Breakdown testing of standard insulation materials with high frequency voltages for an assessment of stresses, generated by repetitive pulses.

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Abstract- **Despite the classic stresses on insulation systems, repetitive voltage pulses are more and more present in modern power systems. Their influence is yet quite unknown. Considering the large slew and repetition rates of HVDC valves with voltage-sourced converters, high frequency noise is generated and subjected to the insulation systems, e.g. oil and cellulose, used in transformers. For an assessment of the material properties of insulating materials, the breakdown strength is the most basic value needed. In order to be able to obtain those values for frequencies up to 400 kHz, with reasonable gap distances, an amplitude of 100 kV is crucial. The voltage should additionally be increasable from zero up to the breakdown, imitating the standard 50/60 Hz AC testing. In that matter, a test system was built for generating such kind of signals.**

For implementation a series resonance circuit was constructed, which is excited by a frequency variable inverter at the resonance frequency. Of special importance is thereby the optimization of the circuit itself to minimize losses and to increase the amplitude reachable. Not only the reactor was therefore specially designed, but the capacitive parts as well. Limiting for the last part, when e.g. thinking of standard test vessels for transformer-oil, is a minimum capacity needed for proper operation of the resonance circuit.

Testing of insulation materials, concerning the breakdown strength against the high frequency voltages was done subsequently, as well as a comparison with standard power frequency values. Different influences on their behavior, like the moisture content of transformer-oil were investigated as well.

I. INTRODUCTION

Modern energy systems consist of systems, which are not only generating voltages in the desired power frequency of 50/60 Hz, but in much higher ranges as well. In particular, power electronic equipment as used for HVDC transmission is of that kind, as well as Flexible AC Transmission Systems (FACTS) for controlling networks for stability or power-flow.

Yet part of all those systems is classical equipment like power transformers, line insulation and cables. Especially the first ones mentioned are of central interest, since they are an important part of the power-electronic systems themselves.

As recently discussed in some investigations [1,2], the impact of the fast transients and the high frequency (HF) noise on the insulation system is a problem, leading to increased failure amongst those pieces of equipment.

It has to be noted, that even classical influences can lead to insulation failures. Switching operations, with vacuum and SF_6 switchgear will also lead to high frequency noise. This is for example more critical, when a transformer is switched via a longer line. In that case, traveling waves phenomena invoke high frequency stresses to the internal insulation by means of winding resonances.

Problematic, especially during the design process, is the lack of material properties for the noise. Any rating of the dielectric materials, subjected with the noise, is therefore difficult, if not impossible. In the matter of power transformers, including HVDC-transformers, mainly mineral oil and cellulose are used for insulation. For any testing to obtain the breakdown values or basic strengths a voltage source is needed, capable of generating defined signals in the desired frequency range.

II. HIGH FREQUENCY, HIGH VOLTAGE POWER SOURCE

Central to any investigation of dielectric materials at much higher frequencies than the usual 50/60 Hz, is the test-signal generation with a suitable power source. In that matter, not only the HF needs to be viewed, but as well the high voltages (HV) needed for breakdown testing. In any case, the higher the possible factors are, the better. But it can be quickly shown that there are several limitations, restricting both values.

Several different leads for HF-HV sources can be followed. First of all, the classical approach with a transformation to the higher voltages comes into mind. Due to the frequencies up to several 100 kHz, the core material would be a problem. Only ferrite can be used there, but the coexistent need for insulation and power transfer would need large diameters of that material, making it nigh impossible to realize.

Other possibilities can be found in the Tesla transformer principle, where two loose coupled resonance circuits are excited by a flashover and afterwards oscillating with their natural frequency of

$$f_{res} = \frac{1}{2\pi\sqrt{L \cdot C}}. \quad (1)$$

Caused by the resistivity of the circuit, the resonance can not be kept indefinitely, but is dampened after several oscillations. Testing of the materials is therefore only possible with those decreasing signals [3]. Properties can be obtained similar to lightning-impulse testing, but not with a continuously rising amplitude, that is normally used, when thinking of the breakdown tests at 50/60 Hz.

As well as the short time testing, it may be desired to investigate long term influences of the high frequencies at high voltages on the dielectric materials, which would not be possible with a retriggered signal.

More promising , especially in the last matter, is another form of triggering the circuits. The application of power electronic valves like MOSFETs and IGBTs, can control the resonance at continuous levels [4]. Still problematic in the use of a source of that kind would be the tuning of two circuits to the same natural frequency. Any mistuning would lead to beating waves as a result or no resonance at all.

Derived by the principles mentioned above, as well as by approaches, done in the 1930s with tube amplifiers, is the direct excitation of a series resonance circuit by a static inverter used here. The driven current is ultimately leading to the voltage drop over the inductance and with it across the test sample, as a part of the capacitive load, as shown in Fig.1.

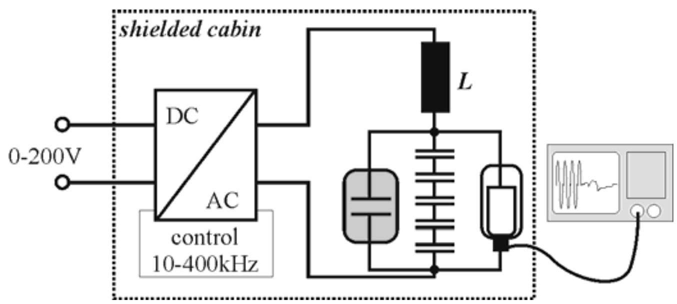

Fig. 1: Setup of the resonance circuit

In the actual setup, the total capacity is divided in several parts as shown. Naturally, the specimen is put in a vessel with an electrode configuration. Adding to that, a tuning of the circuit needs to be performed, done with either a tunable capacity or an series interconnection of several capacitors. The part not seen directly with a single device are the stray parts, that can be kept under control with the use of a shielded cabin around the assembly. Last but not least, the generated voltages need to be measured. Since any additional resistance inside the circuit would increase the losses, a solely capacitive divider is used for that task.

Thinking of the losses, a big contributing part to that is the reactor, why the quality of it is crucial to be optimized by proper build-up.

III. Theoretical Quality-Factor

When looking at the combination of resonating elements, various of them are adding to the losses. Yet only few of them can actually be influenced and thereby optimized.

First to mention is the test vessel. Since a certain diameter is needed and a medium with lower losses (*tanδ*) can not be utilized, since it is the specimen, no changes are possible. The options for the measurement and tuning capacitors are similar in their result for various reasons, as well as the stray capacitances, predominantly generated by the wiring between the different elements. This leaves the type of wire used, and the inductivity.

The easy part of the two is the wire. The displacement of current inside the wire is causing a reduction of conducting diameter and an increase in resistivity with it. The use of so called HF-litz wire, the combination of many parallel and insulated filaments, is highly recommended and wise. Especially for frequencies higher than 200 kHz. Otherwise the needed diameter of the wire would be getting to big.

When having done that, another part can be achieved by the form of the reactor. Usually the task would be to build the highest possible inductivity with a certain amount of cable length, but here it is fixed and derived by the capacity in total.

Therefore the question at hand was obtaining the best quality factor

$$Q_{reactor} = \frac{2 \cdot \pi \cdot f_{res} \cdot L}{R_L}. \qquad (2)$$

by changing the size, form and length of the coil. When looking at (2), a relationship between the resistivity R_L and the inductivity L needs to be found.

Investigating the origin of the resistivity, one part is due to the magnetic field at a certain winding position, originated at another one. Taking the current as a simplified 1, running to all of the windings, according to the Biot-Savart-law a magnetic field will be generated in the surrounding space. A complete and exact calculation of it is obsolete and needs only to be done by taking the distances and directions between all the origins and their effects into account. Thereby we get a normalized magnetic field H_{norm} in a rotationally symmetrical coordinate system:

$$\underline{H_{norm}}(x) = \sum_{n \neq x} \pm \frac{1}{\underline{Pos(Winding\_n)} - \underline{Pos(x)}}. \qquad (3)$$

For the following, the shapes were limited to single layer solenoid reactors and for them their inductivity was linked to the dimensions via a formula suggested by [5]. For an implied number of turns, the length l is fixed by the cross-section of the wires and their number, while the diameter can be calculated backwards, being the only variable left in the equation.

To further assess the implications of the shape on the quality-factor, model coils with similar inductive values, but different sizes were built and measured, as described in [6]. For the calculated magnetic field H_{norm} at all positions, a maximum at the ends of the coil can be seen, followed by a minimum, giving the difference H_{diff}. With an increasing number of turns, a superelevation of the field in the middle above the minimum value H_{min} is involved, resulting in the difference $H_{superelevation}$.

With proper weighing of those two factors, as well as normalizing it to the calculated maximum H_{max}, the frequency dependant Theoretical Quality-Factor (*TQ*) can be calculated:

$$TQ = 1 - \left[k \cdot H_{\text{diff}} - 2.5 \cdot H_{\text{superelevation}} \right]$$
$$k = \frac{21 \cdot \left(\arctan\left(\sqrt{3} \cdot \left(f/10^5 - 1.5 \right) \right) + \arctan\left(1.5 \cdot \sqrt{3} \right) \right)}{32 \cdot \pi}. \qquad (4)$$

Since curve fitting algorithms were used to obtain the factors involved, the error will increase when the calculated frequency differs gravely from the range 100-300 kHz, used for measurement.

IV. Capacitive Test Vessels

According to IEC 156, standard test vessels for insulating liquids should consist of two spheres or calottes, while ASTM prefers plates with sharp edges. For proper operation of the resonance circuit, a minimum capacity is needed, with the one by the standard IEC profile being to small. For both homogeneity and functional reasons, 57 mm plane electrodes with a Rogowski border profile are used and built inside a vessel for containment of the transformer-oil under test.

With the desire towards testing of solid, oil immersed cellulose materials, the construction is getting more difficult. Easiest implementation would be to couch the metal electrodes inside the pressboard. But this would mean to build an exactly similar set for every single one of the many tests needed. Therefore a setup for the use of cut plates is preferred.

For those a standard setup would persist of two 25 mm electrodes with rounded edges, or one of them with a larger one of 75 mm (IEC 60243-1). A large plate would be put between those and altogether surrounded with oil.

When using that kind of configuration inside the resonance circuit, which can be easily tested with the configuration for liquids, a corona will occur at the triple-point –the interconnection of the three materials. In every test, the consequences were always the same. Around 20 kV and a frequency roughly around 100 kHz the corona ignited and produced a loss in the circuit, causing the voltage to drop to 10 kV. At that value it stayed, while the corona got bigger with an increasing inverter voltage.

Therefore an electrode configuration needs to be found, to reduce the triple-point intensity. This will be done by superimposing two effects. First of all there is field-shading and secondly -displacement. For the latter, the distribution of the electric field in a stacked dielectric alignment needs to be investigated more closely. A setup of two electrodes with two different materials (d_1, ε_1, d_2, ε_2) on top of each other in between, would result in E_1 and E_2 as a function of the Voltage U according to

$$E_1 = \frac{U}{d_1 + d_2 \cdot \varepsilon_1 / \varepsilon_2} \quad ; \quad E_2 = \frac{U}{d_1 \cdot \varepsilon_2 / \varepsilon_1 + d_2} \quad . \tag{5}$$

For the triple point, the lower limit for d_1 towards zero, the formula shows a magnification of the field strength by the ratio of the dielectric constants. In our case ε_1=2.2 for mineral transformer-oil and $\varepsilon_2 \approx 4$ for the impregnated board. Yet we can use that fact as an advantage as well. By implementing a surrounding material with a factor similar or higher than the one of the specimen, the displacement will occur in the opposite direction, which will result in the disappearance of the field enhancement..

For the shading part, its task is to smoothen the transition of the different materials. By adding a parallel surface in a small distance towards the surface of the specimen, even a material with lower dielectric constant can adequately be used. All of that combined is leading to the test vessel displayed in Fig. 2.

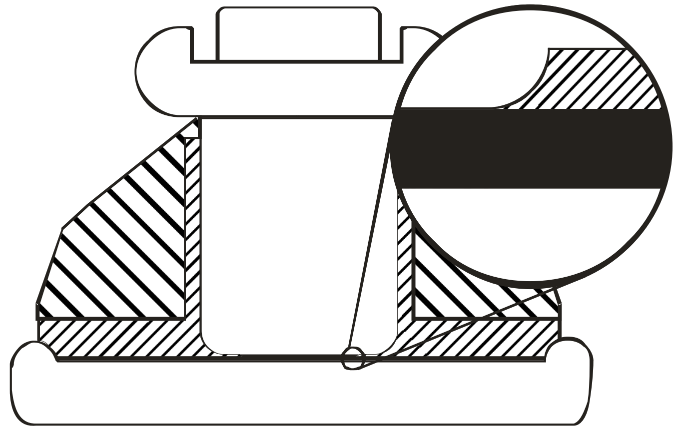

Fig. 2: Test vessel for solid dielectrics

Depicted above is the resulting vessel for the investigation of solid dielectric materials, with certain respect to the standards and the needs of the resonance circuit.

In the middle, the electrode directly adjoins the specimen, shown in black in Fig. 2. At the end of the middle electrode with a diameter of 40 mm, there is a radius of 20 mm linking to the step of 0.5 mm. That stays until the final diameter of the "hot" region is reached at 60 mm and ended with a radius of 10 mm. Thereby no additional triple point is generated past the step for the homogenization and shading part.

If not immanent for the behavior of the specimen itself, all possibilities for a parasitic corona development due to the test vessel should be eliminated or at least be as minimized as possible. Yet the device itself should be taken as a suggestions for future testing. In theory, backed by computer simulations with Finite Elements, it should enable the corona-free breakdown investigation of solid dielectric plates.

The following measurements with mineral transformer oil do not involve the need for a extremely complicated device, since no triple-point will emerge in a liquid.

V. Breakdown Measurements

The first values for the breakdown are gathered for mineral transformer oil, the basic insulation medium, being the most present in power transformers.

During this investigation and especially for the comparison of the findings with standard values for 50/60 Hz, different influencing effects need to be considered. Namely the Area- or Volume-effect as well as the voltage rise time. All of those will easily adulterate or at least distort the results.

As a first step the rise speed needs to be fixed, as constant as possible, which is not that easy as at standard power frequencies, since the HF Amplitude and the DC Voltage do not interdepend linearly.

After that, the influence of different shapes of the electrodes and with them varying stressed volumes and homogeneities are investigated more closely. Therefore, breakdown measurements at 50 Hz and around 100 kHz are done, each with the standard IEC 156 calottes and the 57 mm plane electrodes. The results are shown in Fig. 3.

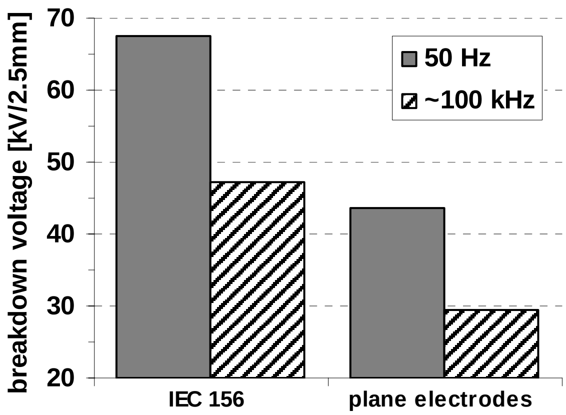

Fig. 3: Comparison of different electrode shapes

Not only the area effect, thus the reduction of the dielectric strength with a larger stressed volume, is clearly visible, but it shows the similar effect for the high frequency measures.

As mentioned above, a stable resonance over a large bandwidth of frequencies can not be achieved by using the IEC electrodes. So a comparison of the high frequency data with the well known power frequency values will be done with the plane electrodes. If necessary, the influence by the laws of enlargement can be calculated subsequently [7].

As displayed in Fig. 4, different moisture levels of the mineral transformer oil (Shell Diala D) were tested.

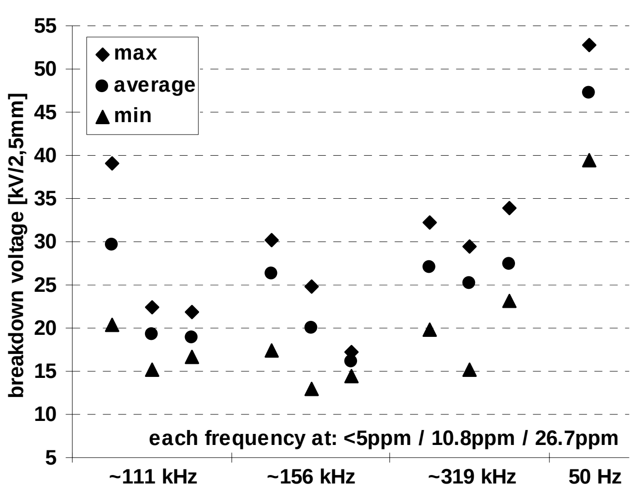

Fig. 4: High frequency breakdown tests for mineral transformer-oil

All of them are showing a significant drop for the voltage withstand levels for safe operation without a breakdown. Almost a bisection of the breakdown voltages can be seen in the complete frequency range of 100 kHz to 320 kHz.

According to the trends of the values with rising moisture, a frequency dependency is likely, but can not be definitely stated. The variety of the seen trends is well within a normal scatter of results, due to the oil itself.

A sensitivity to lower frequencies is also within the nominal scattering; as displayed and additionally investigated for oil with 6.3 ppm water at 42.6 kHz. Even for this rather low frequency, an average breakdown voltage of 25.77 kV for the 2.5 mm gap was measured.

VI. Conclusion and Outlook

For dielectric breakdown testing of power transformer insulation, a laboratory device is presented and specified. For that, a series resonance circuit was designed, consisting of mainly the capacity of the specimen test vessel and a reactor. The latter was especially modified for the higher frequencies, by reducing its losses as far as possible, using the proposed Theoretical Quality-factor. With respect to the testing of solid materials, a special setup for the prevention of corona discharges was presented as well. Finally, high frequency breakdown measurements with mineral transformer oil were done, showing a significant drop of around 50%, compared to standard power frequency values.

Based on the design for the solid insulation test vessel, the actual prevention of any corona discharges need to be verified in the future, followed by the testing of that kind of materials against high frequent stresses. With respect to liquids, both synthetic and biodegradable oils as members of emerging insulation materials in transformers should be investigated. Last but not least, the downward trends with rising moisture level need to be verified by generating a wider statistical base with more measurements.

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