CAN FERRITE MATERIALS OR RESONANT ARRANGEMENTS REDUCE THE AMPLITUDES OF VFTO IN GIS?

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Abstract: Very Fast Transient Overvoltages (VFTOs) in high voltage Gas Insulated Switchgears (GIS) are an undesired phenomenon which causes several problems in insulation systems and connected high voltage equipment. Therefore a reliable and basic solution of VFTO mitigation is of high interest. In order to investigate different damping solutions, a high voltage test setup which enables amplitudes of VFTOs up to 800 kV and more is introduced. Also two possible damping solutions were investigated: First, VFTO suppressing by means of ferrite materials was analysed under high voltage conditions. Different ferrite materials were tested. The second approach is a high-frequency resonator which is placed inside the GIS. It gets stimulated by the VFTOs and due to a special resonator termination the VFTO energy is dissipated. The high voltage test setup and the investigation results of both possible damping solutions are presented in this paper.

1 INTRODUCTION

Very Fast Transient Overvoltages (VFTOs) in high voltage Gas Insulated Switchgears (GIS) are electromagnetic waves propagating along the GIS. Due to an instantaneous change of voltage inside the GIS VFTOs get initiated. The main reason for VFTOs in practice is a disconnector switching operation where steep voltage drops occur several times within a closing or opening operation. As the VFTOs get multiply reflected at each GIS termination, VFTOs have a non-harmonic time dependence and cover a wide frequency range from 100 kHz to 100 MHz. The amplitude of VFTO can reach up to 3 times the phase-to-earth voltage and raise time is in a range of few ns [1],[2].

Therefore VFTOs can cause a high stress for the insulation system of GIS and other directly connected high voltage equipment. The risk of an insulation fault caused by VFTOs raises for 420 kV and higher system voltage levels. Presently, VFTOs are a limiting constraint for the dielectric design of ultra high voltage (UHV) GIS. Therefore a reliable and basic solution of VFTO mitigation is of great interest.

Disconnector switches in UHV GIS are already equipped with a series resistor [3]. Unfortunately, a high effort on technical and electrical design of resistor fitted disconnector switches is necessary. Therefore cost and maintenance of disconnector switches is much higher compared to conventional disconnector switches.

The aim of the presented work is to develop a very reliable and basic solution of VFTO suppression. Therefore a special test setup was designed and a suitable measurement system was installed. This setup enables investigations and measurements under high voltage conditions. In this paper the high voltage test setup and results of two different VFTO mitigation solutions will be presented: (a) investigation of mitigation potential of ferrite ring cores in a GIS and (b) development of a special designed electromagnetic radio-frequency (RF) resonator inside the GIS. As (a) was already discussed manifold [4], [5], (b) is a pretty new approach.

2 EXPERIMENTAL SETUP

The experimental setup enables high voltage tests with different mitigation solutions. Special capacitive sensors ensure correct measurement results.

2.1 High voltage test setup

The high voltage test setup consists mainly of a 550 kV GIS from ABB type ELK-3. A schematic diagram is shown in figure 1. The VFTOs are generated by a breakdown between the spark gap inside the GIS. For this purpose a standard high voltage impulse generator feeds a surge voltage via a bushing to the inner conductor of the GIS. By means of a spark gap the inner conductor is separated into two parts. The spark gap consists of two spherical electrodes and is situated in SF_6 atmosphere. As the surge voltage reaches the breakdown voltage of the spark gap, a sparkover occurs between the contacts and initiates the VFTOs. By means of the SF_6 pressure, it is possible to control the breakdown voltage of the spark gap and thereby the amplitude of VFTOs as well. The end of the inner conductor is connected with two cupper strips to the enclosure and ground. Thus it forms a shorted termination and the transient voltage waves are reflected by a negative factor close to -1. In a test vessel with a third orifice and flexible inner conductor different testing objects (e.g. ferrite rings and resonator) could easily be installed. On both sides of the test vessel capacitive voltage sensors are mounted in a flange of the GIS enclosure and enable very accurate measurement. The testing arrangement is presented in figure 2.

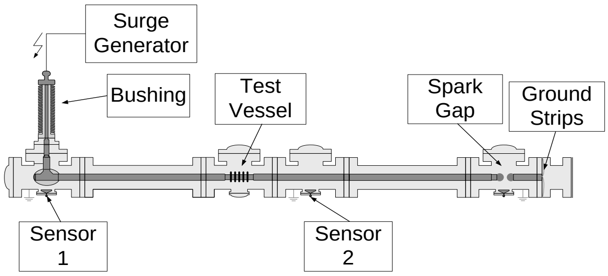

Figure 1: Schematic diagram of high voltage test setup: GIS with spark gap, capacitive voltage sensors and a flexible test vessel for different test installations

Figure 2: The high voltage test setup in the laboratory of University of Stuttgart: ABB 550 kV GIS type ELK-3 with bushing

By means of this setup it is possible to generate VFTOs with an amplitude up to 800 kV and more. This depends on the SF_6 pressure and the distance between the spherical contacts of the spark gap. The dominant harmonic component of the VFTO frequency spectrum is approximately 7.5 MHz and is related to the total length of the GIS.

2.2 Voltage measurement system

For a precise measurement of these VFTOs two capacitive voltage sensors were built up and mounted inside the GIS. The sensors consist mainly of a double layer board and are presented in figure 3. The layer facing to the grounded GIS enclosure is connected to the enclosure by the flange and a copper RF-seal directly. The second layer forms a capacitance as well to the grounded layer as to the inner conductor of the GIS. So a high frequent capacitive voltage divider is arranged with a divider ratio of some 10 000. The top layer is connected to a BNC-connector outside the GIS flange where the divided VFTO voltage can be measured by an oscilloscope.

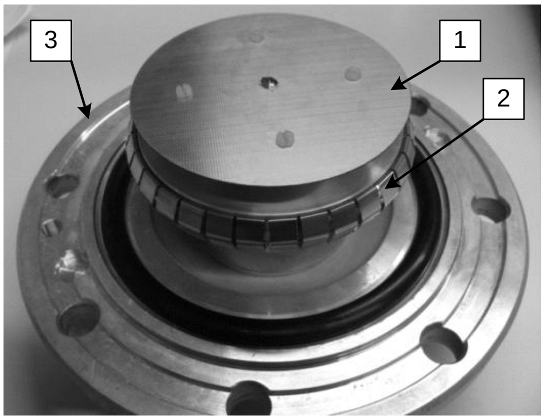

Figure 3: The capacitive sensor which was made at University of Stuttgart: It consists mainly of a double layer board (1) which forms a capacitive voltage divider. The board and a copper RF-seal (2) are mounted on a flange cap (3).

The signals of the Sensors are recorded by an Oscilloscope (LeCroy waveRunner 104 MXi, used Bandwidth: 200 MHz). Before analyzing the results, always 10 signals were superimposed to avoid impacts caused by small variation of the breakdown voltage. The frequency spectrum of the results is computed by a Fast Fourier Transformation with Matlab.

3 FERRITE MATERIAL FOR VFTO DAMPING

Ferrite rings around the inner conductor for VFTO damping were already investigated and results are presented e.g. in [4]. In the majority of cases ferrite rings were tested in low voltage setups or simulations of their behaviour under influence of VFTOs were carried out. The results of these investigations show at least a slight VFTO mitigation. In this chapter the result of tests with different ferrite rings and ferrite arrangements in a high voltage setup will be discussed. Therefore the rings were located inside the test vessel and VFTOs were generated as described in the previous chapter.

3.1 Test with ferrite rings

Rings of different ferrite materials were investigated and the number of rings inside the GIS was variegated from 1 to 6 rings. The rings had either an inner diameter of about 10.4 cm, were 1.7 cm thick and had a length of 2.6 cm or had an inner diameter of about 1.5 cm, were 2.4 cm thick and had a length of 2.5 cm. A smaller ring with an inner radius of 4.5 cm, thickness of 1.5 cm and length of 2.6 cm was also used. The used rings are presented in figure 4. For the tests VFTOs with an amplitude up to 800 kV were used.

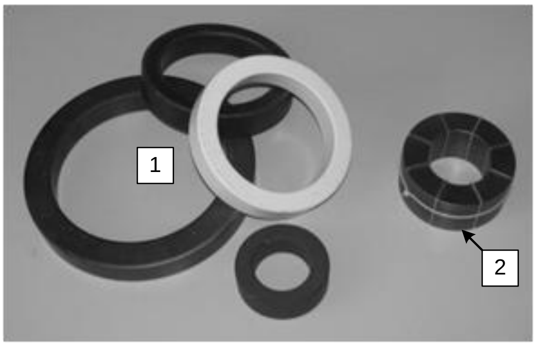

Figure 4: Different kind of ferrite rings (1) and a sheared ferrite ring arrangement with gaps of epoxy resin (2)

All measurements show no mitigation of VFTOs. For example the result of a measurement with 6 rings and VFTOs with an amplitude of 700 kV is presented in figure 5. It is compared to a measurement without ferrite rings.

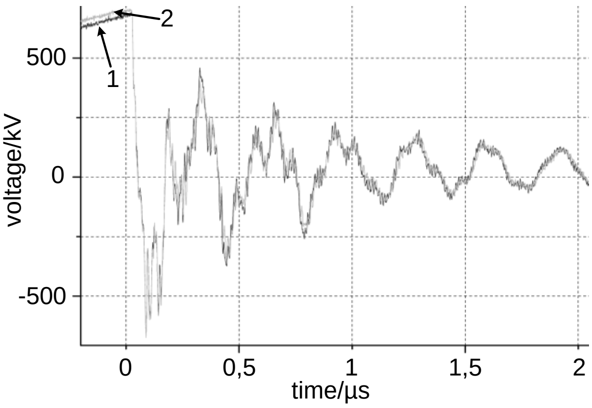

Figure 5: Comparison of VFTOs with a maximum amplitude of about 700 kV: The darker line represent VFTOs without rings (1). VFTOs with 6 ferrite rings are drawn in the brighter colour (2). No damping is visible.

In comparison to most previous studies the resulting current through the rings is much higher and equals real currents of VFTOs in a GIS. The impedance of the GIS setup is approximately 70 Ω. Therefore VFTOs with an amplitude of 700 kV lead to a current of about 10 kA. Thus, the intensity of the magnetic field around the conductor is also very high. If a current of this amplitude flows through a ferrite ring, the high magnetic field saturates the ferrite material completely. The results of these measurements demonstrate clearly that a saturated ferrite ring cannot suppress VFTOs.

3.2 Test with ferrite arrangements

A possibility of reducing the effective magnetic field intensity in a ferrite ring is an insertion of gaps with lower permeability in the ring. Through the so called shearing of ferrite rings, the magnetic field strength which saturates the material could be increased. But shearing the rings with a material of lower permeability reduces the effective permeability too. Therefore, the damping efficiency of the whole ring arrangement decreases. Figure 4 shows a sheared arrangement of ferrite segments with plates of epoxy resin as known from conductor boards. Test with this ring arrangement however show no VFTO suppressing effect.

In summary the investigation of ferrite materials results in no mitigation of VFTOs. The reason of this is the high current of VFTOs which causes a completely saturation of the ferrite material. Saturated ferrite material loses its damping ability and can thus not suppress any VFTOs.

4 RF RESONATOR FOR VFTO DAMPING

A new approach for mitigation of VFTOs is a compact electromagnetic RF resonator with optimised quality factor (Q). The resonator is installed inside the GIS and gets stimulated by the VFTOs. For example, a cavity of an electric shielding could serve as a resonator. The novelty of this idea is not only the design of the low Q resonator. Also the dissipating of the received VFTO energy must be investigated.

4.1 RF resonator design

For basic investigations a resonator around the inner conductor was built as it is shown in figure 6. It is a tube which is connected to the inner conductor on one side. The other side forms a thin, but long gap between resonator and inner conductor.

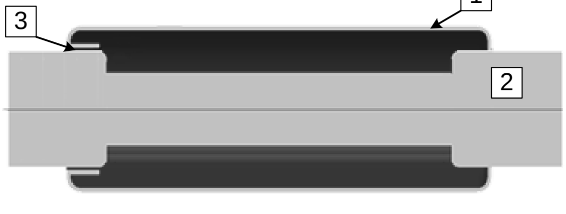

Figure 6: The resonator (1) around the inner conductor of the GIS (2) with a long gap between resonator and conductor (3)

The resonant frequency of the resonator is about 57 MHz. This was determined by a special arrangement, which enables a measurement of the voltage in the gap between resonator and inner conductor (figure 7). Therefore the resonator was mounted in a test vessel with cones on each side. On one side of the test arrangement a terminating impedance was placed so that reflection was avoided. On the other side a waveform generator was connected via a BNC plug to the inner conductor of the test vessel. The output of the waveform generator was a sinusoidal signal with an amplitude of 10 V. By steps of 1 MHz the frequency of the signal was shifted from 1 MHz up to 100 MHz. A third orifice of the test vessel allowed direct access to the resonator. So the voltage in the gap between resonator and inner conductor could be measured by a special kind of field probe made by University of Stuttgart.

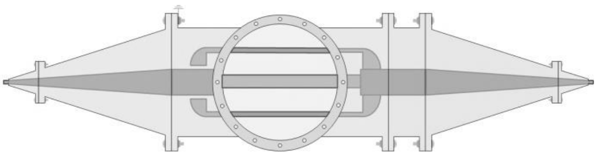

Figure 7: The test vessel with cones in each side and the mounted resonator on the inner conductor

Figure 8 shows the gap voltage measured by the field probe. It changes as a function of the signal frequency. As the amplitude of the input signal is constant, the resonant frequency of this resonator is achieved at 57 MHz when the gap voltage reaches its maximum.

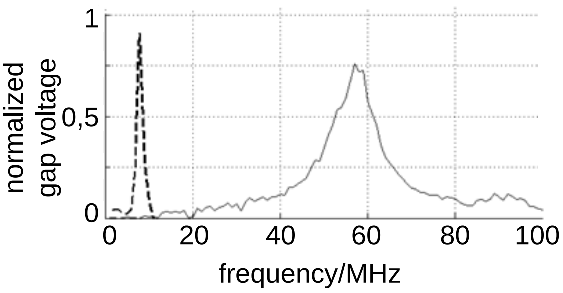

Figure 8: Gap voltage measured by a field probe as a function of frequency: Resonator without external capacitor parallel to the gap (grey curve) and Resonator with 5 nF capacitor parallel to the gap (dashed curve)

The VFTO frequency spectrum of the GIS is a function of the GIS length and termination. As the dominant harmonic component of the used test setup is about 7.5 MHz, it is an inherent difference between the resonant frequency of the resonator and the dominant harmonic of the test setup. For an effective mitigation, both frequencies should equal each other as much as possible. Therefore the resonator has to be adjusted.

It is possible to describe the resonator as a parallel resonant circuit. So the resonant frequency of the resonator is a function of its inductance and capacitance:

$$f=\frac{1}{2\pi\sqrt{LC}} \tag{1}$$

While the gap between resonator and inner conductor forms the capacitance of the resonant circuit, the cavity of the resonator represents the inductance. An increase of one or both parameters leads to a reduced resonant frequency of the resonator. To increase the values of these parameters, several approaches were investigated and are listed in table 1. All test with these modifications and combinations of them results in a lower resonant frequency of the resonator.

Increase in Capacitance		
Dimension of gap		Dielectric properties of gap
Extension of gap length	*Reduction of gap width*	*Increased permittivity of dielectric medium*
Increase in Inductance		
Dimension of cavity	Magnetic properties of cavity	
Extension of cavity volume	*Increased permeability of cavity*	

Table 1: Different approaches for modifying the resonance frequency of the RF resonator

To reach an equality of the resonant frequency of the resonator and the dominant harmonic component of the VFTO frequency spectrum, a simplification was done for the first laboratory tests: The capacitance of the gap between resonator and inner conductor was increased by an additional external capacitor. It was connected parallel to the gap as shown in figure 9. Finally, an external capacitance of 5 nF leads to a maximum of gap voltage at about 7.5 MHz. The gap voltage of the resonator with a 5 nF termination is shown as a function of the signal frequency in figure 8.

In summary it can be concluded, that it is possible to achieve a designated resonant frequency of the resonator with a certain design of the cavity and the gap. For further tests the resonant frequency was adjusted by the external capacitor.

4.2 Dissipation of Energy

For an ideal stimulation of the resonator by the VFTOs, the resonant frequency of the resonator and the dominant harmonic component of the VFTO frequency spectrum should have almost the same value. In this case a significant share of the energy of the VFTO is stored in the resonator. By dissipating the energy of the resonator a mitigation of VFTO will be achieved. Therefore different possibilities were investigated:

(I) Flash over: The impedance of an electric arc is in the range of some few Ohm. If the voltage in the gap between resonator and inner conductor of GIS is high enough, a flash over occurs and the electric arc could dissipate the energy. The gap distance during the tests was 5 mm.

(II) Resistive layer: A resistive layer in the gap between resonator and inner conductor could dissipate the energy. For the tests a resistor parallel to the gap replaced the layer. The testing setup is shown in figure 9.

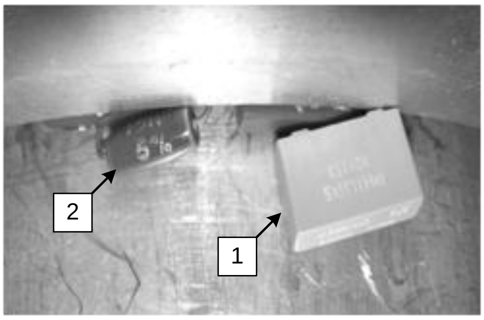

Figure 9: The capacitor (1) and resistor (2) connected parallel to the gap between resonator and inner conductor of GIS

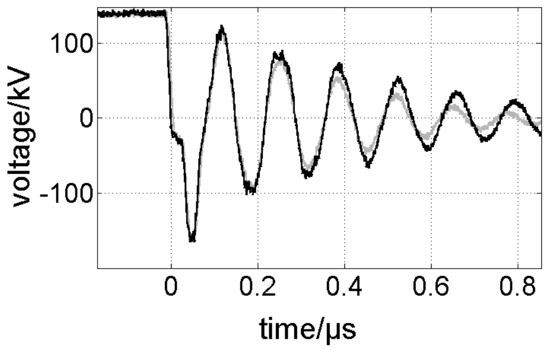

Figure 10: Comparison of VFTOs in a GIS with a resistor fitted resonator (grey line) vs. a GIS without a resonator (black line). Slight damping is visible.

The results of both tests are quite different. While no VFTO damping was measured during test (I) the results of test (II) show a slight mitigation as presented in figure 10. Different quantities of the gap resistor were tested. The major mitigation effect could be achieved with a resistor that equals the characteristic impedance of the resonator. One handicap of this solution is the first VFTO peak. This peak could not be damped as the stimulating and dissipating process take some time.

5 CONCLUSION

The high voltage GIS test setup was developed in order to investigate different VFTO mitigation techniques. VFTOs with an amplitude up to 800 kV were generated. Special designed capacitive sensors ensure an exact voltage measurement.

Mitigation of VFTOs by means of ferrite materials is not practicable in high voltage GIS. The current of VFTOs causes saturation of the ferrite materials. Thus, the damping effect of ferrite materials under the influence of VFTOs is negligible.

RF resonators inside the GIS are able to damp VFTOs. Unfortunately, the first peak is not mitigated. The resonant frequency of the resonator must be in the range of the dominant harmonic component of the VFTO spectrum. By means of a special resonator design the resonant frequency of the resonator is adjustable. Also a certain termination of the resonator is necessary.

6 ACKNOWLEDGMENTS

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