Investigation on the high frequency, high voltage insulation properties of mineral transformer-oil

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Abstract: Based upon the increasing utilization of power electronics in electrical energy systems, high frequency combined with high voltage (HF-HV) phenomena are emerging. Fast switching operations, e.g. by static inverters with their large slew rates, are the origin of the stresses above 50/60 Hz. The impact of HF-HV noise on insulation systems like in power transformers has yet to be investigated and is temporarily unknown. In contrast to drives, where static inverters are in use for some time, their application and interaction with oil-cellulose insulation is rather new. Investigations on that matter are often limited by the ability to generate an appropriate test signal. Although earlier researchers found a significant drop in dielectric strength, impregnated board as well as the mineral oil itself will still need more than 10kV/mm for breakdown. Further, it is nigh impossible to gather useful data with cellulose material at a gap distance less than 1mm. A power source with a resonance principle was build to generate sinusoidal voltages with 100 kV maximum amplitude at frequencies up to 200 kHz.
As the basic insulation material in the combination with cellulose, mineral oil (Shell Diala D) will be investigated first. Basic tests on the dielectric strength and the comparison with the values at power frequency will be observed. Examinations on the breakdown voltage at 160 kHz show a drop, exceeding a bisection of the 50 Hz values. These investigations will be extended here by testing different frequencies and their dependency upon the flashover strength as well as the detailed comparison with standard test methods for insulating liquids.

Introduction

The ongoing rise of energy consumption, paired with the increasing need for long range transportation of electric energy results in an urge to implement active control and compensation of existing power grids. As recently discussed by cigré [1], transformer failures due to high frequency stresses on insulations are occurring with an increasing number. Their close proximity to HVDC components is presented as a possible cause, as well as the excitation of resonances by SF_6 switchgear.

Thinking of an intensified use of power electronic components for Flexible AC transmission systems (FACTS), especially IGBTs in a Static Synchronous Compensator (STATCOM) for providing leading and lagging power, is merely accreting the problem.
The biggest obstruction is the lack of knowledge about the dielectric properties of standard power transformer materials, mainly mineral oil and cellulose. In past applications, these were only stressed with standard power frequency voltages, lightning- and switching impulses. Repetitive impact of high amplitude transients were simply not necessary.

Power source for test signal generation

Most important for any investigation of dielectric materials in higher frequency ranges is the ability of suitable test-signal generation. Prior to any examination a power source needs to be designed and built, capable of exceeding the breakdown voltages.

Easy ways of doing this, like standard transformers with ferrite cores and Tesla transformers can quickly be discarded. With the transformer principle, the large diameter of the core would simply be to big, due to the power that needs to be transmitted and therefore quite not affordable and difficult to produce. A Tesla principle can produce both frequency and amplitude, but only in pulses, as the resonator is triggered [2].

More probable solutions would be a tube transmitter or a controlled Tesla transformer. The latter was used in prior experiments [3]. Test voltages up to 15kV at a frequency of 50kHz were generated there. Values that are already high enough to exceed the dielectric strength of thin polymer foils, but surely not suitable for larger gap distances. Adding to that, is the disadvantage of two resonance circuits that need to be tuned exactly to the same frequency for proper excitation.

Derived by the above principles is a direct excitation of a series resonance circuit by a frequency variable static inverter. Hereby the alternating inverter pulses are driving a current, leading to a high voltage at the opposite connection of the two elements, according to (1).

$$U_{high} = \omega_{res} \cdot L \cdot I_{excitation} \qquad (1)$$

This is of cause only possible when excited at resonance frequency. Otherwise the impedance is to high to allow the current to flow, or the source needs to be capable of providing more power to drive it. Hence the resonance frequency is the operating point for the supply, where the impedance is the lowest, in an ideal case even zero.

Another limiting factor for the operation is the resonator quality. The lower it gets, the more energy is lost. Most visible is that impact in the bandwidth of the resonating circuit. The wider it gets, the more difficult it will become to generate a stable resonation with high amplitude. As described, something that is gravely limited by the losses and the provided power.

An impedance scan of the L-C series connection shows in detail the bandwidth, as seen in Figure 1.

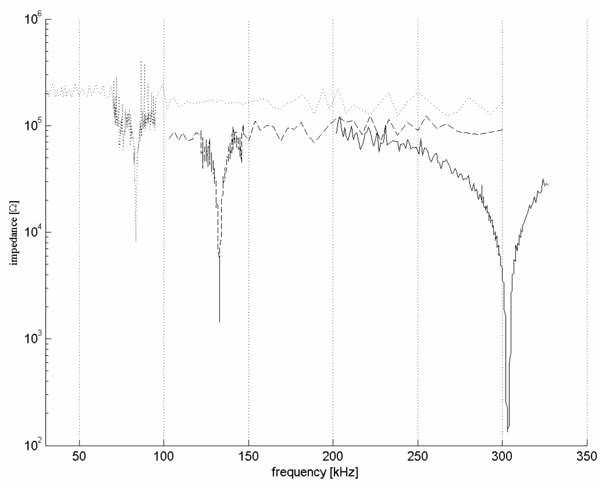

Figure 1: Impedance of the resonance circuit with 100pF Capacitor and 3 different reactors (35mH, 15mH, 3mH)

The noise, present for the lower frequencies is due to harmonics, frequency additions, side resonances caused by the stray capacities and noise of the measurement circuit. The overshoots are as well a commonly seen effect in low bandwidth filters. The impedances measured and shown in Figure 1 must not be taken as an absolute value at it's lowest point. Theoretically it should be zero, yet being problematic to measure with commonly used LCR-meters, utilized here as well.

Effects, influencing the dielectric strength

It has to be kept in mind, that various factors can influence the dielectric strength of any material.

Environmental conditions are mainly varying factors like moisture, temperature and pressure of specimens. Yet their impact is sometimes quite limited. Temperature itself causes a decrease in breakdown strength during a standard IEC 156 test, from almost 80kV to 70kV when varied between 20°C and 90°C [4]. When testing without massively heating the specimen, that influence can be discarded as well as the dependency of the surrounding air pressure.

The moisture, often adulterating temperature dependency measurements, produces a more profound effect on dielectric materials, as the mineral transformer oil under investigation. Due to an increasing ability to absorb moisture with rising temperature, the water content is changing with it. The breakdown voltage itself is rapidly decreasing above 20ppm water content, a region, common with oil being open to air.

Despite any environmental conditions, effects like shape and surface of the electrodes, as well as the gap distance are causing more explicit changes. With changing shape of the electrodes, e.g. Plane-Plane, VDE-Electrodes, the homogeneity of the field changes. In case of the VDE-Electrodes with their calotte profile, the Schwaiger utilization factor η as a degree for the homogeneity of a field, is η=0.97. For all possible configurations this factor is described by (2), where E_{mean} is the average and E_{max} the maximum field strength occurring at the configuration [5].

$$\eta = \frac{E_{\text{mean}}}{E_{\text{max}}} \qquad (2)$$

The lower η is becoming, the more the maximum field strength is dominating. The roughness of the surface as well as impurity of the specimen are of course effects as well.

Last but surely not least, another effect, directly derived by the physical configuration, is the stressed volume [5] or area [6]. There is a dependency noticeable, subject to the size of the electrodes or their distance.

All of the above effects can influence the results, gathered for the high frequency voltage stress.

Breakdown of mineral transformer oil

According to the IEC 156, a spherical form with 25mm radius should be used for testing the flashover strength. Those are the VDE-Electrodes mentioned above. The standard gap distance should be set to 2.5mm resulting in a 97% homogeneous field. To get a bigger load, without the need of adding extra capacitors, ∅57mm plane electrodes with a Rogowski-profile are used in the first high frequency tests.

The increase of stressed volume, as well as imperfections in the Rogowski profile should probably decrease the breakdown voltage. For a worst case scenario, taking the data according to [6], a drop by factor 2 should be explainable. Data provided in [5] is backing that assumption, taken by the values given for the difference between the VDE and the ASTM method. For the latter, ∅25.4mm plane electrodes with sharp edges are used.

Any different decrease will be produced by frequency dependencies. A definitive correlation to a specific effect is yet not necessarily possible and needs to be investigated in more detail afterwards.

The results taken by those measurements and their comparison with standard 50Hz testing are plotted in Figure 2.

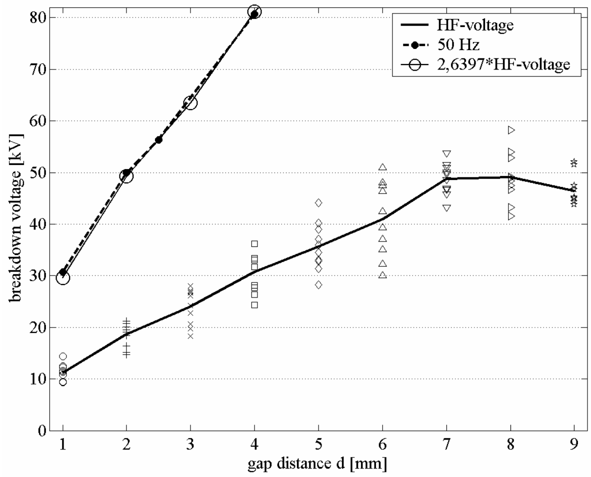

Figure 2: Comparison of the RMS breakdown voltage of mineral transformer oil (16.3ppm) at 50Hz and 135kHz-170kHz [7]

The frequency variation from 135kHz to 170kHz can be explained by the decrease of capacitance during the dilatation of the gap and therefore the increase of the resonance frequency.

The suggested bisection of the breakdown voltage is, as shown in Figure 2, well exceeded by cutting it to almost one third. Weather this is caused by the frequency influence alone, or a greater frequency dependency of the area-/volume-effect or the homogeneity should be investigated by high frequency tests with the VDE-Electrodes.

When including a standard test vessel into the HF generator, a increased capacitive load needs to be added to get a stabile resonance. If done so, the dependency of the gap distance is very limited and therefore stabile at 115 kHz. The connections are yet a little bit more demanding and limit the maximum applicable voltage which results in the 2.5mm gap distance for the VDE-electrodes in Figure 3. With d=3mm, the voltage level would have exceeded the save operational limits, determined in prior tests and was therefore not further pursued, in order not to harm the standard test vessel.

At a gap distance of d=2.5mm, the VDE electrodes should produce the most reliable results, as well as their utilization factor is exactly known there, as mentioned above. The measurement data shows a drop of breakdown strength between 50 Hz and 115 kHz. A possible influence of the area effect is hereby excluded, due to similar electrodes and test conditions.

The area effect is taken into account when comparing the HF IECprofile measurements with the ones of the plane electrodes. An expected bisection of the values is taking place. The remaining difference can therefore be credited to a frequency dependency of the dielectric strength of mineral transformer oil.

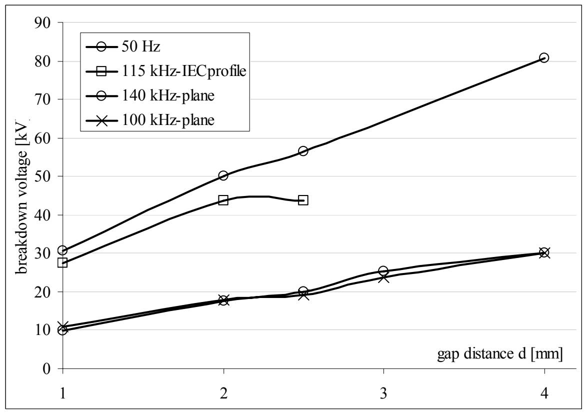

Figure 3: Comparison of the RMS breakdown voltage of mineral transformer oil with different electrode shapes and frequencies

Conclusion

For the measurement of high frequent voltage stress of mineral transformer oil, a power source was designed and optimized as described in this report. The gathered data suggests a drop of the breakdown strength by one third. The area effect seems to remain with a constant influence on the setup, compared to technical frequency.

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