Combined high frequency and high voltage insulation system investigation

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***Abstract*:** **Due to the increasing extension of power grids and decentralization of power generation, the need for control and compensation is more and more increasing. The intensive use of modern power electronics in FACTS elements can provide a feasible solution. Especially STATCOM and UPFC, for their versatile application can be the method of choice. Voltage sourced converters with IGBTs are used for compensation, providing both leading and lagging power. Filters need to be applied to block the high frequencies, generated by the large slew-rate of the converter pulses, from the connecting transformers. Their impact on the oil-cellulose insulation system as well as on most of the other dielectric insulation materials is unknown. This includes the breakdown voltage at higher frequencies as well as possible influences on accelerated aging.**

The first step in a breakdown investigation of any AC insulation system at frequencies beyond 10kHz is the generation of a test voltage. Derived by the strength of transformerboard at 50Hz, an amplitude of 100kV needs to be provided to exceed its insulation capabilities. Based on investigations concerning enameled wires, where the dielectric strength dropped by factor 10, similar eventualities need to be taken into account in the design. A resonance principle was chosen to generate the test voltage of frequencies between 10kHz and 250kHz with an amplitude up to 100kV. Major challenge in the design is a reduction of losses in the circuit, caused either by resistivity or by corona discharge. Insulation failure, other than at the specimen, obviously has to be excluded as well. With the resulting voltage source, miscellaneous dielectric materials will be tested for breakdown and aging, starting in this investigation with oil and its combinations with cellulose.

INTRODUCTION

The continuing rise in energy consumption, accompanied by increasing decentralized generation is creating the need for more compensation and control of energy grids. Furthermore, taking Germany as an example, production will be spaciously separated of the consumers. Therefore more long range transmission capacity needs to be provided.

Innovations in power electronic components, e.g. such as high power MOSFETs (Metal-Oxide-Semiconductor Field Effect Transistor) and IGBTs (Insulated Gate Bipolar Transistors), are allowing the extended use of electronic components in high voltage engineering. Especially for the dynamic compensation and control with Flexible AC Transmission Systems (FACTS), the above elements are offering several advantages because of their turn-off capability. They are absolutely essential for the use in static converters at HVDC applications, where there is no backing net for the commutation of the Thyristor valves. Disengageable elements are equally important with FACTS applications, especially Static Synchronous Compensators (STATCOM), for being able to provide both leading and lagging power.

Particularly suitable for high voltage applications are the already mentioned IGBTs. In contrast to MOSFETs or GTO (Gate Turn Off) Thyristors, they are capable of fast repetitive switching, combined with a high collector-emitter voltage. However those switching operations are as well problematic in combination with conventional equipment like transformers.

High frequency, high voltage noise at transformers

A commonly known occurrence of high frequency noise in combination with power transformers is their switching over longer lines. A traveling wave, generated by the switching operation and propagating along the line is the source for the high frequency there. Its influence on the insulation system, mainly oil-cellulose combinations, is only poorly known. In consequence such kind of operation is avoided.

Another appearance of high frequencies at transformers is with the use of voltage sourced converters (VSC) for HVDC applications [1]. A pulse-width modulated switching pattern is used for reproduction of the sine wave at line frequency. In addition to the repetitive pulses with amplitudes of several kV, their large slew rate itself generates high frequencies in the attached equipment. Despite the coupling transformers, reactive elements for equaling the pulses into a sine wave are used there. Intensive filtering of everything above technical frequency (50/60Hz) is not only taking more space, but generating significant losses of the installation.

A similar application as in HVDC transmission are FACTS for dynamic compensation and power-flow control, since VSC converters are central elements there as well [2]. By inducing leading or lagging power on lines, they can stabilize long distance AC lines and enable more transmittable power. In the matter of UPFCs (Unified Power-Flow Converter) it is possible to get a better load balancing throughout the network and to use it to full capacity. Two parallel lines with different power ratings will both be used at their full capacity, without overloading one or derating the other.

All of the above applications have one element in common, since a transformer is included in the circuit. In low power applications, such as motor drives, VSC converters are already commonly used for excitation and therefore this insulation system, e.g. enameled wires, is examined [3, 4, 5]. Yet with increasing power, the intensity of the unwanted noise is rising as well as the used amplitude of the pulses. The insulation systems, subjected to those higher frequency stresses, consist of oil-cellulose combinations, which are mainly used in the design of transformers, contrary to coated wires and thin plastic foils in motors.

If the influence of such high frequency stresses on the insulation system would be known, a significant part of the filtering could be spared. Even the sine-wave generation of the pulses could be done with the coupling transformer, being a reactive element suitable for that task.

High frequency and voltage test signal generation

Vital to the investigation of material properties at high frequencies combined with high voltages (HF-HV) is the generation of such signals. Considerations on that matter reveal easily, that with increasing frequency and amplitude, the energy density is rising as well. Different approaches can be taken to produce the desired signal and handle the power needed.

The easiest way would be a transformer principle, where a low voltage HF signal is converted to the HV one. That concept would require a non neglectable amount of power on the one hand, as well as a suitable core material for the high frequencies. For the latter, only ferrite material can be used, since iron cores cease to work properly at frequencies of several kHz and above. Ferrite itself has significant limitations in its saturation properties. The core for the needed power transfer would be quite large in diameter and both financially and technically extremely difficult to realize. Hence, this possibility could be quickly discarded. Another way of generating HF-HV signals was used in prior investigations, where the low HF voltage was amplified with a tube to the HV level. This could still be done with a radio transmitter for the desired frequencies. Again this can be discarded, due to cost and complexity of the setup.

The third, and in the past often used option [6, 7] is the Tesla-transformer principle. Derived from the original design, where the primary resonance circuit is triggered by a spark gap, switching elements are used for triggering. The benefit of that method is a steady amplitude for the stimulation of the secondary circuit. In the early works, like Goebler [6] and Inge [8], but as well in newer applications [4], tubes were used for those switching operations. Hardt and Scheurer [3, 7] are using power electronic devices (MOSFET) instead. Major advantage of the tubes is the much higher frequencies reachable. They easily allow more than 10MHz for the HV signal, compared to about 500kHz for the MOSFET variant. Faster frequencies, as used in microchips, are not yet reachable with power electronic devices. Connection between the primary and the secondary resonance circuit is done by two air-coupled coils, as suggested by Tesla. Yet the stray capacitances, forming one part of the resonator, are replaced by a plate capacitor or similar device for the specimen.

Disadvantages of this setup can only be seen in the complicated tuning of primary and secondary circuit, both at the same frequency. Similar work has to be done twice. A simple change in the design, replacing the voltage- with an inline current source, has the same effect. The basic schematic for that setup is shown in Fig. 1, together with the excitation of the resonator with a frequency variable inverter.

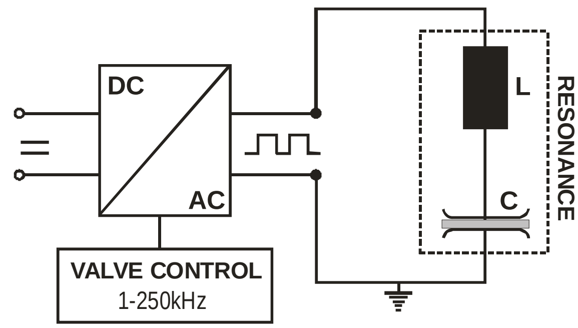

Figure 1 – Schematic of the resonance circuit

Physical tuning only needs to be done with one resonance circuit, by adding capacity in parallel to the specimen or changing the reactor. Later on, the excitation frequency needs to be adjusted for proper correlation. Remaining problems are mainly concerning dielectric strength of the used, not the investigated, insulating materials, as well as losses like corona discharges. Due to high field strengths they are also occurring with all other setups mentioned before.

Since there is no more loose coupling between the generation and the resonating circuit, proper protection of the inverter circuitry needs to be installed. Simulations and tests in that matter showed, that voltage surge protection with suppressor diodes, gate-source resistors as well as additional fast free wheeling diodes are common measures to use. The often suggested snubber networks are not giving positive results, as they prefer fixed frequencies for proper operation. Absorption circuits were installed, to dampen unwanted frequencies, given by resonances of the valve circuitry (mainly stray capacities and reactances). In addition, the current is constantly monitored for immediate shutdown of the inverter when getting to high. A constant amplitude of the HV signal is achieved with a total capacity of 20mF as stabilization of the DC voltage. Improper smoothing results in superposition of the line frequency. With all the above, the secure and constant operation can be assured.

Based on the reliable operation of the source, the oscillatory circuit needs closer examination, given that the reachable amplitude is directly linked to its losses. The latter need to be compensated with the induced power and only a small amount is needed for increasing the resonant oscillation. Primarily the reactor constitutes the largest problem. As seen in Fig.2, the wanted variation of the resonance frequency is accompanied by a counterproductive change in oscillator quality.

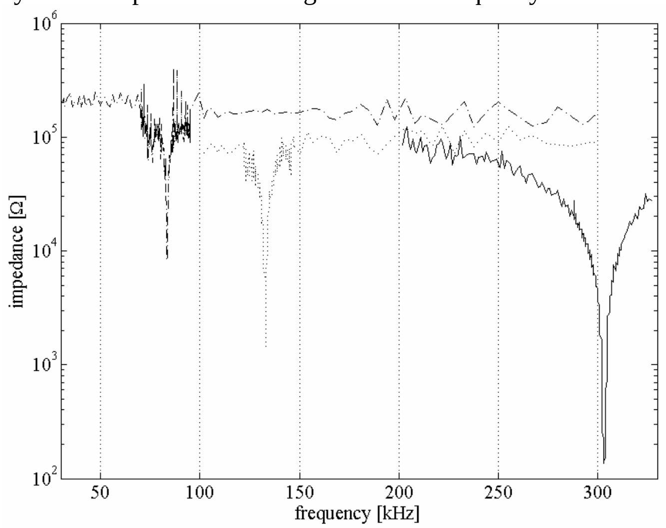

Figure 2 – Resonance circuit impedances with 3 different reactors

The minimum impedance shown in the measured curves must not be taken as an absolute value, since the resolution of the LC measurement device was the limiting factor. Yet the oscillator quality is all the more obvious, shown by the width of the impedance drops. Especially at high frequencies, where the lowest reactance is needed, this is of great importance and seriously limiting the reachable voltage. Either more power needs to be supplied, or the balance between L and C is to be changed with the constraint of the specimen in the capacitor.

Dielectric strength of Oil at high frequency voltages

First investigations are done with mineral oil, being one major part in the insulation system of power transformers. Because basic values, e.g. flashover strength, are not available, they will be observed first. Liquid insulation is hereby posing the least difficulties. An unavoidable Tripelpoint in the conjunction of three elements, electrode, surrounding insulation (e.g. air or oil) and a solid specimen, is equally nonexistent as the superelevation of the electric potential. Latter is generating corona discharges at low voltage amplitudes and hence preventing a further rise and ultimately the flashover.

According to IEC 156:1995 a spherical form of the electrodes is used for measurements. As this setup would gravely limit the quality of the resonance circuit, 57mm plane electrodes with a Rogowski-profile were chosen. The maximum field strength will occur in the homogeneous part of the parallel electrodes.

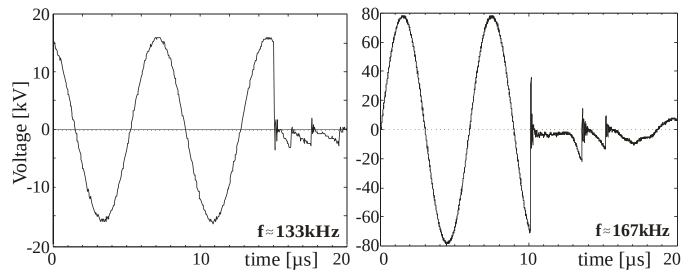

Figure 3 – Flashover in oil with 1mm/133kHz (left) and 7mm/167kHz (right) gap distance

In Fig.3, traces of a flashover at different distances can be seen. A peak strength of 17kV/mm, even extremely humid oil is usually used up to 20kV/mm at 50Hz, suggests a significant frequency dependant drop. Measurements at 7mm result in an even more severe decrease. Linear extrapolation with a factor of 7 would offer 119kV, yet only 77kV peak are possible to achieve. This requires a more detailed look at the comparison between dielectric strength at 50Hz and HF-voltage as shown in Fig. 4. The oil used was ‘Shell Diala D’ with a water content of 16,3ppm.

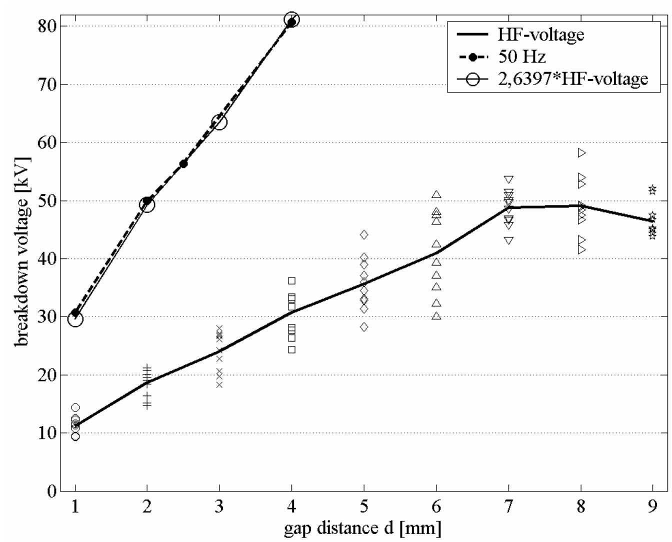

Figure 4 – dielectric strength of oil at 50Hz and HF stress (RMS)

The 50Hz values are the arithmetic mean of 10 Measurements each. For the HF curve, all data is shown to see the dispersion around the average. By pulling the electrodes apart from distance d=1mm to 9mm, the capacity falls and the resonance frequency rises as noted in the following table.

d [mm]	1	2	3	4	5	6	7	8	9
f [kHz]	135	150	157.6	161.6	163.7	166.5	167.8	168.6	170.3

The direct comparison explicitly shows a drop in dielectric strength due to high frequency stress.

There are several differences between the power frequency electrode setup and the HF one. For the reference, the standard test method described in IEC 156 was used. Only the fixed gap distance of 2.5mm was varied. The required accuracy of the rise time could not be achieved for the HF test. The biggest difference in comparison of the two configurations, as already mentioned, is the shape of the electrodes.

Two influences need to be taken into account with the decrease of the flashover strength. Either the frequency or a nonlinearity in the increasing distance is responsible. Multiplying the HF results with factor 2.6397 for fitting the 2.5mm values, shows a congruent shape with the reference. At least between 1mm and 4mm. A linear drop due to frequency is therefore likely.

A further change of the gradient above 7mm gap distance is quite surprising. One suggestion could be that the oil quality dropped significantly after 70 breakdowns, even with stirring between the single shots. Another, that there are still undiscovered problems at the resonance circuit components. According to those speculations the curve progression needs further research.

CONCLUSION AND OUTLOOK

For the dielectric testing of insulating materials, a constant and reliable power source is crucial. Yet building a source according to estimated specifications for breakdown testing is not so easy. An oscillatory circuit principle at resonance frequency with static inverter is chosen for the task. With this setup a maximum amplitude of 80kV at 160kHz is already reached. Major challenge in the design is the reduction of the losses.

The values presented in this report are illustrating a drop of the transformer oil breakdown voltage at high frequency stress, exceeding a bisection of the 50Hz values. If nonlinearities of maximum field strength by distance are present, they already exist at power frequency, derived by the comparison of the two curves after adaption.

Based on the data presented here, tests at different frequencies need to be done to verify the correlation between frequency and flashover strength. Oddities like the change of gradient needs further investigation as well. Apart from liquid insulation systems, solid ones should be investigated. Described problems there need to be abolished. Last but not least the emittable power must be boosted by increasing the quality of the LC-circuit, where reactor design is of major importance.

REFERENCES

[1] CIGRE Working group B4.37 “VSC Transmission”, Report No. 269, April 2005.

[2] Hingorani, N. G., Gyugyi, L. “Understanding FACTS”, IEEE Press New-York, 2000.

[3] Scheuerer, F. “Untersuchungen des Isoliervermögens fester Isolierungen bei Beanspruchung mit hochfrequenten Überspannungen”(in german), TU Darmstadt, PhD Thesis, 1993

[4] Pfeiffer, W. “Dielectric Testing of Solid Insulation with Respect to Insulation Coordination of Low-Voltage Equipment”, IEEE Electrical Insulation Magazine, Vol. 17 No. 3, 2001, pp. 34-47

[5] Guastavino, F., Coletti, G., Torello, E. “Medium Term Aging Characterization of Enamelled Wires for High Frequency Applications”, IEEE Trans. On Dielectrics and Electrical Insulation, Vol. 12 No. 3, 2005

[6] Goebler, E. “Über die dielektrischen Eigenschaften der Luft und einiger fester Isoiermaterialien bei hochgespannter Hochfrequenz”(in german), Arch. f. Elektrotechnik, Vol.14, 1925, pp. 491-510

[7] Hardt, N., Koenig, D. “Testing of insulating materials at high frequencies and high voltage based on the Tesla Transformer principle”, IEEE Intl. Symposium on Electrical Insulation, 1998, pp. 517-520

[8] Inge, L., Walther, A. “Breakdown of solid Insulators at high frequency”(in german), Arch. f. Elektrotechnik, Vol.24, 1928, pp. 209-227

[9] Beyer, M., Boeck, W., Möller, K., Zaengl, W. “Hochspannungstechnik – Theoretische und praktische Grundlagen” (in german), Springer, Berlin, 1986