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TESTING OF INSULATING MATERIALS AT HIGH FREQUENCIES AND HIGH VOLTAGE BASED ON THE TESLA TRANSFORMER PRINCIPLE

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Abstract

Insulation materials used in high-voltage switched-mode power supplies are exposed to high-frequent high voltages. Ageing tests performed with high DC voltages or low-frequent high voltages might not reveal the true ageing effects which take place during rated operation at high frequency.
Studies on different voltage source principles have been carried out. Finally the tesla transformer principle turned out to be superior for the purpose of testing the ageing performance of insulating materials under high voltages at high frequency. For this reason a voltage source based on the tesla transformer principle was developed to enable relevant testing.
Ageing experiments on plastic foil samples performed up to now have confirmed the suitability of the chosen principle and the reliability of the applied voltage source. Options are availabe to increase the test voltage level and to modify the test voltage frequency.

Introduction

Breakdown of insulating materials stressed by high voltage occur by different mechanisms. The time until breakdown of an insulating material can be very short (intrinsic breakdown). In this case the insulating properties of the material are destroyed in a split second. However, the degradation (ageing) of the material can also take a long period of time (several decades). The typical sources of deterioration are partial discharges or environmental influences such as temperature, humidity, etc. A further breakdown mechanism which can be temporally ranked inbetween the mentioned ones is based on internal thermal heating of the material caused by (a) electrical conductivity and/or (b) at high frequencies by dielectric losses (thermal breakdown) [1].
The mechanism or a combination of different mechanisms responsible for breakdown of an insulating material in a certain case is influenced by many factors such as geometry of the test sample, geometry of electrodes, test temperature, environmental conditions and the amplitude and time characteristic of the electric field [2].
So it makes quite a difference if an insulating material is stressed by DC, low-frequent AC or high-frequent AC voltage. High-voltage switched-mode power supplies using the resonance principle include voltages up to a few 10 kV and frequencies up to a few 10 kHz. This must be taken into account if insulating materials used in such power supplies are tested. Since apparatus applied in the power grid usually work with high DC or high AC service voltages up to a rated frequency of 60 Hz at maximum the standard test voltages for these apparatus are of the same characteristic. Additionally these apparatus are tested with impulse voltages. For the generation of these test voltages standardized generators exist. This is different with respect to the generation of high test voltages with a frequency of a few 10 kHz.

Test voltage features

Figure 1 shows the voltage source in principle. It is supplied from the low-voltage power grid and generates a high voltage $u_t(t) = \hat{u}_t \cdot \sin(2\pi f_t \cdot t)$

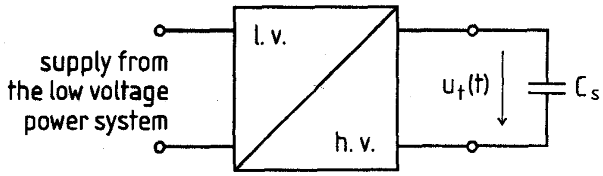

Figure 1: 50 kHz test set-up in principle.

The test voltage $u_t(t)$ had to meet certain given requirements which are listed up in the following in the order of their importance for the tests to be carried out:

1. The maximum test voltage amplitude $\hat{u}_t$ needed is 15 kV.
2. Sample capacitances range up to C_s=100pF.
3. Breakdown mechanisms initiated at frequencies other than the rated frequency at which the insulating material is supposed to work were to be excluded. So the shape of the voltage has to be a pure sine wave of this frequency (f_t=50kHz) without harmonics.
4. Depending on the ageing mechanism the time until breakdown of the sample may last long. So the voltage source must be able to operate for weeks without interruption., i. e. long time stability on the test voltage is requested.
5. The voltage source must be supplied from the low-voltage power grid.
6. In the apparatus, in which the insulating material shall be applied, the superposition of the high-frequent AC voltage by a remarkably high DC voltage is likely. The possibility for superposition of DC and high-frequent voltage for the ageing tests has to be considered and the AC voltage source has to face this work regime.
7. An option for the performance of partial discharge measurement in the test set-up is desirable.

Principles to generate high-frequent high voltages

Testing insulating materials at low frequency or DC usually does not require high power of a testing voltage supply since the test specimens have capacitive characteristic and by this a high impedance. This is different for tests carried out with higher frequencies since the impedance of the test sample decreases with rising frequency and thus the power demand on the voltage supply rises. An example is given: A sine-wave test voltage of 10 kV (RMS) at 50 kHz at a sample capacitance of only 30 pF requires a voltage supply with a rated power of at least $S_r = (10\text{kV})^2 \cdot 2\pi \cdot 50\text{kHz} \cdot 30\text{pF} \approx 950\text{VA}$.

Using a capacitive divider or a coupling capacitor during partial discharge measurements increases this load capacitance of the voltage source. Load capacitances of a few 100 pF have to be faced.

One of the most common ways to generate high AC voltage is the use of a transformer. Different from transformers used in the 50 Hz or 60 Hz power grid special transformers have to be used for the range of a 50 kHz voltage. The cores of those transformers have to be made of ferrites instead of iron. Since ferrite-core transformers are able to work only with a magnetic flux density which is about a fourth of a usually applied iron core it is quite lavish and costly to design such a high voltage transformer needing a high magnetic flux in order to keep the number of windings low. Furthermore, the reactive power needed by the capacitive load has to pass the transformer and must be supplied by a 50 kHz sine-wave generator with a high rated power. Due to these disadvantages the design of a test voltage source according to this principle was not pursued.

Presumed the dissipation factor of the test sample is low enough mainly reactive power is needed in the test circuit. Applying the resonance principle this high amount of reactive power can be used with the help of a resonance circuit. The voltage source, which supplies the resonance circuit, has only to deliver the active power to compensate circuit losses. From this principle a voltage source with a much smaller rated power is needed. Another advantage of the resonance circuit is that for the circuit's excitation a square-wave generator is sufficient. The design of a square-wave generator in the required voltage range of some 100 V is more simple compared to that of a pure monofrequent sine-wave generator at 50 kHz. It is reasonable to apply the resonance principle to a transformer. By this the transformer inductances and the sample capacitance can be used for resonance frequency tuning. Furthermore the transformer can be used to step up the voltage from the low voltage of a few 100 V up to the high voltages in the kV range. The sample capacitance C_s and the inductance of the secondary coil determine the resonance frequency of the circuit. For given capacitances C_s of a few 100 pF an inductance of the secondary coil of a few 10 mH is needed. To achieve the needed value of the inductance at a small transformer size a magnetic core has to be used. Resonance circuits have been designed and realized as prototype ferrite-core transformers. However, the small size of the transformer results in a small distance between the primary and secondary coil. By this a comparatively high coil capacitance appears which is in the order of the sample capacitance. Consequently the transformer itself oscillates at a resonance frequency in the vicinity of the required test frequency which allows only to apply very small load capacitances given by the test specimens. Furthermore ferrite cores produce at a high flux non-linear effects. This results in a test voltage with unacceptable harmonics. These two main disadvantages, i. e. high coil capacitance, generation of harmonics, became apparent when testing prototypes.

In a next step the tesla transformer principle was pursued. This principle avoids non-linear effects because the relevant coils are coupled via air. In order to achieve the required values of

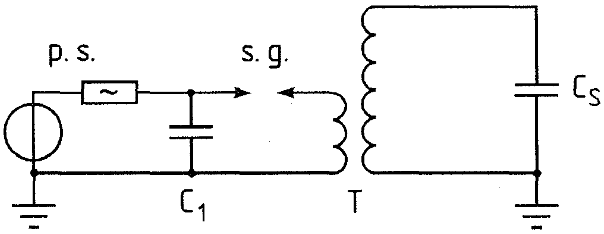

Figure 2: Tesla transformer T with sample C_s, l. v. resonance capacitor C_1, power supply (p. s.) and spark gap (s. g.) as described in literature [3].

inductance the coils' size is much bigger. Due to this the distance between the two coils can be bigger as well - there is not the size limit given by a core - so that the self-capacitance becomes smaller. Thus the natural frequency frequency of such a transformer is far beyond the required test voltage frequency. Figure 2 shows the tesla transformer scheme as described in literature [3]. The components are two coils T, a h. v. tuning capacitance C_s and a l. v. tuning capacitance C_1. Tesla transformers for the generation of million volts have already been in operation. The resonance frequency chosen can range between a few kHz and a few MHz. The transformer according to [3] was excited with medium voltage. Spark gaps or mechanical switches were used as switching devices. The disadvantage of both are that they wear out and have a limited lifetime. Furthermore their possible switching frequency is not high enough to switch within every period of the high-frequent test voltage. Damping in the resonance circuit causes a non-constant amplitude of the test voltage. These switches do not work synchronously to the test voltage causing beat effects with a change of the test amplitude as well. In the meantime modern power semiconductors are available suitable to switch

Table 1: Comparison of different principles for the generation of high-frequent high voltage.

Transformer principle Advantages: - High voltage amplitude fairly independent from load Disadvantages: - Low voltage source of high power needed
Resonance transformer with ferrite core Advantages: - Small size Disadvantages: - Non-linear performance of transformer core - Stray capacitances reduce the value of appliable load capacitances
Tesla transformer (air-coupled transformer) Advantages: - Low voltage source of low power needed - High voltage with monofrequent characteristic Disadvantages: - Fairly big in size - Exact tuning necessary

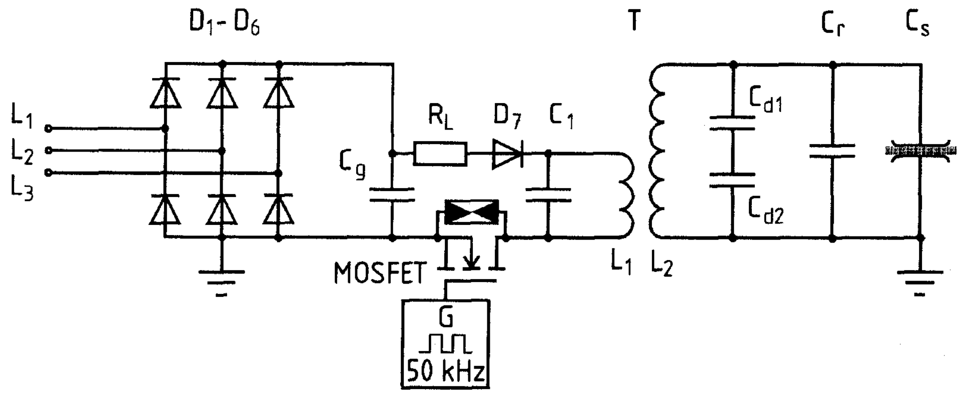

Figure 3: Circuit of the test voltage power supply based on a tesla transformer T.

synchronously to the test voltage within every period of the test voltage. Using these modern elements a constant test voltage amplitude can be achieved. Preconditions are a constant DC power supply voltage and an exact tuning of the tesla transformer. Experiments have shown that it is advantageous to place the switching element between the power supply and the resonance circuit different from the principle shown in Figure 2. Table 1 summarizes principle advantages and disadvantages of the different principles to generate a high-frequent high voltage.

The test set-up

Figure 3 shows the test set-up in its final design. The main element is the tesla transformer T with primary coil L_1 (9 windings) and secondary coil L_2 (400 windings). The coils are wound on a polypropylene tube with a diameter of 35 cm. L. v. as well as h. v. coil were made of enamelled copper wire the diameter of which was chosen according to damping and thermal points of view. Furthermore the skin effect has to be faced, especially in the l. v. coil stressed by higher current values. Five parallel twisted insulated wires of 0.5 mm diameter each were applied. At longtime service the coil temperature did not exceed about 50°C at room temperature of 20°C. Due to the lower currents the high voltage coil was made of a single wire with a diameter of 1 mm. Table 2 summarizes the data of the tesla transformer T.

The resulting h. v. capacitance determining the circuit resonance frequency consists of three parts (s. Figure 3):

1. The test sample capacitance C_s.
2. The capacitive divider needed to measure the 50 kHz high voltage built up with a h. v. capacitor C_{d1} (100 pF) and a secondary capacitor C_{d2} (100 nF).
3. The tuning capacitance C_r consisting of an arrangement of low-loss capacitors in series and in parallel to enable easy and precise tuning.

The l. v. circuit consists of the resonance capacitance C_1, a switching element (MOSFET) and a DC power supply. The capacitance C_1 consists of capacitor decades ranging from 100 nF to 100 pF per step and enables the precise 50 kHz tuning as well as tuning in a very broad frequency range, if desired.

A semiconductor able to switch high peak currents and with a high breakdown voltage and low on-resistance was required. The requirements wer fulfilled by a MOSFET (Type IRFP450) with a peak current ability of 50 A, a breakdown voltage of 500 V and a static on-resistance of 400 mΩ. The MOSFET's gate is driven by a CMOS circuit which generates a square wave with a frequency between 1 kHz and 250 kHz. The pulse duty factor is variable. In order to enable the MOSFET to switch fast and to keep the switching losses low the use of a gate driver circuit was necessary. A 250 V varistor is connected to the MOSFET's source and drain pin for overvoltage protection. A fast recovery diode D_7 determines the current to flow in only one direction. A resistor R_L decouples the power supply part from the resonance part to prevent the capacitances in the power supply from contributing to the resonance circuit. The power supply is connected to the three phases of the low-voltage power system. The power supply is seperated from the grid with the help of a unity ratio transformer. The voltage can be regulated from zero to full voltage by a second transformer with a variable ratio. The transformers are not plotted in Figure 3. The rectifier D_1-D_6 converts the voltage into a DC voltage. The ripple is kept small by a smoothing capacitance C_g. This circuit allows a small ripple compared to a one-phase AC supply even at higher currents.

Protection circuits supervise the current in the MOSFET and the high test voltage. If the test sample breaks down the whole resonance circuit is mistuned so that the current on the primary rises considerably and might destroy the MOSFET if the voltage source is not switched off.

Table 2: Data of the tesla transformer.

Element	Value
Inductance of coil L_1	65.7 µH
Resistance R_1 of coil L_1	220 mΩ
Inductance of coil L_2	29 mH
Resistance R_2 of coil L_2	9.2 Ω
Mutual inductance M	143 µH

Circuit performance

Figure 4 shows the high-frequent test voltage of a circuit according to Figure 3 at an amplitude of 10 kV applied to a plastic foil sample C_s. Temporally related to the test voltage the current through the MOSFET has been measured and is shown in Figure 4 as well. The MOSFET switches once a period of the test voltage. The measurements show that optimal tuning was achieved. For the generation of an amplitude of 10 kV a DC supply voltage at C_g of about 165 V is needed. The impulse currents are smaller than 10 A. The total average active power input is less than 40 W with a resulting load capacitance of $C_{d1}+C_r+C_s$=350pF.

Figure 5 shows the amplitude spectrum of the test voltage calculated by the FFT algorithm from measurement. The analysis shows that the test voltage is monofrequent at the test frequency of 50 kHz. An additional frequency analysis at frequencies lower than 5 kHz confirmed that there are no amplitude spectrum portions, i. e. that there is no influence due to switching or due to the 50 Hz power grid as well.

Once the tesla transformer is perfectly tuned the test voltage has an excellent long-time stability as far as the parameters of the resonance circuit do not change. A change of the performance of the circuit's components is not likely because they are operated within their rated parameters. The only element in the circuit which might change its properties due to ageing is the test sample itself. A change of the test sample's capacitance C_s is tolerable in a certain range because its

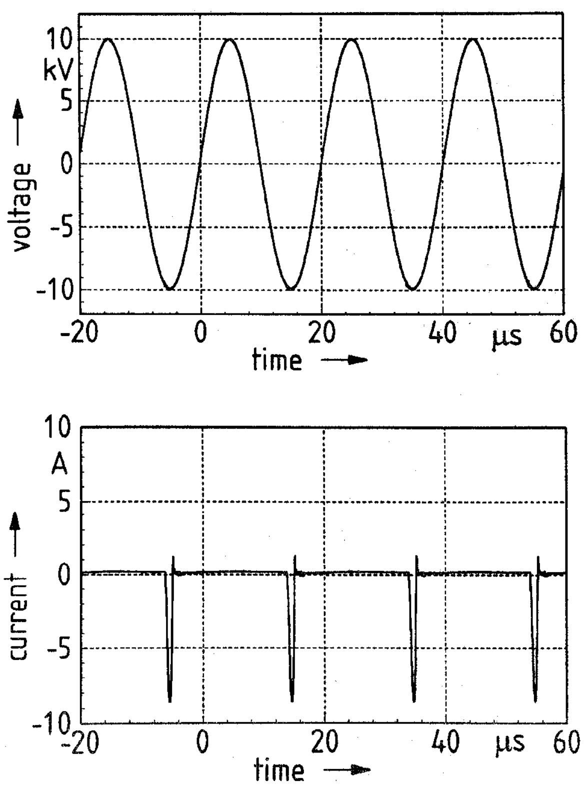

Figure 4: High-frequent test voltage measured at sample with a capacitive divider and primary current through MOSFET versus time.

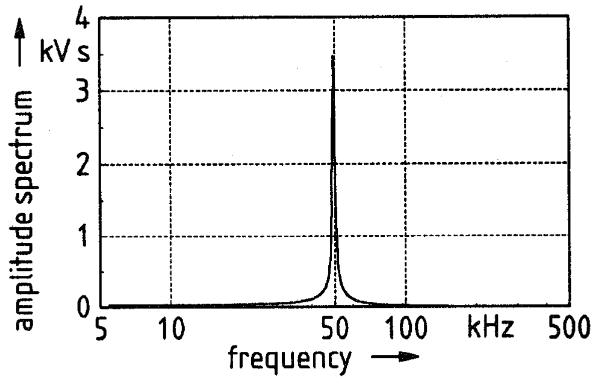

Figure 5: Frequency analysis of the high test voltage by Fast Fourier Transform (FFT).

capacitance is less than 10% of the parallel capacitance $C_{d1}+C_r$ and from that does not influence tuning essentially. However, a change of the sample's dissipation factor tanδ might have more importance. Dielectric losses in the test sample cause a damping in the resonance circuit and contribute to a reduction of the test voltage crest value. This must be compensated by a higher DC supply voltage at capacitor C_g. This change can be done manually or by a control device. By experiments it was found that changes of the samples' tanδ-value exceeding 10^{-3} for a resulting capacitance of 350 pF require action to increase the supply voltage. Preliminary investigation has shown that the breakdown mechanisms of the tested foils seems to be a thermal one if a certain test voltage value is exceeded resulting in an increasing tanδ-value during the test.

Conclusion

For the evaluation of the performance of insulating foils used in h. v. switched-mode power supplies at high frequency the test of these materials with high-frequent voltages is necessary.

A peculiar problem dealt with in this paper is the design of a test set-up which has to consider the low impedance of the foil samples due to their capacitance at high frequency. A resonance circuit based on the tesla transformer principle using air coupled coils turned out to be recommendable. Improvements using semiconductors on the low voltage side compared to the classical tesla transformer circuit are required to ensure long-time test service and the generation of a monofrequent test voltage. General considerations as well as details on a developed and applied test set-up working correctly in the long-time mode are presented.

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