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A Laboratory Investigation of Di-electric Characteristics of Electrical Insulation Materials in Air and in Oil

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ABSTRACT

Electrical measurements of insulation in air and in oil were performed on four different types of insulating materials – two cellulose based and two polymeric materials. Extensive measurements were carried out in air and in oil on the selected materials. Results of their breakdown voltages show higher values for insulations soaked in oil than those measured in air. It also shows that cellulose based materials have better performance in oil than polymeric, and they equally show a recovery rate of up to 70% in oil. All materials tested show averagely high breakdown strength for a long time (≥5hrs) before deterioration under stress. To confirm this, the materials were maintained in transformer oil at 100 deg. Celsius for five hours and then subjected to a high dielectric strength.

Keywords: Measurements, Insulation, Breakdown, Strength

Introduction

Electrical insulation is of paramount importance in high voltage systems. Wrong selection of insulation materials could cause serious damage to lives and equipment. Some major equipments that will require proper insulation are electric motors, generators, transformers, cables and capacitors. Determination of breakdown stress of insulation materials is therefore, indispensable in high voltage engineering. Of particular importance is their behaviours in oil since most of these equipment require oil impregnation or immersion.

This project is, therefore, based on electrical measurements of insulations. The measurements are to determine the breakdown stress of each insulation material from which their electric strength will be calculated. There is a direct relationship between electrode gap and breakdown voltage [1]. He, however, could not establish a relationship between the thickness of electrode and breakdown voltage. A comparison between break down voltage of sampled insulation materials revealed that Kraft paper had the lowest withstand voltage but it can be re-used after damage[2]. He equally discovered that polypropylene has a higher withstand strength but cannot be re-used, once damaged. It is important to consider the electrical behaviour of insulation materials and systems under DC voltages. This is very apposite now in view of the increasing application of HVDC cables in long transmission lines such as the Europe-North Africa transnational networks under consideration [3].

Experimental studies on space charge distribution and dissipation process in oil-paper insulation[4], discovered that:

- There are more ionised charges in oil-paper insulation under lower electric field.
- When a field of between 50KVmm^{-1} and 57KVmm^{-1} is applied, the oil-paper insulation breaks down.
- The withstand time decreases as applied field increases.
- Oil-paper insulation has longer time insulating performance behaviour.

Electric stress, thermal and mechanical stresses contribute to ageing of an insulation which is a major factor responsible for break down[5].

Mechanical stress, according to the paper is due to vibration, rapid changes in loads and differences in coefficient of expansion of various materials involved in the process. He noted also that breakdown of insulation plays a major role in the failure of high voltage equipment. It was also discovered that:

- Break down voltage is linearly related to electrode separation with a tolerance of ±2% for separation of between 0.2m and 2m, for rod – rod geometry. E/N = 20Td

- For break down in air between parallel electrodes, E/N = 120Td, a factor of six higher. (E/N is breakdown characteristics in Townsends, E = Field, N = gas no 1Td = 10^{-17} Vcm^2) [6]

The use of composite materials should be discouraged. When insulation materials are homogenous, constant field strength would be maintained, voids will be minimised and corona discharges will be eliminated[7]. In another study, it was also discovered that the higher the supply frequency the lower the breakdown voltage[8].There is the need to perform the measurements in a vacuum tight vessel[9].

Objectives

Insulation oils are used to strengthen the internal insulation of power transformers, cables and circuit breakers. Materials such as paper, polyethylene, polypropylene and PVC have some degree of insulation which allows them to be used in electrical systems. The insulation properties of some can be enhanced if dipped in insulation oil while in others, there is no significant effect. These characteristics of different insulation materials in air and in oil are what this project sets to investigate. This will guide high voltage engineers in selecting appropriate insulation materials for power equipment and cables.

Background Theory

Insulation materials can be solid, liquid or gaseous. All of them find different areas of application in high voltage systems. Solid insulation might be used in conjunction with either liquid or gas to strengthen the process.

a. **Solid insulation materials**:
    - Organic materials which are produced from plants and vegetables. Examples are wood, paper, cotton tapes and press board.
    - Inorganic materials which are mainly ceramics, glass and mica. Porcelain and Bakelite belong to this group too.
    - Synthetic polymers comprising of PVC, Polythene, Polyethylene, Perspex and a few others.

b. **Description of liquid insulating materials could be found in [10] as**:

- High Molecular Weight Hydrocarbon (HMWH): This type of oil has a paraffin origin. It is a viscous liquid and therefore, is better used in hot regions. It is not popular because there are no adequate raw materials to manufacture it. It is bio-degradable.
- Silicones: Made from saturated silicon oxide. It is highly flame resistant and has high temperature stability too. It is used for compact transformers such as that used for traction.
- Natural esters. They are vegetable oils made from renewable, and with wider application in conjunction with the synthetic esters. They are used in transformers and switchgears.
- Synthetic esters: They are also bio-degradable and moisture tolerant with very good insulation properties. Widely used in power transformers and all oil insulated windings.

Electric Stress

Insulation materials are constantly being subjected to electrical stress, which is similar to the mechanical stress, when current flows in the conductors they are protecting. The stress is proportional to the level of voltage applied to them. The effect of this stress is apparent when it is above the designed value of the insulation. This stress, E is the force placed on a unit charge in the insulating material measured in MV/cm. or kV/mm.

When the kinetic energy, K.E becomes too high the insulation is damaged and it becomes conducting. Potential difference between two electrical points is defined as:

$$V = -\int \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

While the stress $E = \frac{dv}{dx} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$

For a uniform field therefore, electric stress,

$$E = \frac{V}{d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where; E = Electric stress in $MVcm^{-1}$

V = Applied voltage in volts.

d = Thickness of insulation in cm or mm.

Electric Strength

It is defined as the capacity of an insulation material to withstand the stress on it [11], [12]. It is also the maximum stress the material can withstand. Its quantitative definition is however complex due to so many factors that come to play. Some of these factors are pressure, temperature, voltage pattern, type of electrode, quality of insulating material and the type of field.

Electric strength of insulating materials needs to be maintained by controlling the stress it may be subjected to. This will ensure normal operating regime and ensure longevity of the material. Electric field estimation techniques are required for practical estimation of electric field strength. A simplified representation of electric field strength is:

$$E = \frac{q}{4\pi \mathcal{E} r^2} \; V/m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where;
- E = Electric field strength.
- q = A point charge.
- r = Distance of the charge.
- $\mathcal{E}$ = Permittivity of the insulation material.

Breakdown Theory

Extensive studies have been carried out on electrical degradation and break down, yet the problems that lead to failure in insulation of high voltage windings have not been exhaustively determined [16]. Insulation breakdown do occur in solid, liquid and gaseous materials, either due to application of stress above operating value or due to defects in the materials. Major defects could be during manufacture such as voids or low quality material which could lead to reduction in designed strength. Major breakdown mechanisms in solids are intrinsic, thermal, tracking, treeing and electrochemical [18]. Breakdown in liquids could be traced to impurities such as suspended liquids, solids and dissolved gasses. For a short duration pulse (≤10μs) the effect is relatively small. For suspended solids the duration may be up to 1mS.

Thermal Breakdown

The flow of current through a material generates heat due to I^2R loss. When the stress is so high, this heat increases and the surrounding gets heated up. If rate of generation is higher than that of dissipation, the insulation's temperature becomes excessively high and breakdown may occur.

Partial/Internal Discharges

Another major cause of breakdown in solid insulation is the presence of voids and cavities in the insulation or boundaries between the di-electric and electrodes. These voids have di-electric constants of 1 and their di-electric strength is less than that of the parent insulation material [11]. A stress far below the insulation value could lead to breakdown of the voids and cavities and eventually leads to partial discharges. It is therefore ''a localized di-electric breakdown of a small portion of a solid or fluid electrical insulation system under a high voltage stress'' [18].

Surface Flash Over

This is the breakdown of the medium in which the solid insulation is immersed. The solid di-electric will distort the electric field so that electric strength of the fluid in which it is immersed is exceeded. When this happens the temperature rises sporadically (500-1100^{0}C). The following are the features of surface flash over:

- A conducting film across the surface of the insulation.
- A mechanism through which the leakage current is interrupted accompanied by a spark and possibly a fire, depending on the stress and operating temperature.
- Degradation of the solid insulation caused by the spark.

High Voltage insulation measurement

This is basically the di-electric measurement of high voltage insulation materials. Insulation measurements could be done in air, in vacuum and in oil. In whatever medium the test is carried out a high voltage is applied across two electrodes separated by a gap. The gap is the thickness of the insulation under test. For this particular project, the medium is transformer oil. The measurement requires samples of insulation materials of varied thicknesses and characteristics to be placed between two electrodes immersed in oil inside a test vessel. High voltage A.C and HVDC will be generated and applied in turn for a number of repeated measurements and readings recorded for analyses.

Materials and Equipment

Four insulation materials were tested. Two from the group of cellulose - Minitan (25µm), Press phan (250µm), and two of polymeric. Nomex (150µm) and Mylar (50µm) were selected. These materials are widely used in electrical equipment and cables. Materials for insulation measurements in air were cut into samples of 120mm x 120mm, while those for measurements in oil were cut into circular shape of 800mm diameter. The 45 samples of press phan paper used for oil breakdown test were of a ring form with external diameter of 800mm and internal diameter of 200mm.

Equipment used for the a.c measurements were two cascade connected 150kV transformers, with an output of 300kV. Both equipment and their ancillaries are located in the High Voltage laboratory of Heriot Watt University. The test cell used for the oil measurement is made of vacuum tight glass vessel with fixed flat electrode connected to ground and a movable electrode to be connected to the test voltage.

Test Procedure and Methodology

Over five hundred specimens of the four selected materials were tested in about twenty five (25) experiments. One set used for measurements in air were cut into 1200mm x 1200mm squares while those used for measurements in oil were cut into circular pieces of 800mm diameter. The specimens consist of 130 each of Minitan (25µm), Press Pahn (250µm), Nomex (150µm) and Mylar A (50µm) materials. Each set is further broken down into 100 for test in oil, 30 for test in air and 45 of Press Pahn for breakdown test of transformer oil.

Prepared insulation material was placed between two flat plate electrodes or one flat and one pointed electrodes as the case demanded, all placed inside an oil-filled test cell. HVAC was gradually applied until breakdown occurred and reading taken and recorded. Each test was repeated ten times and the average values for stress were used to compute the breakdown strength for each insulation material. The test cell in air is as shown in figure3.1 while the arrangement for test in oil is shown in figure 3.2. The upper electrode is connected directly to the multiplier while the lower one is connected to the ground. The gradual increase is done on the control panel.

Fig.3.1

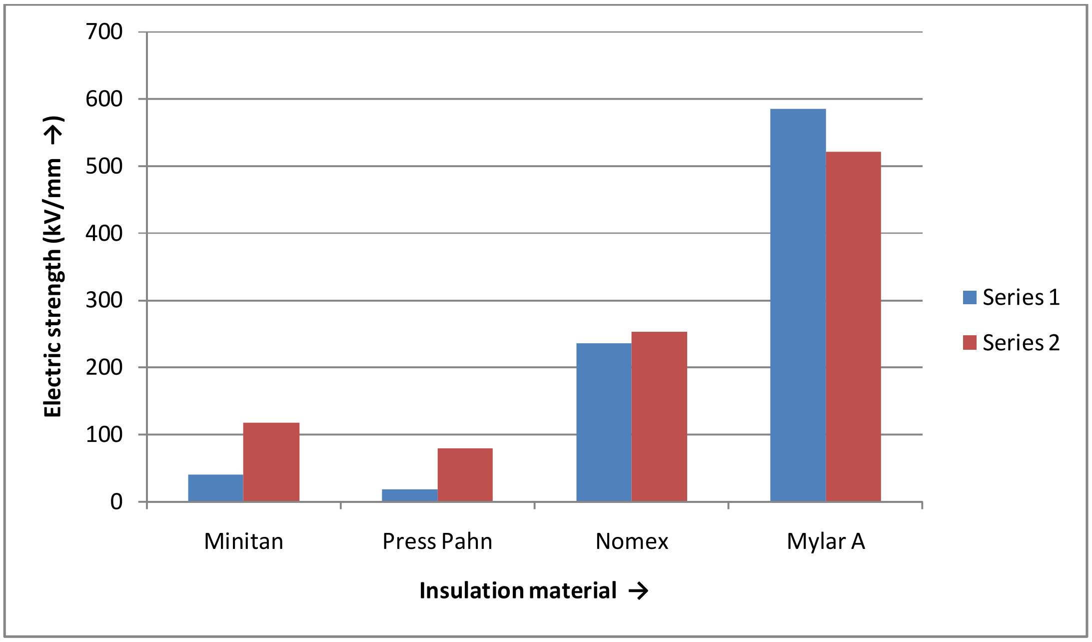
Fig.3.2

Results

The results of electrical measurements in oil are presented in tables 4.1 – 4.9 below. Relevant discussions are presented in the discussion section immediately after this section.

Table 4.2 Electric Strength in Air and Oil Results

Material	Strength in air (kV/mm)	Strength in oil (kV/mm)
Minitan	39.4	117.3
Press Pahn	18.08	79.2
Nomex	236	252.7
Mylar A	585.0	521.0



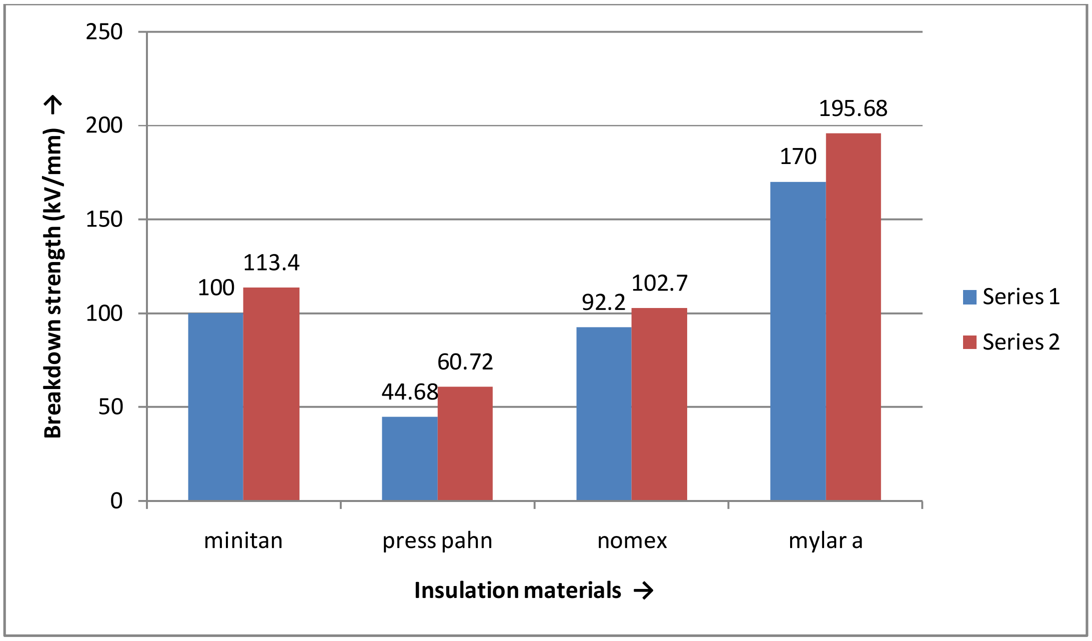
Series 1 = Strength in air   Series 2 = Strength in oil

Fig. 4.1 Electric Strength of Insulation Materials in Air and in Oil

Figure 4.1 shows the relationship between electrical strength of insulation materials in oil and in air. There is significant difference in cellulose materials (233 – 400%) while polymeric materials show no significant difference (‹1%). This shows the importance of insulation oil in high voltage equipment employing the use of paper insulation. Impregnation or immersion of paper insulations in oil therefore multiplies the insulation strength of the equipment.

Table 4.2 Effects of Type of Electrode on Breakdown Strength

Material	Breakdown strength (kV/mm) flat plate	Breakdown strength (kV/mm) pointed elect.
Minitan	100	113.14
Press pahn	44.68	60.72
Nomex	92.2	102.7
Mylar A	170	195.68



Series 1 = Measurements with A.C Flat plate electrodes.

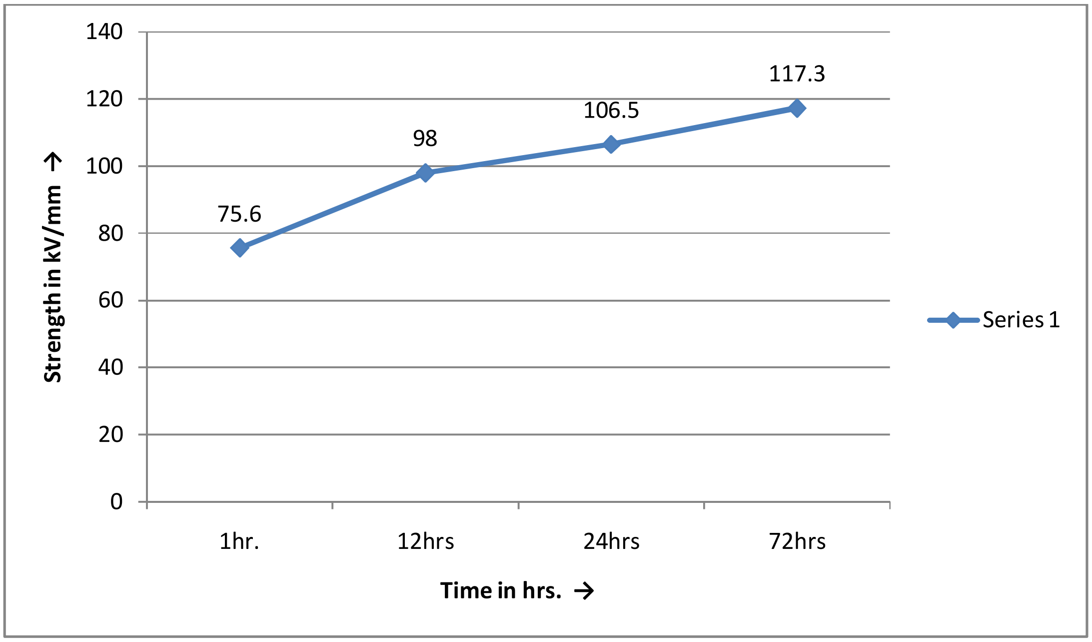
Series 2 = Measurements with A.C Pointed electrode.

Fig. 4.2: Type of Electrode and Breakdown Strength

According to the result shown in figure 4.2, noticeable differences exist between breakdown values for flat plate electrodes and pointed electrode. The values for pointed are higher, this might be due to voids or weak points present in the larger area enclosed by the flat plate electrodes. Contamination of test oil due to moisture content and suspended particles is another possibility.

Table 4.3 Stress and strength values for Minitan, at different periods

Stress in kV	Strength in kV/mm, at stipulated period of time of immersion in oil			
	1HR	12HRS	24HRS	72HRS
A.C (Peak)	75.6	98.0	106.5	116.45



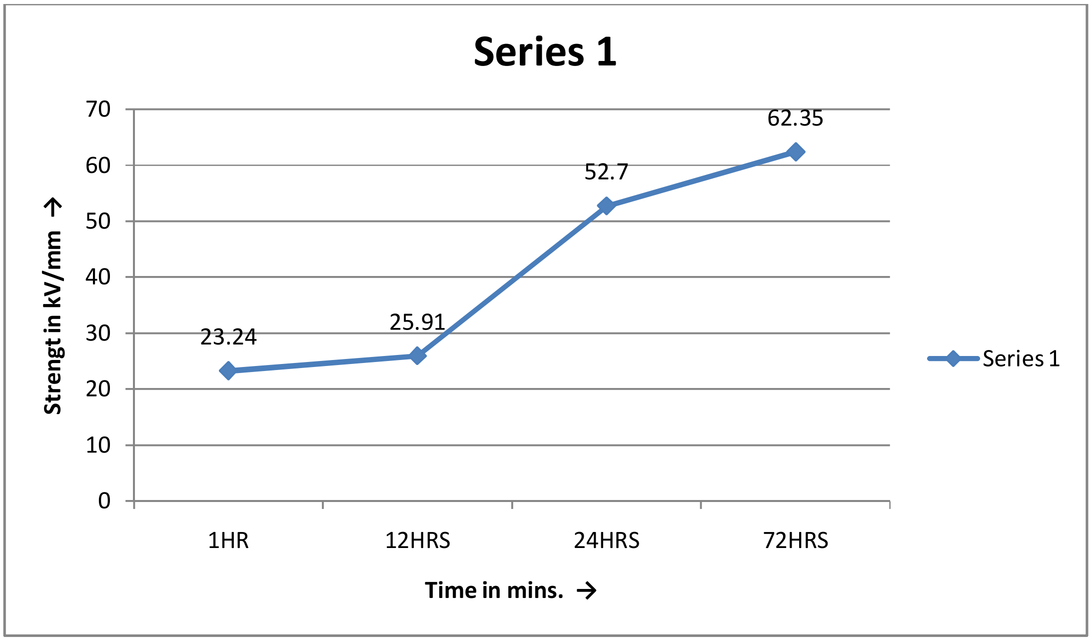
Series 1 = A.C Stress in kV.

Fig 4.3: Relationship between Time of Immersion and Breakdown Strength for Minitan

Figure 4.3 shows that for A.C stress, breakdown strength steadily increases with time of immersion in insulation oil. This trend is characteristic of cellulose materials. The rate of increase however decreases gradually – from 30% to 9%, with time, which suggests that after saturation, the increase might stop. This trend thus qualifies Minitan to be used where oil impregnated insulation materials are required

Table 4.4 Stress and Strength Values for Press Pahn at Different Periods

Stress (kV)	Strength (kV/mm) at stipulated time of immersion in oil			
Time →	1HR	12HRS	24HRS	72HRS
A C	23.24	25.91	52.7	62.35



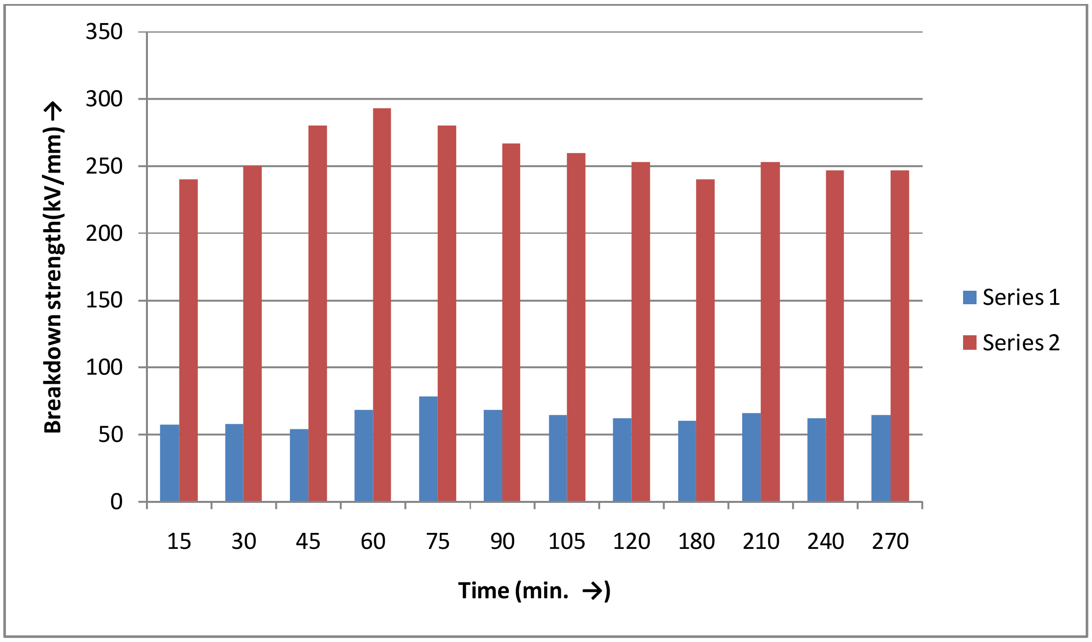
Series 1 = A.C Stress in kV/mm

Fig. 4.4: Relationship between Time of Immersion and Strength for Press Pahn

Unlike the pattern observed in Minitan, within the first 12hrs, strength is almost constant for both A.C and D.C stress. Between 12hrs and 24hrs, the differences are 53% for D.C and 100% for A.C. There is an increase of 31% for A.C and 18% for D.C between 24hrs and 72hrs.This also indicates a decay until saturation when there will be no further increase. The trend here shows that Press Pahn absorbs higher and longer, and thus exhibits higher insulation characteristics during immersion in oil.

Table 4.5 Effect of Temperature on Insulation Breakdown

Time(min.)	15	30	45	60	75	90	105	120	180	210	240	270
$E_{\text{Press Pahn (kV/mm)}}$	57	58	54	68	78	68	64	62	60	66	62	64
$E_{\text{Nomex (kV/mm)}}$	240	250	280	293	280	267	260	253	240	253	247	247



Series 1 = Press Pahn   Series 2 = Nomex

Fig. 4.5: Effects of Heat on Insulation Materials

The shape of figure 4.5 reveals the behavioural pattern of the selected insulation materials to high temperature. Both of them initially have an increase in breakdown voltage after 45minutes of immersion in the heated oil. This trend later changed since the insulation materials must have been saturated with oil. The subsequent decrease reflects the effect of temperature on impregnated pressboard [21]. That is, the negative effect of heat on insulation.

Discussions

Figure 4.1 show that cellulose materials presented a significant increase of 233-400% when impregnated in oil, while polymeric materials produced no significant effect. Compositional and textural factors could be responsible for the recorded changes. The issue of space charge is another reason proffered by [9]. The relationship between breakdown voltage, using flat electrodes as compared to pointed electrodes is the subject of figure 4.2. It shows a higher value for pointed electrodes, of 13.5% - 36% for cellulose materials and about 15% for polymeric. The engineering explanation for the disparities is premised on a number of factors. Effect of flash-overs is practically zero for pointed electrodes and this enhances the breakdown strength. Secondly, the flat plate electrode encloses a larger area of insulation with the possibility of voids. Contamination of oil due to moisture determination and suspended particles are possible factors too.

Figures 4.3 and 4.4 show that there is the need for saturation of insulation materials in oil before maximum strength could be achieved. This takes an average of 72hrs for cellulose based materials subjected to this test. Figure 4.5 shows an initial gradual increase in strength subjected to 100˚c temperature for the first 75 mins. There is gradual depreciation due to thermal effect on the insulation [21]. That is the negative effect of heat on insulation.

Conclusion and Recommendations

This study examined the characteristics of insulation materials under different conditions. Different aspects of cellulose and polymeric materials were examined with a view to determining the most appropriate one to apply for particular conditions. Results obtained confirmed a significant difference between the breakdown strength of cellulose materials in oil and that in air, figure 4.2. This is however, not so significant in polymeric materials.

The response of each material to temperature change was also confirmed for both categories. This is discussed under figure 4.5. It could be concluded that polymeric materials can withstand higher stress and this makes it veritable for a wider application in long distance High Voltage transmission system while cellulose materials which have considerable increase in breakdown strength in oil find wider application in oil insulated high voltage equipment such as transformers, switchgears and cables. The results will go a long way in helping high voltage engineers select appropriate insulation materials for equipment and cables. Further studies should be carried out on the following suggested areas: Behaviour of insulation materials under varying temperatures, including negative values; Detailed comparison between behaviours of insulation materials in oil and in air, and finally, Determination of strength pattern between composite insulation materials.

REFERENCES

1. Murray, N. ((2009) 'Electrical Breakdown at Micrometre Separations', MSc. Dissertation, Heriot Watt University, Edinburgh.

2. Waseem, A. (2009) 'Breakdown of Electrical Insulating Materials in oil' MSc. Dissertation, Heriot Watt University, Edinburgh.

3. Cavallini, A., Montanari, G. C., Palmieri, F. Electrical Measurements of Insulating Materials Used in Oil Filled HVDC Cables: Paper and Paper-Polypropylene-Paper Laminate. IEEE Explore [accessed 12 August 2012].

4. Zhou, Y., Wang, Y., Li, G., Wang, N., Liu, Y., Li, B., Li, P. and Cheng, H. ''Space charge phenomena in oil-paper insulation materials under high voltage direct current'', Journal of electrostatics, 2009. 67, 417-421.

5. Bructsch, R., Tari, M., Weier,T., Volgelsang, R. (2008) 'High Voltage Insulation Failure Mechanisms', IEEE International Symposium on Electrical Insulation, Vancouver, BC: Canada. June 8-11, 1-4.

6. Lowke, J.J (1992) 'Theory of Electric Breakdown in Air-The Role of Metal Stable Oxygen Molecules' J. Appl. Physics, 25, 202-210.

7. Mayerhoff, E. (2004) 'High Voltage Insulation Methods', Application Engineering, 1-3, High Voltage Connections Inc. Available: (http://www.highvoltageconnection.com[accessed 3 March, 2012].

8. Elanseralathan et al., 1999. Bernstorff, R.A, Niedermier, R.K, Winkler, D.S (2004) 'Polymer Compounds Used in High Voltage Insulation' Husbel Power Systems Ohio, USA, 1-12 Available: http://www.hubbellpowersystems.com [Accessed 2 March 2012].

9. Kuang, Y. C., Chen, G. Jarman. (2004). Recovery Voltage Measurement on Oil-Paper Insulation with Simple Geometry and Controlled Environment. IEEE International Conference on Solid Di-electrics. (2) 739-742.

10. Dohnal, D. and Frotscher, R. (N.D) ''The Importance of Insulating Liquids for Power Transformers and Tap Changers''.

11. Lucas, J.R (2001) 'High Voltage Engineering' [Online] Available: http://www.scribd.com/doc/.../High-Voltage-Engineering-Lucas [Accessed 5 May 2012].

12. Lecture Notes on High Voltage Engineering, HWU.

13. Tommasini, D. (2009) 'Dielectric and High Voltage Issues, Available: http://www.cas.web.cern.ch/cas/Belgium-2009/lectures/PDF [Accessed 4 March 2012].

14. Keithley Instruments Inc. (2001) 'Volume and Resistivity Measurements of Insulating Materials Using the Model 65171 Electrometer/High Resistance Meter' Available: http://www.keithley.com [Accessed 27 February, 2012], 1-4.

15. Loss Tangent (2012), [online], Available: http://www.wikipedia.org/loss_tangent [accessed 2 March 2012].

16. Volgelsang, R. (2004) 'Time to Breakdown of high Voltage Winding Insulations with Respect to Microscopic Properties and Manufacturing Qualities', Dissertation, Haertung-Gorre Verlag: Germany.

17. Rosentino, Jr. A.J.P, Saraiva, E., Delaiba, A.C., Gumaraes, R., Lynce, M., De Oliveira, J.C., Fernandez Jr. C. and Neves, W. (N.D) 'Modelling and Analysis of Electromechanical Stress in Transformers Caused by Short Circuit', Hydroelectric Company San Francisco: USA.

18. [HVPD (2012) 'Introduction to Partial Discharge', [Online], Available: http://www.hvpd.co.uk/technical/ [Accessed 6 March 2012.

19. Bernstorff. A., Niedermier, R.K, R. K., Winkler, D. S. (2004) Polymer Compounds Used in High Voltage Insulation. Husbel Power Systems, Ohio, USA, 1-12. Available: http://www.hubbellpowersystem.com [accessed 2 March, 2012].

20. Sokolov, V., Berler, V. and Rashkes, V. Effective Methods of Assessment of Insulation System Conditions in Power Transformers: A View Based on Practical Experience. Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Conference, 1999 Proceedings, 659-667.

21. Nagel, M., Leibfried. ''Investigation on the High Frequency, High Voltage Insulation Properties of Mineral Transformer Oil'' [Online], Available: http://www.leh.kit.edu/1428.php [Accessed 15 August 2012].

22. Cascade Connection [online], Available: http://www.encyclopaedia2.thefreedictionary.com/cascade+transformer [Accessed 2 March 2012].

23. Wang, Y., Li, J., Wang, Y., Grzybowski, S. ''Electrical Breakdown Properties of Oil-Paper Insulation under AC-DC Combined Voltages'', Power Modular and High Voltage Conference (IPMHVC), 2010 IEEE International. 115 – 118.

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