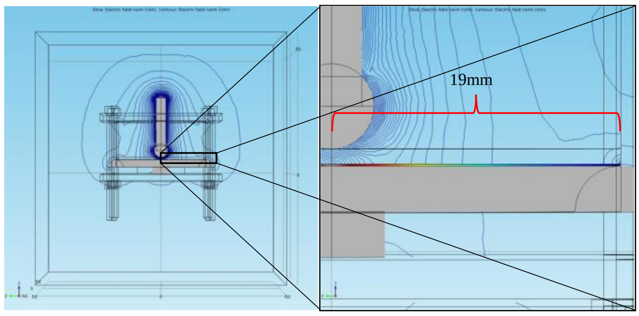


Figure 10: Electric field pattern with polyimide material in CIGRE Method II Electrode Configuration

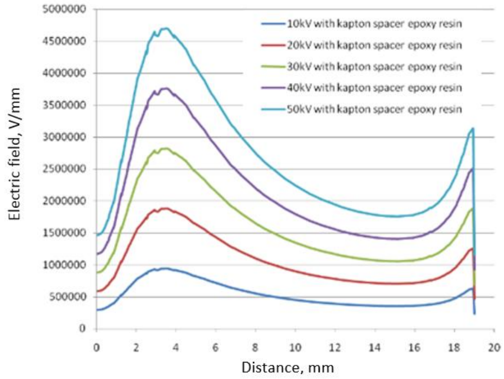


Figure 11: Electric field graph across epoxy resin

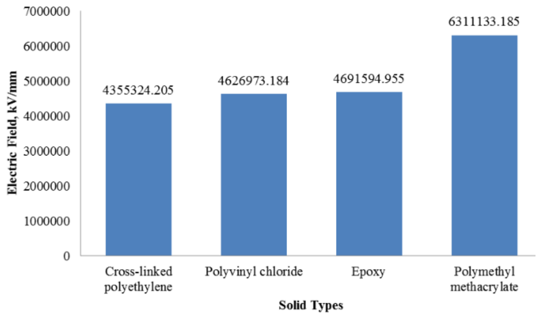


Figure 12: Maximum Electric Field at 50kV

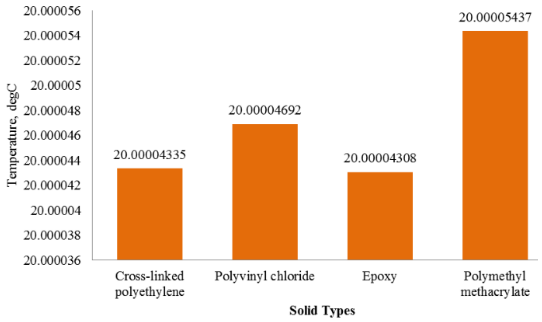


Figure 13: Maximum Reading for Temperature at 50kV of voltage application

IV. CONCLUSION

The simulation of electric field distribution including heat transfer of liquid and solid insulation material under high voltage stress has been successfully completed in this study. Major contribution to the cause of failure of the equipment is the misunderstanding on the electric field distribution, electric potential distribution, and thermal flow theory, during the design stage of the liquid dielectric material.

By conducting this work, the electric fields of liquid and solid insulating materials according to specific electrode configuration which are commonly used in partial discharge research was successfully investigated. Upon the computational simulation, the voltage injected is proportional to the electric field. The increasing of distance from the electrode will lead to decrease the value of the electric field. This varies to the all insulating material. Further experiment can be carried out by performing the simulation under the time-dependent mode, so that the scope of research can be wider. The research can also investigate the effect of time towards the electric field, electric potential and thermal flow.

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