Research Article

Study on Very Fast Transient Overvoltage Characteristics of Gas-Insulated Switchgear Substation Based on Hybrid Reactive Power Compensation

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In recent years, gas-insulated switchgear (GIS) substations have become widely used in power systems. Due to their compact structure, extremely high oscillation frequencies are prone to extremely high oscillation transient overvoltages or very fast transient overvoltages (VFTOs) when the isolating switch or circuit breaker is operated. The characteristics of these special fast transient processes in GIS and the effect of hybrid reactive power compensation (HRPC) on these fast transient processes were studied. A simulation of the GIS model was established, and based on the transient model of HRPC and the theory of the transmission line, the effects of VFTO produced by HRPC switching operation and the parameters of HRPC on VFTO were studied and the differences in the characteristics of VFTOs in substations with or without HRPC. Based on the conclusions of our study on the influence of HRPC on VFTO, the inhibitory effects of a ferrite magnet ring and an inhibitor busbar on VFTO were verified.

1. Introduction

With the advantages of large transmission capacity, wide coverage, and low losses, ultrahigh-voltage (UHV) AC transmission can solve the problem of uneven energy distribution effectively over a large scale, but it also brings a series of new problems related to current distribution and reactive power. Hybrid reactive power compensation (HRPC), consisting of series compensation (SC) and a stepped controlled shunt reactor (SCSR), can take into account the requirements of UHV transmission for both increasing transmission power and flexibly regulating reactive power, and this method is expected to be popularized and applied in UHV AC transmission projects. Due to increases in voltage levels, the problems resulting from operational VFTOs are becoming ever more serious, so it is important to study the VFTO process inside UHV gas-insulated switchgear (GIS) substations.

Many research institutions have carried out studies on the VFTO generation process and its characteristics. In particular, great progress has been made on VFTO simulation and calculations. For example, references [1–5] studied the characteristics of simulated VFTOs in different switching arc models and compared them with the actual measurements of VFTO waveforms in order to verify the rationality of different switch arc models. The study makes the calculated results for VFTO simulations more compatible with the actual measurements of VFTO waveforms in order to verify the rationality of different switch arc models. The study makes the calculated results for VFTO simulations more compatible with the actual measurements of VFTO waveforms in order to verify the rationality of different switch arc models. The study makes the calculated results for VFTO simulations more compatible with the actual measurements of VFTO waveforms in order to verify the rationality of different switch arc models. The study makes the calculated results for VFTO simulations more compatible with the actual measurements of VFTO waveforms in order to verify the rationality of different switch arc models.
references [11–14], which is a relatively novel VFTO inhibition measure. This method also provides a broader way of studying VFTO inhibition methods in future.

Most of the existing studies only focused on the generation of VFTO in the substation and its impact on different equipment, but the impact on VFTO brought by HRPC is less. Research on VFTO phenomenon has generally been systematic [15], but very few papers have considered the installation of UHV HRPC as a part of their study of VFTOs, such as the influence of HRPC installation location, HRPC internal parameters, and HRPC assembly schemes on VFTO characteristics.

This paper explores the mechanism of VFTO formation by modelling the typical VFTO occurrence circuit in combination with transmission line theory. The generation of VFTO is simulated using electromagnetic transient analysis software, and its characteristics are discussed in relation to the results obtained by our simulation. On the basis of the above research, UHV HRPC was added to the model to study the effects of HRPC on the VFTO generation process and characteristics. On the basis of these measures, a series of VFTO suppression measures are proposed and verified.

2. Characteristics of VFTO

Due to the lack of special arc-extinguishing equipment for isolating switches, when high-voltage switching equipment such as the isolating switches in GIS are switched on and off, the arc generated by the switch fracture will result in a fast transient overvoltage, which is the main reason for a VFTO occurring. The rise time of a VFTO waveform is very short, approximately 5–20 ns, and the rate of voltage rise can reach 40 MV/μs.

2.1. Characteristics of VFTO. VFTO is transmitted in GIS in the form of a traveling wave and is reflected at the connection between the GIS busbar and shell, forming a periodic oscillation. It may cause faulty operation of the protection system, and the increase in shell potential caused by a VFTO may also directly threaten human safety.

The generation of an arc is the cause of VFTOs and their accompanying transient phenomena. Therefore, it is critically important to study the VFTO, along with other transient processes caused by the switching arc. The arc occurring between the fractures of isolating switches has been added in the established model.

At present, the most widely used arc models are multiple reignition arc and exponential arc models. This paper focuses on the variation in the characteristics of the numerical results; thus, the single exponential arc model can meet the requirements of the research conditions.

The exponential arc model can be expressed as follows:

\[ R_α(t) = R_0 + R_α e^{-t/τ}, \]  

where \( R_α(t) \) represents the resistance between the fracture of circuit breakers, which is a function of time; \( R_0 \) is a static point-arc resistance, representing the point-arc resistance after the formation of a stable arc path, and has a value of 0.5Ω; and \( τ \) is the time constant (take \( τ = 1 \) ns).

The transient model of other components in typical GIS units is simulated by a centralized capacitance or inductance. The equivalent models of various appliances are listed in Table 1.

In the calculation of busbar wave impedance, R1 and R2 are the inner and outer radii of the busbar, respectively.

According to Table 1 and the exponential arc model, the circuit model of VFTO generation in typical GIS can be expressed as shown in Figure 1.

In Figure 1, \( Z = 100Ω \); DC is the model of isolating switch; impulse voltage source can reach 40 MV/μs; DS is the circuit breaker; and A, B, C, D, and E are the VFTO measurement points at five positions, such as the transformer, the MOA, isolating switch, circuit breaker, and insulating bushing of GIS.

2.2. Other Recommendations. The line voltage of the UHV transmission system is 1000 kV. In the simulation, the default transmission system adopts a star connection, so the amplitude of the power supply voltage in the model is given by

\[ U = U_0 \times \frac{\sqrt{2}}{\sqrt{3}} \]

\[ = 816 kV. \]

Electromagnetic transient simulation software EMTP was used to build a typical VFTO circuit model, as shown in Figure 1. When parameter setting was completed, a typical VFTO waveform and the amplitude–frequency characteristics at the position c are shown in Figure 2.

The power supply voltage amplitude in the model was set as the reference value, that is, 1 pu. = 816 kV. As shown in Figure 2, the maximum amplitude of the VFTO at position c was approximately 1.6 pu, in which the fundamental wave amplitude was the largest, and the main harmonic frequency was in the range 4–16 MHz, while the harmonic amplitude above 20 MHz was small. It can be seen that the rising speed of the VFTO is very fast, which can reach 2100 kV/μs. The parameters of the VFTO voltage wave generated by this model were close to the parameters of the VFTO voltage wave measured in the substation and can be used for further research and analysis [16].

As can be seen from Figures 3–5, it can be seen that the VFTO amplitude at position d is slightly lower than the VFTO amplitude at the position c, but the amplitude–frequency characteristics of both are similar. This is because the circuit parameters between them are all transmission line properties, only amplitude attenuation, but no new harmonic components are added. The VFTO at the position a is lower in amplitude and its amplitude–frequency characteristics contain almost exclusively primary harmonics with a frequency of around 8000 Hz, with very small amplitudes of higher harmonics. The VFTO at the position c, which is not as high in amplitude, nevertheless shows a very clear oscillation pattern. This is due to the fact that the bushing is
at the end of the circuit model, where the voltage traveling wave formed by the VFTO is refracted and reflected, and therefore, the VFTO at the bushing position shows a periodic oscillation.

2.3. Effect of Installing HRPC on a VFTO. The influence of HRPC was not analysed in the previous simulation study of VFTO. In this section, the HRPC was added to the GIS system in order to improve the simulation analysis. The VFTO waveforms at each position were plotted and analysed. The waveform and characteristics of the VFTO generated by the isolating switch without and with the HRPC at the corresponding position were compared to provide theoretical support for the study of the VFTO suppression strategy in the next section.

The HRPC is composed of stepped controlled shunt reactor (SCSR) and series compensation (SC). Generally, there is an overhead line connection between the controllable high reactance and the series compensation. Under the simulation analysis of the VFTO, the isolating switch, transformer, and circuit breaker are still represented by centralized parameter components. The wave impedance of the bushing is similar to that of the busbar, and it can be

<table>
<thead>
<tr>
<th>Key equipment</th>
<th>Equivalent model</th>
<th>Circuit diagram</th>
<th>Circuit parameter</th>
</tr>
</thead>
</table>
| Transformer     | Entrance capacitance equivalent inductance |                | $C_T = 9000 \text{ pF}$  
|                 |                                      |                 | $L_t = 20 \text{ mH}$  |
| Grounding switch| Centralized capacitance to ground     | $C_{ES}$        | $C_{ES} = 240 \text{ pF}$ |
| High impedance  | Centralized capacitance to ground     | $C_{CT}$        | $C_{CT} = 4000 \text{ pF}$ |
| Bushing         | Centralized capacitance to ground     | $C_{BS}$        | $C_{BS} = 300 \text{ pF}$ |
| MOA             | Centralized capacitance to ground     | $C_{MOA}$       | $C_{MOA} = 19 \text{ pF}$ |
| GIS busbars     | Transmission line (wave impedance)    | $Z$             | $Z = 60 \ln (r_1/r_2)$ |

**Figure 1:** Typical VFTO circuit type model.

**Figure 2:** (a) VFTO waveform at position c. (b) Amplitude–frequency characteristics of VFTO at position c.
simulated by a transmission line of finite length. Figure 6 represents a model of the substation with HRPC following simplification.

Electromagnetic transient simulation software was used to build a substation model with HRPC. The simulation step and time were set to be the same as for those without HRPC, and then, the simulation was carried out. Figure 7 shows the VFTO waveform at the position $c$ in the substation with HRPC.

The amplitude–frequency characteristics of the VFTO waveform at the position $c$ with HRPC and without HRPC were carried out, and the results are compared in Figure 8.
It can be seen from the comparison of the two spectra that more harmonic components are introduced and the high-frequency components increased with installation of HRPC. This is due to the fact that in the model, the addition of HRPC brings more capacitive components in the circuit, and the capacitive and inductive components form oscillations during the transient process. The high-pass characteristics of capacitor components create more high-frequency signals in the circuit, which makes the composition of the VFTO more complex. Therefore, high-frequency signal processing and filtering should be considered in the actual installation and use of HRPC. The latter also has a certain effect on the amplitude of the VFTO. Compared with the amplitude of VFTO without HRPC, the amplitude of VFTO with HRPC has increased, which requires us to pay attention to adjusting the strategy of suppressing VFTO when adding HRPC to substation to avoid accidents caused by the increase of VFTO amplitude.

Based on the above analysis, it can be seen that the amplitude of VFTO at various frequencies will increase after HPRC is installed. Therefore, when adding a HRPC, it is necessary to study the effect of the internal parameters of the device on the VFTO in order to explore how to reduce the increase of the VFTO amplitude.

Among the internal parameters of HRPC, the inlet capacitance of the SCSR affects the value of the VFTO. Keeping other parameters unchanged, the entrance capacitance of the SCSR is changed and the value of the VFTO is obtained. As can be seen from Table 2, with an increase in the inlet capacitance of the SCSR, the VFTO value at the bushing decreases significantly, while that at the isolating switch increased slightly. Therefore, the increase in the inlet capacitance of the SCSR is beneficial for inhibiting the decrease in the amplitude of the VFTO after the SCSR was added. However, for the device before the SCSR was added, the value of the inlet capacitance had little effect on the amplitude of the VFTO. Therefore, the VFTO at the bushing can be suppressed by increasing the entrance capacitance of the SCSR, and the VFTO value at the isolating switch needs to be controlled in other ways.

When installing the HRPC, generally speaking, the series compensation is installed on the overhead line, while the SCSR is generally installed near the transformer. Since HRPC installation is equivalent to the introduction of capacitive components into the transient process, the positions of the SCSR and SC in the HRPC will have a certain effect on the amplitude of the VFTO.

Figure 9 shows the effect of distance of the SCSR from the transformer on the VFTO value of the bushing. As can be seen from the waveform comparison in the figure, when the SCSR was close to the installed transformer, the amplitude of the VFTO was greater, by approximately 83 kV, but the attenuation speed of the VFTO waveform was faster. When the SCSR was installed far away from the transformer, the amplitude of the VFTO decreased to approximately 71.6 kV, but the attenuation speed was slightly slower. In this simulation calculation, when the VFTO waveform changed, the timescale was at the 10-6 s level, and the subtle attenuation speed did not have a great impact. Therefore, in the actual installation, the SCSR should be installed far away from the transformer to avoid large VFTO values.

In general, the series compensation is installed in the overhead line. However, when working with the SCSR, the installation position of the series compensation can be changed. The installation position of the series compensation in our experiments was changed, and the values of the VFTO at each position before and after the change in position were compared. The results obtained are listed in Table 3.
As can be seen from the data in Table 3, when the installation position of the SCSR was close to the transformer, the installation position of the series compensation basically did not affect the value of the VFTO at each position. When the installation position of the SCSR was far away from the transformer, if the installation position of the series compensation was close to the transformer, although the VFTO amplitudes of the transformer and circuit breaker positions were almost unchanged, the VFTO at the bushing decreased from 82.6 kV to 71.6 kV, a decrease of nearly 13%. According to Figure 10, when installing HRPC, the series compensation can be installed close to the transformer, and the SCSR can be installed far away from the transformer so as to reduce the amplitude of the VFTO.

3. Method for Suppressing the VFTO of a Hybrid Reactive Power Substation

The suppression of VFTO is a main part of VFTO research. This section first explores the factors effecting VFTO and then compares the inhibitory effects of magnetic ring and inhibitory busbar in order to discuss the advantages and disadvantages of the two methods.

3.1. Factors Affecting VFTO. The factors affecting VFTO are mainly the transformer inlet capacitance, the arc resistance, the busbar length, and the busbar residual voltage. When the arc is generated at the isolating switch, the distance of the fracture will result in the formation of a different arc resistance. This parameter is the phase parameter that most directly affects the VFTO value. Table 4 lists the VFTO values of the isolating switch fractures under different arc resistances by setting the latter for the simulation calculation.

As can be seen from Table 4, the maximum value of VFTO decreased significantly with increasing arc resistance, proving that the increase of resistance can effectively reduce the amplitude of VFTO. This property can be applied to the suppression of VFTO, such as in the first method of adding a closing resistance near the switch, as well as to the methods that have received widespread attention recently, including ferric oxide magnetic ring suppression and busbar suppression, which are related to the idea of increasing resistance.

The inlet capacitance of the transformer equivalent model is different for different voltage levels. The value of the general transformer inlet capacitance can be calculated using the following empirical formula:

$$C = K^n \sqrt{S}.$$  \hspace{1cm} (3)

The unit of capacitance (C) is the picofarad (pF) and S is the three-phase capacity of the transformer. The inlet capacitance of a transformer can be obtained by referring to Table 5.

![Figure 8: (a) The amplitude–frequency characteristics of the VFTO waveform without HRPC. (b) The amplitude–frequency characteristics of the VFTO waveform with HRPC installed.](image1)

![Figure 9: Effect of the SCSR installation position on the VFTO waveform.](image2)

<table>
<thead>
<tr>
<th>Entrance to the capacitance/pF</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFTO at the bushing/kV</td>
<td>1200</td>
<td>1110</td>
<td>1036</td>
<td>968</td>
<td>906</td>
</tr>
<tr>
<td>Circuit breaker VFTO/kV</td>
<td>1685</td>
<td>1706</td>
<td>1735</td>
<td>1755</td>
<td>1771</td>
</tr>
</tbody>
</table>

Table 2: Effect of stepped controlled shunt reactor (SCSR) port capacity and inlet capacitance on the value of the VFTO.
The system studied in this paper was a UHV system with an inlet capacitance of 8000–10000 pF. The inlet capacitors selected were 8000, 8500, 9000, 9500, and 10000 pF for the simulation calculation, and the amplitude of the VFTO was obtained from Table 6.

It can be seen that the amplitude of the VFTO increased with an increase in the inlet capacitance of the transformer. This is because the energy storage function of the capacitor components gives the capacitor a certain quantity of charge storage before arc combustion. When the inlet capacitance and the storage capacity were larger, the amplitude of the VFTO also increased. However, the increase of VFTO is not particularly high, so the parameters of the transformer can be adjusted appropriately according to the requirements during the actual design.

Although the busbar is equivalent to the transmission line model with constant wave impedance when establishing the circuit model, the inductance and resistance values of the busbar affect the level of the VFTO. Keeping the other parameters unchanged, take busbar lengths of 20, 40, 60, 80, and 100 meters and obtain the VFTO amplitudes from the simulation calculation, as given in Table 7.

It can be seen from Table 7 that the increase in busbar length decreases the magnitude of VFTO because the impedance of the busbar increased proportionately with increasing busbar length. However, when the busbar length was 60 m, the calculated result was more than expected, which may have been due to the change in harmonic components caused by the changing value of busbar inductance in the simulation calculation, resulting in a change in the VFTO amplitude at this length. Following this, however, the VFTO amplitude decreased with increasing busbar length.

The formation of an arc and the amplitude of the VFTO are directly affected by the residual busbar voltage. On the premise of keeping other parameters unchanged, the remaining busbar voltages were selected as 400, 600, 800, and 1000 kV in order to conduct a simulation calculation and compare the VFTO values at the circuit breaker fracture. The calculated results are listed in Table 8.

As can be seen from Table 8, the greater the residual voltage of the busbar (positive polarity), the greater the amplitude of the VFTO. When the residual voltage reached 800 kV, the VFTO value exceeded 2.0 pu. Even when the residual voltage was 600 kV, the amplitude of the VFTO was close to 2.0 pu. This means that the presence of a residual voltage on the busbar can easily lead to failure of the insulation, resulting in overall failure. Therefore, we should pay attention to the construction of the grounding network and timely discharge to ensure that the residual voltage of the busbar is lowered.

3.2. Inhibition of VFTO by a Magnetic Ring and an Inhibitory Busbar. VFTO suppression can be based on the research results described in the previous section and include increasing the closing and opening speeds of isolating switch, shortening the arc time of isolating switch, and reducing the number of arc reignitions, thus reducing the harm caused by the VFTO. The installation of a closing resistance, a closing inductance, and other equipment can reduce the VFTO amplitude and speed up the attenuation of oscillation. At present, a relatively new research direction is the application of a ferrite magnetic ring and a restraining busbar. In this section, the inhibitory effects of a ferrite magnetic ring and a spiral tube damping busbar are simulated and compared.

The ferrite ring is a ferrite ring structure, which is generally sleeved at the busbar terminal behind the circuit breaker. In transient simulation, it can be equivalent to the parallel connection of resistance and inductance. Figure 10 shows the ferrite magnetic ring equivalent circuit.

The magnetic ring model is added to the VFTO generating circuit in this chapter for the simulation calculation, and the VFTO waveform between the circuit breakers is shown in Figure 11.

Referring to Figures 11(a) and 11(b), compared to the VFTO waveform without a magnetic ring, the suppression of the VFTO with a magnetic ring is clear.

The spiral tube damping busbar was constructed by a hollow conductive rod in the shape of a thread and installing a mechanical support device and damping resistance inside. A threaded hollow conducting rod can have the same effect as a multistrand magnetic ring. It is a more reasonable VFTO suppression measure to replace the original busbar.
Table 5: Inlet capacitance of the transformer port.

<table>
<thead>
<tr>
<th>Voltage grade/kV</th>
<th>110</th>
<th>220</th>
<th>330</th>
<th>550</th>
<th>750 and above</th>
</tr>
</thead>
</table>

Table 6: Effect of transformer inlet capacitance on the VFTO amplitude shadow.

<table>
<thead>
<tr>
<th>Inlet capacitance/pF</th>
<th>8000</th>
<th>8500</th>
<th>9000</th>
<th>9500</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude/kV</td>
<td>1236</td>
<td>1243</td>
<td>1249</td>
<td>1255</td>
<td>1260</td>
</tr>
</tbody>
</table>

Table 7: Effect of busbar length on the VFTO shadow amplitude.

<table>
<thead>
<tr>
<th>Busbar length/m</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude/kV</td>
<td>1250</td>
<td>1246</td>
<td>1601</td>
<td>1565</td>
<td>1425</td>
</tr>
</tbody>
</table>

Table 8: Effect of busbar residual voltage on the shadow amplitude.

<table>
<thead>
<tr>
<th>Busbar residual voltage/kV</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude/kV</td>
<td>1409</td>
<td>1552</td>
<td>1919</td>
<td>2285</td>
</tr>
</tbody>
</table>

Figure 10: Ferrite magnetic ring equivalent circuit.

(a) VFTO without a magnetic ring. (b) VFTO with a magnetic ring.

Figure 12: Transient equivalent circuit of the spiral tube damping busbar.
with a spiral tube damping busbar, which can achieve not only VFTO suppression but also completely replace the transmission function of the busbar. The restraining busbar is equivalent to the parallel structure of resistance, inductance, and an air gap, and the multistrand spiral structure can be regarded as a series of these parallel structures. The transient equivalent circuit of the spiral tube damping busbar is shown in Figure 12.

In the transient process, assuming that the air gap of the spiral busbar structure does not ionize; it is equivalent to a small capacitance. Adding the structure of the restraining busbar into the generating circuit of the VFTO, VFTO waveform is obtained from the simulation calculation, as shown in Figure 13.

As can be seen from Figure 13, the effect of the spiral tube damping busbar on the amplitude of the VFTO was very significant, but the VFTO waveform following the addition of the spiral tube damping busbar was more severe, and the harmonic content was more complex. This is because the addition of the spiral tube damping busbar brings with it inductance and capacitance effects, so that the oscillation in the circuit was more severe. The resulting harmonic components are therefore more complex than those occurring before the spiral tube damping busbar was installed.

4. Conclusion

In this paper, the typical generating circuit of VFTO was established. The generation characteristics of a VFTO, the effect of HRPC installation on the VFTO, the effect of various parameters in HRPC on the VFTO characteristics, and the effect of various circuit parameters on the VFTO were studied. Finally, two kinds of VFTO suppression measures were discussed, and the following conclusions were drawn.

(1) A VFTO has its largest amplitude at position of the isolated switch and has complex harmonic components. The harmonics are distributed mainly between the fundamental wave and 4–8 MHz. The amplitude–frequency characteristics of the VFTO at the position of isolating switch are similar to those at the position of circuit breaker, but the amplitude–frequency values of all harmonics are lower than those at the fracture. The amplitude of the VFTO at the bushing is the lowest, but the periodicity of the VFTO at the bushing is the most obvious, which can reflect the folding and reflection of the VFTO traveling wave at the position of bushing.

(2) The addition of HRPC leads to a significant increase in the amplitude of the VFTO. The inlet capacitance of the SCSR in HRPC has an impact on the VFTO value. In the HRPC installation scheme, when the SCSR is installed away from the transformer, the VFTO of the system is less than that when the SCSR is installed close to the transformer. When the series compensation is close to the transformer installation and the SCSR is far away from the transformer installation, the increase in VFTO is smallest, which is the best installation scheme.

(3) The VFTO decreases with increasing arc resistance, increases with increasing transformer inlet capacitance, decreases with increasing busbar length, and increases with increasing busbar residual voltage.

(4) The inhibitory effect of a ferrite magnetic ring and a restraining busbar on VFTO is obvious. The structure of a ferrite magnetic ring is simple, but it needs to be installed on the busbar, which is more complicated. The spiral tube damping busbar has a very obvious inhibitory effect on VFTO and introduces more harmonic components. The spiral tube damping busbar can replace the busbar as the responsibility of transmission, and following installation, it can be used conveniently all the time, without any additional equipment.

Data Availability

The data used to support the findings of this study are obtained from references and experiments.
Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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