OIL IMPREGNATED PAPER INSULATION AGING IN THE GRID OF THE FUTURE

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Abstract: The method in which electricity is generated and transmitted is going to change in the coming years. Renewable sources are becoming very attractive as their exploitation is becoming cheaper and very well looked upon by society. These changes often include the utilisation of power electronics that generate fast repeating transients capable of degrading the insulation of HV components such as power transformers and cables depending on parameters such as rise time, repetition frequency and magnitude. The insulation investigated in this contribution is paper-oil impregnated, a type of system that has not been studied thoroughly for transient effects. The impregnated paper samples were stressed with variable frequency and rise time transients to investigate their effect on sample life time and breakdown strength. The results showed a significant life time reduction of up to 17 times the normal life span and reductions of 15% in breakdown voltage.

1 INTRODUCTION

The power grid is currently undergoing many changes and many more are set to come in the coming 30 years. The two main trends at the moment seem to be: higher dependence on renewable energy sources and a smart method of management of the HV components in terms of power flow. As good as these improvements sound, problems related to them are becoming the main topic of discussion as they bring much uncertainty.

The motivations behind these changes are twofold: less carbon dioxide emission into the atmosphere and higher reliability of electricity supply in the expectation that demand will increase. Higher energy demand will mean increasing the capacity of the current electrical grid. Since most of the components are already in service for 20 to 30 years, it is unsure how they will react to increased loading conditions and fast repeating transients generated by power electronics. For these reasons, careful planning needs to be carried out and aging models need to be created for these components based on the new stresses that are going to be present in the grid.

This paper will present the effects of repetitive transients generated by power electronics on paper-oil insulation. Three main parameters: rise time, magnitude and repetition frequency tend to have a life shortening effect on the discussed insulation system.

2 FUTURE TRENDS OF THE POWER GRID

The problems on HV equipment related to fast repeating transients can still be called "in its infancy" and relatively contained to locations such as wind parks and HVDC substations. However, this is soon to change as these facilities are on the increase [3]. Global trends in CO2 emissions dictates a reduction in the reliance on oil and coal as primary energy generation fuels and shifting towards an increased reliance on renewable energy sources such as wind, solar, hydro and geothermal. Figure 1 shows an example of the predicted increase of wind power in the EU in the last 13 years.

Figure 1: Trend of increasing amount of energy generated from wind in the last 13 years [4]. Power production from wind has almost tripled in the last 5 years in the EU.

Wind generation has increased almost 30 times in the last 13 years and as targets to achieve energy generation of 20% from renewable sources [3], this trend will be upheld. One of the main problems faced relying on green energy, is the geographical location. Certain places are richer in resources than others. For example, the north of Europe has strong winds whereas the south is richer in sun. This would involve interconnecting all the power generations plants into a large-scale grid or supergrid in such way that any dips in power delivery from one resource can be compensated by the other.

One such project is the Desertec project [5]. Shown in Figure 2, Europe will be interconnected by HVDC links from the south to the north exploiting the available energy resources.

Figure 2: The Desertec plan. Europe will be interconnected with HVDC links in order to exploit the energy of the sun in the south and the wind rich in the north in order to supply a steady energy to customers around the continent [5].

Such new projects are very beneficial to the consumers; however some problems are always introduced. When energy is generated from the wind or sun, it is usually in DC form. This means that it needs to be changed to AC in order to be transferred through the current HV network that operates on AC. HVDC use the same principle. Energy is interchanged between AC and DC as transferring power over long distances is more efficient in DC. The capacity of the transmitted power is increased and synchronization problems are eliminated. AC to DC inversion is performed by power inverters that use IGBTs to switch the DC waveform. This switching produces unwanted repetitive transients on the output waveform that is believed to be harmful to the insulation on well established HV components such as transformers [3, 6]. The main reasons for their fast degradation coefficient are: fast repetition (1 kHz to 10 kHz), fast slew rates (dV/dT) and magnitudes.

3 THE EFFECT OF TRANSIENTS

The effect of fast slew rates and fast repeating transients on motor insulation has been tackled in many publications [3,4]. The material investigated is treated epoxy resin. It varies from paper-oil insulation in both breakdown strength and physical composition.

The available knowledge about the response of this material to fast repeating transient is limited at this time.

Two test set-ups have been designed in order to assess the degradation acceleration coefficient.

3.1 The effect of frequency

Repetition frequency of the transients can be defined as the number of transients that influence the sample every second. From literature research and expert interviews, it was concluded that this value fluctuates between 1 kHz and 10 kHz. Overall, the transient appear superimposed on the sinusoidal voltage and tend to have a fixed rise time.

Such a waveform was simulated using a MOSFET and a high frequency transformer. The set-up's operation, schematically shown in Figure 3, is very simple, however, its design was not trivial as transients with 1 kV amplitude and 1 µs rise time are difficult to reproduce.

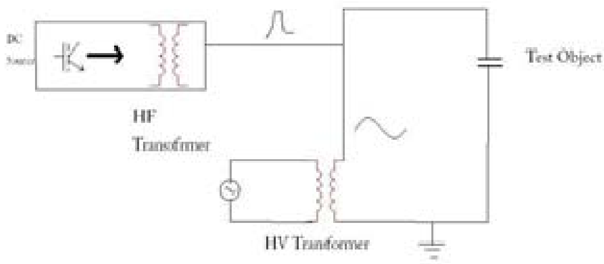

Figure 3: Schematic of the circuit used for the generation of transients.

A MOSFET is used to create the desired pulse by switching the voltage generated by a DC source. This pulse is around 50V as the maximum applicable voltage to the MOSFET is 100V. The operation of the MOSFET is controlled by a logic circuit (not shown in the diagram). This pulse is then amplified by a high frequency (HF) transformer. This HF transformer required a special construction as the fast switching rise time needed to be preserved. This involved designing and constructing the HF transformer from scratch using a special type of core with better conducting properties. The pulse was the superimposed on the HV voltage generated by the HV transformer. The positive pulse was generated on top of the positive cycle of the HV waveform, whereas a negative pulse was superimposed on the negative cycle of the sinusoid. This was done by synchronising the HV supply with the MOSFET's logic circuitry. The resulting outcome is shown in Figure 4.

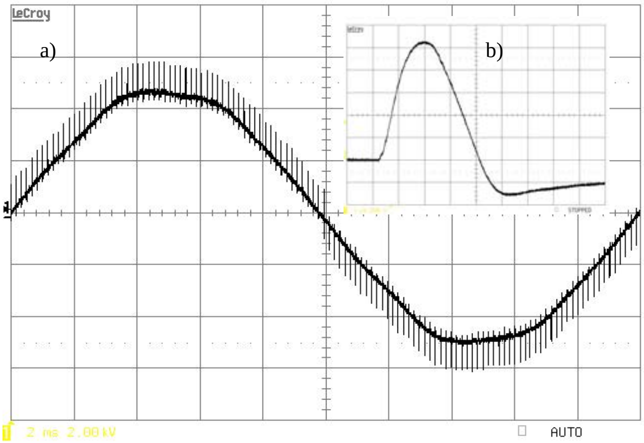

Figure 4: The generated waveform used to test paper samples with the effect of the repetition frequency of transients.

The samples used for testing are made of cellulose and are 0.06mm thick. They have been pre-impregnated with oil before the test in order to remove any excess humidity and air gaps that may interfere with the test results. The AC breakdown voltage was found to be 3.1kV (RMS-mean).

The electrodes used are flat with a 15mm diameter. The edges are rounded off in such way that they follow a Rogowski profile in order to minimise the effect of electric field concentration. The rounding off has proven to be effective as 90% of the breakdowns occurred within the flat part of the surface and not on the edge.

The life time of the sample was investigated, i.e. the time to breakdown. The voltage levels chosen for the sinusoidal carrier voltage were selected to be 2.91kV and 2.22kV. These values coincide with 95% and 72% of the breakdown voltage respectively. It should be noted also that 2.22kV is just below the partial discharge inception voltage of paper. In addition to the sinusoidal voltages, transients were added. These transients were always 1 kV in magnitude and with a 1kV/µs rise time. The only parameter that was altered was the repetition frequency.

The average aging times at 2.91kV and 2.22kV were found to be 178 hours and 1023 hours. These values were obtained by calculating the average breakdown times of 16 samples. Due to the nature of the paper, the spread was relatively high with breakdowns occurring as early as 20 hours and late up to 1300 hours. More information about these breakdowns is presented in a previous publication [2]. With superimposed transients, these values were significantly reduced. Each transient frequency has a specific aging coefficient which shows the ratio of the times to breakdown of pure AC sinus aging compared to transient aging. This coefficient is dependent on the AC component and the frequency of the transients. It is calculated using the proposed formula in (1):

$$r(v) = \frac{\overline{\tau_{ac}^{bd}(v)}}{\tau_{ac+tr}^{bd}(v)} \qquad (1)$$

Where:

r(v) is the aging coefficient as a function of the voltage,

τ^{bd}_{ac} is the mean breakdown time for the AC waveform,

τ^{bd}_{ac+tr} is the mean breakdown time for the AC waveform plus transients.

The compiled results are shown in Figure 5.

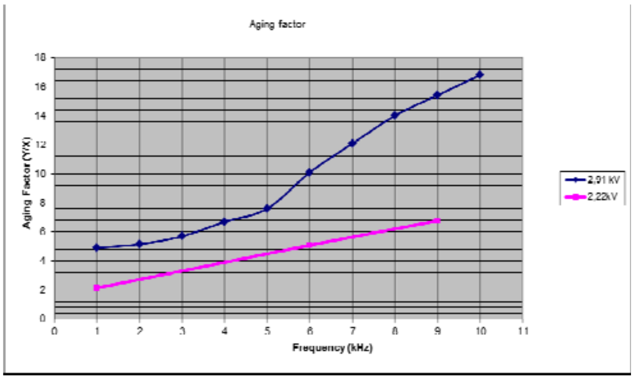

Figure 5: The acceleration coefficient for different frequency transients based on formula shown in (1).

From figure 5 we can deduce that increasing the repetition frequency of transients has a higher degradation coefficient.

For the voltage level of 2.91 kV, the effects are more pronounced. At 10 kHz the aging factor is 17, whereas when the transients have been reduced to 1 kHz, this value drops to 5.

At 2.22kV, the results are not fully complete. Data has been gathered for 1 kHz, 4 kHz, 6 kHz and 9 kHz. However, at these frequencies, similar results have been observed but with lower coefficients. For 9 kHz, the lifetime acceleration coefficient is 6, whereas for 1 kHz it drops to 2.

3.2 The effect of rise time

Rise time is a very influential parameter [1,2]. An impulse generator has been designed to investigate the effects of this parameter whilst eliminating the repetition frequency.

The impulse generator uses a spark gap, whose width is used to control the magnitude of the impulse. The rise time is controlled by a series of resistances whose values are chosen to achieve the desired rise time. The simplified schematic of this device is shown in Figure 6.

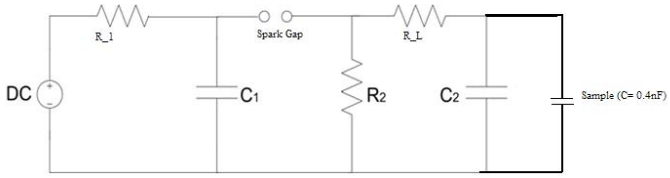

Figure 6: The impulse generator used to create single transients.

A DC source feed the capacitor C_1 and charges it. Once the spark gap has been broken, a large pulse is created and applied to the sample. The main characteristics of this spark generator are that the rise time of the pulses and the magnitude can be varied. This is performed by increasing the resistance R_L and R_2 achieve slower rise times and by increasing the spark gap to achieve higher magnitudes. R_1 can be varied to achieve faster charging times

The pulses were applied to the same paper-oil specimens as described in the previous section according to the standard IEC 60243. Two types of pulses were applied: positive polarity and negative polarity. The results are presented in Figure 7.

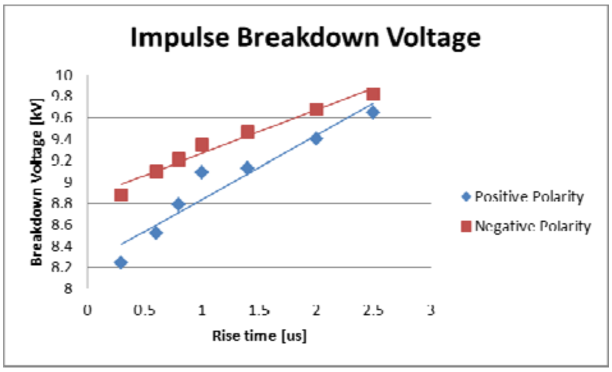

Figure 7: Impulse breakdown voltage on paper oil insulation. The rise time of the impulse was varied and the breakdown voltage investigated.

The results show that the rise time of an impulse has an effect on the breakdown strength of the paper insulation. The breakdown voltage of the samples was achieved faster when stressed with a positive polarity pulse than with a negative one for any investigated rise time. The collected data points show a linear trend throughout the investigated rise time range. 15 samples were stressed for each rise time and polarity of the pulse. The scatter obtained in the tests was uniform providing samples ±0.5kV from the average values shown.

From the results we can see that positive polarity pulses are more damaging to the insulation system as breakdown occurs at lower voltage levels. The slope of the positive pulse trend line is sharper when compared to the slope of the negative polarity one. This shows that for positive pulses, faster rise times cause a higher breakdown factor.

4 DISCUSSION

Paper-oil impregnated cellulose is negatively affected by the presence of transients. This is reflected in the significant reduction in life-time and breakdown strength.

As previously discussed, repetitive transients are short pulses with a very fast rise time, high magnitudes and a fast repetition frequency. Each time a pulse is applied, an electric field is generated that acts on the fibres of the paper. A representation of the charge distribution is shown in Figure 8.

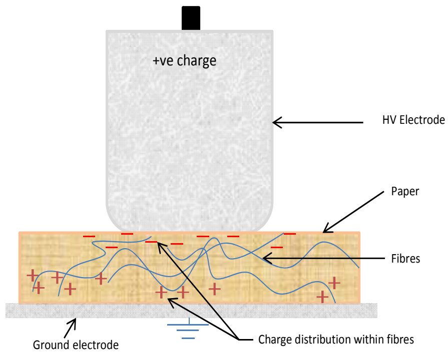

Figure 8: The effect of polarisation on paper fibres. An electric field is generated by the transients that polarises the fibres and creates a pulling force.

Each field application polarises the fibres by redistributing the charge of the molecules and creates a force that pulls the fibre towards the source of the electric field. This force is calculated with the formula shown in (2) [Kruger].

$$F = \frac{\varepsilon_0}{2} V \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1} \cdot \nabla E^2 \qquad (2)$$

Where:

V is the volume of the particle

ε_0 is $8.85 \cdot 10^{-12}$ AsV^{-1}m^{-1}

ε_1 is the permittivity of the liquid

ε_2 is the permittivity of the particle, usually >> ε_1

E is the local field strength

This phenomenon of electrostatic induction causes the fibres to move and stretch on a microscopic level. The speed at which the fibres move is determined by the changing electric field, i.e. the rise time of the transient. The amount of elongation is determined by the magnitude, whereas the amount of times the fibre is stretched is established by the repetition frequency.

As we have seen with the rise time tests, the faster the rise time, the earlier the breakdown occurs in terms of voltage applied. When pulling on a piece of paper faster, a tear is more easily achievable. The same comparison can be applied to frequency, the more a sheet of paper is bent, the weaker the integrity of the fibres become at the bending place.

5 CONCLUSION AND RECOMMENDATION

Many changes to the way electricity is generated and transmitted are going to occur in the future with a direct effect on the electric grid. One of them is the introduction of transients caused by power electronic inverters.

Paper samples 0.06 mm thick were stressed with an in-lab generated sinusoidal waveform with superimposed transients. The transients had a positive polarity whilst the sinusoid was in the positive cycle and a negative polarity when the sinusoid was in the negative one. The sinusoidal voltage magnitude was altered between 2.91 kV and 2.22 kV whereas the transients were preset to 1 kV in amplitude and 1 kV/μs rise time. The repetition frequency was altered between 1 kHz and 10 kHz. The results showed that the life duration was altered both by the frequency of the transients and by the magnitude of the sinusoidal component by factors ranging from 2 to 17.

The rise time alteration experiments showed that paper-oil insulation's breakdown voltage is dependent on the rise time of a single transient. The rise time was altered between 0.3 μs and 2.5 μs with the breakdown voltage increasing from 8.25 kV to 9.65 kV in the case of positive polarity pulses and 8.9 kV to 9.8 kV in the case of negative polarity pulses respectively.

This data shows that even though it is good to have high repetition rates and fast rise times to produce smoother waveforms, it creates extra stresses on the HV components already in service. Due to this, grid operators should find appropriate levels to minimise the damage whilst maintaining a high level of efficiency in the grid.

If higher electric loads were to be needed, it would be recommended to decrease the switching frequency of the inverters. This would create less smooth waveforms, but would extend the life time of the HV components and reducing the chance of failure. In the opposite scenario, loading could be reduced to give way for much smoother waveforms. Such a scenario would appear if a machine would need to be precisely controlled.

6 FUTURE WORK

The worked carried out in this project can be considered as the first step into understanding the behaviour of cellulose-oil impregnated insulation under transient conditions.

A hypothesis has been proposed why the paper fails prematurely and it has been tested with electrical methods to determine its electrical withstand capabilities. Further research is needed, however, to understand the material's behaviour under a material engineering point of view. If indeed the fibres of the material are weakened by the actions of the transients, such losses should be reflected in the loss of tensile strength.

It was mentioned at the beginning of this paper that loading conditions will increase for the current components in the grid causing extra thermal and electrical stress on the components. Experiments are currently being performed to estimate the effect of transients on samples whose temperatures have been raised to 40°C, 60°C and 80°C. Since the oil's viscosity is reduced by higher temperatures, the fibres could have an less obstructed movement under fast changing electric fields.

The findings of these tests will be presented in future contributions.

7 REFERENCES

[1] M. Madrigal and E. Acha, "Harmonic Modelling of Voltage Source Converters for HVDC Stations", IEEE AC-DC Power Transmission conference publication No. 485, 2001.

[2] T. Koltunowicz, R. Kochetov, G. Bajracharya, D. Djairam and J.J. Smit, "Repetitive Transient Aging, the Influence of Repetition Frequency" to be published in Electrical Insulation Conference (EIC), Annapolis, USA, June 2011.

[3] Cigre Brochure 225, 2003, "Electric Power Systems 2020", Joint Advisory Group SC15/D1 – JAG 02 TC.

[4] Blewbury Energy Initiative, Green Energy. URL: http://www.blewbury.co.uk/energy/green.htm, 2008. Las accessed 10 Mar. 2009.

[5] http://www.desertec.org/

[6] L. Paulsson, B. Ekhov, S. Halen, T. Larsson, L. Palmqvist, A. A. Edris, D. Kidd, A. J. F. Keri and B. Mehraban, "High-frequency impacts in a converter-based back-to-back tie; the Eagle Pass installation", IEEE Transactions on Power Delivery, Vol. 18, No. 4, pp. 1410-1415, 2003.

[7] F.H. Kruger,"Industrial High Voltage", page 111, Delft University Press, 1991