Comparison between suppressing approaches of very fast transient over voltages in gas insulated substation

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Abstract. Very Fast Transient Over-Voltage (VFTO), which is a unique electromagnetic transient phenomenon generated by SF6 gas discharge in disconnector gap in Gas Insulated-Substation (GIS), could bring damage to power devices, especially to power transformers. The peak magnitude and high-frequency oscillations of VFTO cause reduction of dielectric of gas insulation, high inter-turn voltages and internal resonance in the transformer windings. Due to all of these disadvantages related to VFTO, VFTO becomes a criterion to determine the insulation level of the GIS, and VFTO damping is rising as an essential issue to be solved. However, the researchers concern on finding the optimum technique for suppressing VFTO, this paper aims to discuss the most feasible methods for mitigation of the overvoltage magnitude of VFTO and determine the most efficient approach for VFTOs attenuation by presenting the advantages and disadvantages of each approach. In this review paper, some suppression methods of very fast transients in GIS are presented, including adopting a resistor-fitted disconnector, ferrite rings, surge arresters, and high-frequency resonator. The results show that the peak value of VFTOs can be decreased to a great level by employing the proposed damping methods. Finally, the best approach for the suppression of VFTOs is chosen based on deep discussion for each method with its features.

1. Introduction

Gas Insulated Switchgear is considered very credible component of electrical power networks because the space needed for GIS is much less than it is for an Air Insulated-Switchgear (AIS) [1], also requires less maintenance effort and sulfur hexafluoride is employed as an insulation medium in GIS system. VFTO is generated by disconnector operations during switching of small capacitive currents due to the repetition of restriking between the disconnector contacts, because the operating speed of disconnector is relatively slow compared with a circuit breaker. Thus, the maximum overvoltage is up to 3 p.u. High amplitude and steepness VFTOs are formed by reflection and superimposition of the travelling waves in GIS. However, suppression of the VFTO is a long-standing problem, with many suggestions of solving it. Some of those include avoiding undesirable layouts of the GIS, as well as dangerous operation procedures with the disconnector switches. However, this has a consequence of imposing significant limitations on the design and the control operation of the GIS. The travelling wave nature of VFTO leads to model GIS elements as electrical equivalent circuits composed of distributed parameter lines (surge impedance, traveling wave velocity) as well as lumped elements. Thus, any change in the surge impedance leads to reflection and refraction of travelling waves. In addition, the disconnector opening and closing operation lead to high amplitude waves to propagate
during GIS. So design and control operations of GIS are classified as another way to avoid VFTO. Don’t forget a critical parameter which is speed disconnector, precisely high-speed one.

Once the electric field between two contacts of disconnector switch (DS) exceeds its normal value through the closing operation, sparking occurs. Consequently, current will charge the capacitive load to the source voltage during its flow through the spark. When this occurs, the spark will extinguish due to the potential difference falls [2]. Two types of VFTO occur in GIS: internal and external modes. Internal transients lead to over-voltages between the inner conductor and the enclosure, while stress on secondary and adjacent equipment can be caused by external transients. Moreover, high stress of the insulation system is a result of internal VFTO [3], [4]. However, multiple reflections and refractions can increase travelling voltages and very high oscillations occur. Thus, in this paper, some approaches are discussed:

- Suppression of VFTO in GIS by adopting resistor-fitted disconnector.
- Rings of different ferrite materials to attenuate VFTO in various installations.
- Inductive arrangement with surge arresters to limit the effect of VFTO.
- High frequency RF resonator for VFTO damping.

2. Mitigation methods
The serious VFTO has many effects on the GIS equipment like the insulation of GIS, and the inter-turn insulation of transformer can be damaged. Transient enclosure voltage (TEV) and electromagnetic interference (EMI), which lead to failure of control circuits connected to GIS can be produced [5]. Flashover to ground at the disconnector switch contacts is a problem associated with the VFTO. It is worth noting that the dielectric strength is decreased under VFTO, if non-uniform electric field is formed because of particles (mainly metallic). As well, GIS components such as bushing and transformer have an impact. The wave shape of the very fast transient over-voltages and the associated Very Fast Transient Currents (VFTCs) lead to these problems during switching operations in GIS [6]. All of these problems make the damping of VFTO required.

2.1. Suppression of VFTO in GIS by adopting resistor-fitted disconnector
The resistor-fitted disconnector has a resistor which is connected in series with the circuit in the event of restriking, and the purpose of this design is no mechanical contacts to connect the resistor but only a movable electrode [7], [8]. However, inserting the resistor into a discharge path, where the gap between electrodes is long, and discharge voltage is high, is the principle to suppress the over-voltage. Thus, because of the high-frequency components of VFTO, most of the GIS has been simulated as capacitances dominating the other parameters. Distributed parameters and lumped elements can be used to model GIS bus duct. Surge impedances, wave velocity and lengths of GIS section define that the physical dimensions of the duct are an important factor to calculate these parameters. Over-voltage was calculated when the voltage at the load side and power side have the same value with different signal (-1.0 p.u., +1.0 p.u.), where restriking occurred.

Figure 1 shows typical results of VFTO analysis for DS operations without a switching resistor for a 1100 kV hybrid GIS planned in China. The peak value of the VFTO is 2.7 p.u. for a full GIS and Figure 1(b) shows typical results of VFTO for DS operations with a switching resistor (500 Ω), which can decrease VFTO to less than 1.2 p.u. [9]. In China, the VFTO was estimated at the 1100 kV Jindongnan GIS substation, and it was confirmed that the optimal resistance is about 500-700 Ω in parallel [10]. Thus, it can be concluded that:

- If the resistance is 1 KΩ, these over-voltages can be suppressed to about 1.25 p.u.
- Over-voltages can be suppressed to about 1.2 p.u.by using resistance with a value of 500 Ω.

2.1.1. Discussion. The VFTO can be successfully suppressed in 1100 kV by using a resistor-fitted DS but this method has some disadvantages like:

- Energy dissipation requirements for the resistor are very high.
• Increase of the disconnector complication (reliability and maintenance requirements), and special testing requirements which cost too much. The resistor for DS switching needs unique demands on its dielectric and thermal ability.
• The operating speed of DS is relatively slow (2-3m/s even in case of GIS DS) which means no ability of arc extinction, and this nanoseconds arc duration leads to reduce the lifetime of the contactor.

![Figure 1](image1.png)

**Figure 1.** Typical VFTO waveform due to DS operation (a) without a closing resistor (b) with a parallel resistor (R = 500Ω) [9].

2.2. Ferrite rings for VFTO damping
Magnetic cores of various types, sizes, and material properties have an impact on VFTO attenuation. Species like ferrite, amorphous and nanocrystalline [11], [12] are discussed in this paper. The rings of a nanocrystalline alloy, placed around the inner conductor of the GIS, have very high values of the permeability and the saturation flux density. Figure 2 indicates the high voltage test setup which is mainly 550kV GIS from ABB type ELK-3. The VFTOs in the GIS are generated by a breakdown between the spark gap filled with SF6 gas, the test set-up introduced in measuring VFTO damping consists of high voltage impulse generator to supply Lightning Impulse Voltage (LIV) 1.2/50 µs to the AIS-GIS bushing. Each breakdown in SF6 spark gap initiated VFTO propagation in the GIS components. Full-scale VFTO measurements were carried out for two options of VFTO attenuation: the new nanoflakes material, and the standard nanocrystalline cores [13], [14].

![Figure 2](image2.png)

**Figure 2.** Schematic graph of the high voltage test setup, 550kV GIS [11]-[13].

Test about the effect of the number of nanocrystalline alloy rings on the damping effect was carried out and obviously showed that the damping effect for eight rings better than three rings as shown in Figure 3(a). The main rate of VFTO damping is about 20%, which has been noticed at the first peak by using eight rings. The effect of permeability of the used ring is an important factor on VFTO attenuation. It can be concluded, as shown in Figure 3, the following qualitative results:
• More rings lead to increase the damping effect. The relation is almost linear.
• The damping effect is increased by a higher permeability.

![Figure 3](image1.png)

**Figure 3.** VFTO measured on sensor 2 (Figure 2), (a) comparison between the number of rings, (b) comparison between permeability of rings [12].

Another procedure was done to understand the effect of the new material on VFTO. The mitigation effect was measured for two GIS configurations, with open and grounded end, characterized in different VFTO main frequency components: 15 MHz and 7.5 MHz respectively, as illustrated in Figure 4. Figure 4 illustrates the VFTO attenuation (first peak) for new nanoflakes material, for 8 magnetic cores and without magnetic material (reference). Consequently, it is clear that the VFTO attenuation is achieved by using this new nanoflakes material for two GIS arrangements.

![Figure 4](image2.png)

**Figure 4.** VFTO for different magnetic material for 500 kV at sensor 2 (Figure 2), (a) GIS with an open end at 15 MHz, (b) GIS with the grounded end at 7.5 MHz [13].

Furthermore, avoiding the local dielectric overstress is required by finding a convenient place for rings. Results show that the highest maximum attenuation is achieved, where distances between rings are modelled by adding a short section of transmission line of surge impedance. The aim of the distances between rings is to reduce the discontinuity of the surge impedance, also these distances have an effect on the effective transmission and reflection coefficients from rings.

**2.2.1. Discussion.** Increase the number of rings with nanocrystalline material leads to increase the damping effect as shown in Figure 3(a). The high current of VFTOs causes a fully saturation of the ferrite material which loses its damping capability. Thus, by layering of ferrite rings it is possible to increase the magnetic field strength at which the material saturates. However, layering with a material
of lower permeability also reduces the effective permeability. Better damping is achieved by using rings with higher permeability (see Figure 3(b)). That means, mitigation effect can be increased by development ferrite material properties as shown in Figure 4.

2.3. Inductive arrangement with surge arresters
A spiral slotted part of a GIS conductor is employed as a small inductance. In this method, these arresters are connected to both sides of the inductance and installed inside the conductor parallel to the spiral slotted component. Reference [15] illustrates deeply the theoretical consideration and test results. Figure 5(a) explains this arrangement and Figure 5(b) illustrates the equivalent circuit of this arrangement, which is an inductance and resistance.

![Figure 5](image)

**Figure 5.** The inductive arrangement with surge arresters, (a) schematic graph of an inductive arrangement, (b) the equivalent circuit of the arrangement [15].

As shown in Figure 5(b), $U_i$ is a voltage drop across this inductance because of high-frequency components of VFTO and $U_r$ is the residual voltage of the entire surge arrester stack which is determined by the number of arrester discs. The impedance of the inductance has no serious value in the low-frequency range and no losses are generated. When the voltage drop across this arrangement $U_i$ surpasses the residual voltage $U_r$, the arrester becomes conductive and current flows through it. Consequently, energy is absorbed by the surge arresters and the VFTOs are damped. The results of tests with one, five, nine arresters and measurement without the arrester stack are compared in Figure 6. The residual voltage of each disk is $21\,\text{kV}$. $U_r = n, U_{r+1}\,\text{kV}$ is a residual voltage of a stack of $n$ discs, where each disc has a residual voltage $U_{r+1}$. Obviously, the mitigation effect is related to the residual voltage $U_r$ of the arrester stack. Lower damping during the first 100 ns is achieved when residual voltage has a less value (dark gray line). Better damping during the first 100 ns is achieved by using more discs with a high value of residual voltage (light gray line).

![Figure 6](image)

**Figure 6.** VFTO measured on sensor 2(Figure 2) with and without installation arrester stacks (black dashed line). The residual voltage of the stacks is $21\,\text{kV}$ (dark grey line), $105\,\text{kV}$ (black line), and $189\,\text{kV}$ (light grey line) [15].
2.3.1. Discussion. The difficulty in this approach is finding out and installing the optimum number of arrester discs which are suitable to the inductance of the slotted conductor. In addition, no flashovers across the slots are allowable by achieving an adequate slot width and high SF6 pressure. Finally, results imply that the conductor must be designed with an inductance of at least some μH and should cover ampacity requirements.

2.4. High frequency RF resonator for VFTO damping
By using several shielding parts of different sizes and at various locations inside a GIS, the electric field is being smoothed like the shielding around the energized parts of a disconnector switch. These shieldings could be formed as a matched RF resonator with a particular resonant frequency as shown in Figure 7. First, we have to adjust the shielding to a compact electromagnetic Matched Radio-Frequency (MRF) resonator. This adjustment could lead RF to be stimulated by the VFTO.

Our task is to shape these shieldings as an identical RF resonator with a particular resonant frequency. Actually, matching the resonance frequency of High-Frequency (HF) resonators with the dominant frequency component of the VFT wave determines the damping ability of HF resonators [16], [17].

![Figure 7. Schematic graph of the resonator in GIS, (b) schematic diagram of the resistor between the resonator and GIS [15].](image)

The main idea is that matching between the frequency of the resonator and high frequency component of the VFTO, where the resonator is induced by the VFTO and energy is cached in the resonator. The VFTO is damped when the resistance in the resonant circuit absorbs the energy. Optimum mitigation could be achieved by an ideal value for this resistor. Where the cavity, placed in front of the gap of the resonator, was filled up with water of a changeable salt content. Changing the salt content could lead to adjust the resulting resistance easily. Consequently, higher damping effect is achieved by higher resistances as illustrated in Figure 8(a). This approach proved that the damping effect of the resonator by measurements in which the ratio of the VFTOs amplitude reduction is 20-30% [12]. In addition, VFTOs generated by circuit-breakers or earthing switches which can cause VFTO could be suppressed by the resonators.

2.4.1 Discussion. Actually, the disadvantage of this approach, which reduces the efficiency of this method, is no observed damping when resonant frequency of the resonator doesn’t fit the dominant harmonic component of the VFTO as appeared obviously in Figure 8(b) which compares the VFTO at 7.5 MHz with different resistors (8 and 52) on the resonator gap and a bridged gap, but the resonance frequency of the resonator is still 15MHz. Furthermore, the resistor across the gap is considered as a
crucial factor in damping VFTO because breakdowns occur on the gap when its value is too high. Subsequently, the gap gets bridged, and the mitigation effect gets lost. On the other hand, small resistors cause only small damping.

![Figure 8. VFTO measured on sensor 2(Figure 2), (a) comparison with a resonator ending of different values of resistors and the reference measurement with a bridged resonator with a prevailing harmonic frequency of 15 MHz, (b) with a prevailing harmonic frequency of 7.5 MHz [12],[15].](image)

3. Summary

Different mitigation methods are known for different sources of VFTO and various equipment. Reduction of the VFTO up to 25 % was provided by integration of a damping resistor. Moreover, by using other internal damping measures, it would be possible to overcome the drawbacks of such an impractical design. So a resistor with suitable design could be used to absorb the transient energy produced by remaining charge on the main contact of DS. However, test results applied to a 1100 kV confirmed that the VFTO maximum magnitude could be reduced from 2.88 p.u. to 1.5 p.u., when the resistance is 200Ω. The suppression rate increases to 60%, i.e. VFTO could be suppressed to 1.25 p.u. by paralleling a 1kΩ resistance. Actually, changes in construction of DS in GIS are probably needed, which makes this method complicated and expensive with low reliability. Furthermore, an electromagnetic high-frequency resonator with low-quality factor was implemented for damping VFTO, which was specially designed to cover a wider frequency range. Designing the resonators and dissipating the received VFTO energy make this idea as a unique one. That cavity filled with water of a changeable salt content around GIS central conductor is represented as L and a SF6 gap at the end of this cavity is represented as C. Simulation and experimental study confirmed that the ability of this method to decrease the energy of VFTO surge about 20% and mitigating the dominant frequency about 60%. Although this method is classified as a suitable method in damping high frequencies of VFTO, it can’t damp the first peak of VFTO and also it is difficult to adjust the resonant frequencies by changing the dimensions of cavity and SF6 gap.

Finally, nanocrystalline rings were placed around the GIS conductor, which form a paralleled nonlinear resistance and inductance circuit connected in series with the main GIS conductor. These rings lead to a significant mitigation effect (10 - 30 %), even the amplitude of the first peaks was significantly reduced by 20 %. Depending on the number, material type and size of the rings, good results could be achieved.

4. Conclusions

Several techniques are used to decrease the harmful effects of VFTO. The important techniques were studied in this review paper to illustrate the suitable method for suppressing the VFTO. In addition to a theoretical consideration, the advantages and disadvantages of each approach were presented. In the
first concept, the resistor-fitted disconnector with 25% mitigation effect is considered as a proven method except for some difficulties related to its design.

Furthermore, an essential mitigation effect is achieved by adding nanocrystalline rings. The rings were placed on the inner conductor of the GIS. It was clear that the first amplitude of the VFTO was mitigated up to 30% and all further peaks were almost damped completely. Using more rings can lead to increase the damping effect. An improved damping is achieved by high permeability and low diameter of the rings. The mitigation effect increases approximately in a linear way with the number of rings arranged around the GIS conductor. Another concept showed that the shielding parts inside the GIS could serve as a RF resonator with 20% mitigation effect. Finally, an inductive arrangement with surge arresters leads to a good damping effect. In summing up all references, all suppressing methods could damp VFTO in GIS. The choice of the best method depends on the application area and targets. However, the rings with a particular type of ferrite materials such as (Nanocrystalline or Nanoflakes), taking into account the number of rings, their characteristics, a suitable place and the arrangement of the rings, could achieve an optimal damping effect of VFTO.

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