Research Article

Interference to the Secondary Cable Caused by a Very Fast Transient Overvoltage in a Gas-Insulated Switchgear Substation

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When a very fast transient overvoltage (VFTO) propagates in a high-voltage bus, the capacitive voltage transformer (CVT) causes considerable interference on its secondary side, which will affect the normal operation of the secondary equipment. In this article, a CVT equivalent calculation circuit model was established, and the disturbance voltage of the secondary cable was deduced and calculated. Using electromagnetic transients simulation software, a simulation model of the secondary cable disturbance caused by the VFTO in a 500 kV gas-insulated switchgear (GIS) substation was established, the disturbance voltage at the end of the secondary cable was simulated and analyzed, and the effects of the length of the secondary cable and the grounding mode of the shield on the disturbance were studied. Combined anti-interference measures are also suggested, which use a spiral tube damping busbar, grounding at both ends of the shield using multistrand conductors and installing filter capacitors, all of which greatly reduce the amplitude and harmonic components of the disturbance voltage of the secondary cable.

1. Introduction

In recent years, in order to adapt to climate change, a large number of new energy sources have been developed and new energy technologies have evolved rapidly. Ultra-high-voltage (UHV) and extra-high-voltage (EHV) transmission technology can realize ultra-long distance and ultra-large capacity transmission of electrical energy, which is important for promoting the development of new forms of power generation, such as nuclear energy, wind energy, and solar energy. Gas-insulated switchgear (GIS) has been widely used in the development of UHV and EHV transmission because of its advantages of safety and reliability, compact spatial structure, outstanding antidisturbance ability, and easy deployment and installation. When the isolating switch of GIS is operated with power, its contact gap voltage drops rapidly. With multiple breakdowns and discharge of SF₆ gas, a very fast transient (VFT) of several megahertz to tens of megahertz is generated between the contacts [1–3]. VFT propagates in the form of a traveling wave and forms a very fast transient overvoltage (VFTO) with a short rise time and large amplitude after multiple refractions in GIS [4–8]. Due to the distributed capacitance between the transformer and the high-voltage bus, a VFTO will invade the secondary side of the transformer through the distributed capacitance and then enter the control chamber through the cable in the form of conduction, interfering with the secondary equipment and threatening the safe operation of the whole system [9–13]. Therefore, it is of great theoretical and practical importance for studying disturbances to secondary equipment by VFTOs.

Thus far, several researchers have made theoretical studies and derived expressions for VFTO and the secondary cable. The results of VFTO computations that have been carried out using EMTP software for various switching conditions in a 420 kV GIS have been presented in Reference [14], and the variation in VFTO peaks along with the nodes for disconnector and circuit breaker operations, as well as the variation in VFTO with different trapped charges, have also been studied. Zhang et al. [15] designed a VFTO...
harassment measurement system and measured the harassment voltage on the UHV GIS test platform and the shielding layer under four different grounding modes. Wu et al. [16] designed a simulation test platform for a 252 kV GIS substation, obtained the disturbance voltage at the simulated sensor port and the port of the control cabinet, and made a comparative analysis with International Electrotechnical Commission (IEC) standards. In [17], the VFTO levels were estimated using PSpice models (https://www.pspice.com) for all the equivalent circuits of the GIS components, including spark channel development. The above-cited studies have carried out theoretical derivations, practical measurements, and laboratory simulations for characterizing the interference of VFTO with secondary equipment but have carried out few modeling or simulation studies on the disturbance voltage, nor have they carried out the corresponding calculations and simulations for the anti-jamming measures of secondary equipment.

In this article, the mechanism of the interference to the secondary cable caused by the VFTO in a GIS substation is thoroughly discussed. Using electromagnetic transient simulation software, the equivalent simulation model of a disconnector operating in a 500 kV substation was established. By studying the structure of a capacitive voltage transformer (CVT) and a secondary cable, the interference caused by VFTO to secondary equipment was also studied. Through the simulation, we discovered the characteristics of interference to the secondary cable caused by VFTO through the CVT, which, in our opinion, is the big novelty in our work. On this basis, we investigated the suppression effect of filter capacitance and spiral tube damping busbar. The results reported herein may provide theoretical foundation and simulation support for further studies on generation mechanism and suppression methods of the interference to the secondary cable caused by VFTO.

2. Conduction Interference Calculation and CVT Model

In the GIS substation, information from the primary equipment and the related operation and control signals must be connected to the secondary equipment in the control and protection chamber through the secondary cable. When the VFTO propagates on the high-voltage bus, a high-frequency transient voltage is transmitted to the secondary cable and equipment through the distributed capacitance between the bus and the mutual inductance equipment, as well as the distributed capacitance between the primary and secondary sides of the mutual inductance equipment, threatening the insulation of the secondary equipment in serious cases. We studied the interference caused by the VFTO to the secondary equipment through the capacitive coupling voltage transformer.

Figure 1 is a schematic diagram of the interference caused by the VFTO on a high-voltage bus to the secondary cable through a CVT. The transient overvoltage \( U_B \) on the high-voltage bus is divided by the voltage-dividing capacitors \( C_3 \) and \( C_4 \) and is then conducted to the secondary cable, which is connected to the secondary side of the CVT through the distributed capacitor between the primary and secondary sides. In addition, part of the transient overvoltage \( U_B \) is injected into the grounding network through the grounding inductance and grounding impedance of the transformer, resulting in a rise in the local ground potential on the grounding network, which also results in interference with the secondary equipment connected to the grounding network. Figure 2 shows the equivalent circuit model of interference caused by the VFTO to the secondary cable and secondary equipment through the CVT.

In Figure 2, \( C_3 \) and \( C_4 \) are the voltage divider capacitors, \( U_B \) is the transient potential at the head of the CVT, \( L_G \) is the grounding inductance of the transformer, \( Z_G \) is the equivalent ground impedance, and \( Z_2 \) is the difference between the secondary winding and the cable shielding layer. \( Z_0 \) is the wave impedance of the secondary cable, and the load impedance at the end of the secondary cable is \( Z_L \). According to circuit theory, the interference source \( U_G \) can be expressed as

\[
U_G = \frac{(j\omega C_2/(1 + j\omega Z_m C_2)) + (1/(Z_G + j\omega L_G))}{((j\omega C_2/(1 + j\omega Z_m C_3)) + (1/(Z_G + j\omega L_G)))(1/j\omega C_3)(1/j\omega C_4)} U_B, 
\]

where the input impedance is

\[
Z_{in} = Z_0 \frac{1 + \rho_1 e^{-2\pi l}}{1 - \rho_1 e^{-2\pi l}} \quad (2)
\]

Assuming that the line is lossless, the propagation constant is

\[
\Gamma = j\omega \sqrt{L_G C_0}, \quad (3)
\]

where \( L_0 \) and \( C_0 \) are, respectively, the inductance and capacitance per unit length of the cable. The quantities \( \rho_1 \) and \( \rho_2 \) are reflection coefficients:

\[
\rho_1 = \frac{Z_S - Z_0}{Z_S + Z_0}, \quad \rho_2 = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (4)
\]
VX_hedisturbancevoltageonthesecondaryequipmentwhentheVFTOisgeneratedcanbecalculatedfrom(6).

3. Modeling of the Mode Disturbance Voltage of the Secondary Cable Discharge by VFTO

Many different pieces of equipment are found in GIS substations, including not only transformers, arresters, and other equipment but also switchgear, such as mutual inductors, high-voltage busbars, bushings, circuit breakers, and isolating switches [18–21]. For an accurate simulation, it is necessary to establish an accurate and reliable model for these pieces of electrical equipment. Except for the transformer, the other equipment is sealed in the GIS metal casing, and the inside is filled with SF₆ insulating gas. When the isolating switch is opened and closed, due to the slow speed of contact movement, repeated restriking and pre-breakdown occur between fractures. The breakdown pulse wave propagates along the wire to both sides. The wave is reflected at the discontinuity of the GIS wave impedance, and these forward and reverse waves are superimposed on each other to form a VFTO.

VFTO in GIS belongs to internal transient overvoltage. Due to the lack of special arc extinguishing equipment, the arc generated at the switch fracture when the disconnect switch and other high-voltage switchgear inside the GIS is opened and closed can cause rapid transient overvoltage, so the operation of the disconnect switch is the most important cause of VFTO. In the simulation described in this article, the transformer was equivalent to the inlet capacitance; the isolating switch was equivalent to a time-varying resistance when arcing and was equivalent to a concentrated ground capacitance with different values when closing or opening. The GIS bus was equivalent to wave impedance. When the circuit breaker was closed, it was equivalent to a part of the circuit, and when it was opened, it was equivalent to a series capacitor. Lightning arresters, current transformers, and bushings can all be equivalent to concentrated ground capacitors. The equivalent models of the various pieces of electrical equipment are listed in Table 1.

Using electromagnetic transient simulation software, a model of the conduction interference of the VFTO to the secondary cable and secondary equipment in a 500kV GIS substation was formulated. This simulation selected the operation mode with the highest overvoltage level: single variable, single bus, single-line operation mode. The GIS substation structure layout is shown in Figure 3. DS1, CB1, and DS2 are all in the closed state, while the CB2 bus has been powered on, and only the isolating switch DS3 needs to be operated.

4. Analysis of Model Simulation Results

Using this VFTO simulation model of the disturbance to the secondary cable and the secondary equipment in Figure 4, the disturbance voltage under various conditions can be studied. The parameters of the GIS bus and the shell used in this study were as follows: the bus had an inner diameter of 50 mm and an outer diameter of 90 mm, and the material was copper. The GIS shell had an inner diameter of 406.4 mm and an outer diameter of 422.4 mm, and the material was aluminum alloy. The secondary control cable was plastic-insulated control cable KVVP2-22, the outer diameter of the core wire was 0.00338 m, the cable core and the metal armor were copper materials, the cable core and the shielding layer were filled with air, and the insulation layer material was standard polyvinyl chloride (PVC).

When the isolation switch DS3 was closed, the VFTO at each device and the disturbance voltage waveform generated by the CVT on the secondary cable were obtained. The
overvoltages at each point in the circuit are listed in Table 2. The maximum value of the disturbance voltage appeared near the isolation switch DS3, which was 931 kV (2.07 P.U.). From Fourier analysis, it can be found that the maximum amplitude of the fundamental wave was 450 kV, and the main harmonic components were 0.85, 1.15, 1.65, 2.25, 4.9, 9.75, 12.5, and 23.75 MHz. The waveforms are shown in Figure 5. The conducted disturbance voltage of the VFTO entering the cable end of the secondary side of the CVT is shown in Figures 6(a) and 6(b), and the disturbance voltage was up to 6003 V. The harmonic component frequency of the disturbance voltage at the end of the secondary cable was concentrated mainly in the 0–50 MHz range, and the main harmonic frequencies were 1.7, 3.3, 6.15, 8.7, 9.75, 12.55, 18.05, 24.45, 30.25, and 41.8 MHz. Compared with the VFTO at the isolation switch, the VFTO at the end of the

### Table 1: Equivalent models of electrical elements.

<table>
<thead>
<tr>
<th>Electrical elements</th>
<th>Equivalent model</th>
<th>Circuit diagram</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power transformer</td>
<td>Inlet capacitance and equivalent inductance</td>
<td>$C_T = 9000 , \text{pF}$ $L = 20 , \text{mH}$</td>
<td></td>
</tr>
<tr>
<td>Arc</td>
<td>Time-varying resistance</td>
<td>$R_d(t) = R_0 + R_0 e^{-t/\tau}$</td>
<td></td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>Lumped series capacitance</td>
<td>$C_B = 410 , \text{pF}$</td>
<td></td>
</tr>
<tr>
<td>GIS busbar</td>
<td>Wave impedance</td>
<td>$Z_1 = 70 , \Omega$ $V_1 = 270 , \text{m/\mu s}$</td>
<td></td>
</tr>
<tr>
<td>Lightning arrester</td>
<td>Concentrated capacitance to the ground</td>
<td>$C_{MOA} = 19 , \text{pF}$</td>
<td></td>
</tr>
<tr>
<td>Casing</td>
<td>Concentrated capacitance to the ground</td>
<td>$C_{DS} = 200 , \text{pF}$</td>
<td></td>
</tr>
<tr>
<td>Current transformer</td>
<td>Concentrated capacitance to the ground</td>
<td>$C_{CT} = 700 , \text{pF}$</td>
<td></td>
</tr>
<tr>
<td>Isolating switch</td>
<td>Concentrated capacitance to the ground</td>
<td>$C_{DS} = 150 , \text{pF}$</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 3: Layout of a 500 kV GIS substation.](image3.png)

![Figure 4: Simulated model of the secondary cable disturbance voltage by the VFTO.](image4.png)
Secondary cable had more complex harmonic components and higher frequencies of the main harmonic components. An excessive disturbance voltage causes serious interference to the secondary equipment, and the amplitude of the disturbance voltage is closely related to the magnitude of the primary VFTO. Therefore, the suppression and protection of VFTOs on the disturbance voltage of secondary cables and secondary equipment can be studied and simulated by reducing the amplitude of the VFTO on the primary side and carrying out relevant protective measures on the secondary side.

5. Analysis of Protection Measures against Secondary Cable Interference

In order to protect the VFTO on the primary side, the VFTO on the high-voltage bus can be reduced by adopting the use of a spiral tube damping bus. To suppress the secondary side disturbance voltage, this part of the study examined the grounding method of the secondary cable shielding layer and the length of the secondary cable and carried out simulation analysis and research on two measures of using multistrand conductors and installing filtering equipment.

5.1. Effect of a Spiral Tube Damped Bus on the VFTO

Most of the overvoltage generated during the operation of the GIS isolation switch comes from the transmission wire. The overvoltage exists in the form of a flow wave, and its propagation is equivalent to the establishment of an electromagnetic field, which transmits or stores electromagnetic energy in different directions around the line. In order to simplify the calculation, the electromagnetic wave process in the surrounding space is usually replaced by the current and voltage wave on the line.

Table 2: Overvoltage at each electrical component.

<table>
<thead>
<tr>
<th>Location</th>
<th>DS3</th>
<th>CT1</th>
<th>CVT</th>
<th>MOA</th>
<th>T</th>
<th>ZL</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFTO/kV</td>
<td>931</td>
<td>659</td>
<td>670</td>
<td>550</td>
<td>548</td>
<td>6.0</td>
</tr>
</tbody>
</table>

![Voltage waveform](image-a)

![Amplitude frequency characteristics](image-b)

Figure 5: VFTO at the disconnector DS3. (a) Voltage waveform. (b) Amplitude frequency characteristics.

![Voltage waveform](image-a)

![Amplitude frequency characteristics](image-b)

Figure 6: Disturbance voltage on the secondary cable. (a) Voltage waveform. (b) Amplitude frequency characteristics.

![Voltage waveform](image-a)

![Amplitude frequency characteristics](image-b)

Figure 7: Disturbance voltage on the secondary cable. (a) Voltage waveform. (b) Amplitude frequency characteristics.
The spiral tube damping bus is a threaded coil structure with a hollow center, which is equipped with noninductive damping resistance and epoxy support. Because of this structure, the inductance is larger than that of a normal bus, and the wave impedance of the line can be changed. Damping resistors increase the active power of transmission, thereby suppressing traveling waves and reducing the amplitude and frequency of the overvoltage. Its principle of inhibition is similar to that of a magnetic ring, and because the conductor does not conduct magnetism, it will not appear to be subject to magnetic saturation and thereby reduce the protective effect. Using a screw tube damped bus to restrain the overvoltage can achieve the conduction of a normal bus. The damping bus is equivalent to the parallel structure of “resistance + inductance + air gap,” and the multibus is equivalent to a series of such multiple structures. Its equivalent circuit is shown in Figure 7.

With regard to these components, $L_n$ is the inductance of the single-turn single-damped bus, $R_n$ is the noninductive resistance, $L_{R_n}$ is the residual inductance of each turn of the damped bus, $g_n$ is the gap distance, and $r_n$ is the arc channel resistance. The spiral tube damping bus is used to replace the original transmission conductor, and the corresponding simulation analysis is carried out. When the spiral tube damping bus is used, the disturbance voltages at the end of the secondary cable are listed in Table 3.

The expression for the suppression effect $\alpha$ in this article is given by (7), where $U_1$ and $U_2$ represent, respectively, the initial disturbance voltage and the disturbance voltage after adopting protective measures.

$$\alpha = \left(1 - \frac{U_1}{U_2}\right) \times 100\%.$$  (7)

When the damping bus was adopted, the VFTO amplitude of each position was reduced. Of the components in the circuit, the VFTO amplitude at the isolating switch DS3 was reduced by 15.6% and, at the end of the secondary cable, suppression of the disturbance voltage was the most significant effect, reducing the amplitude of the overvoltage by 48.3%. Using Fourier analysis, it was found that the main harmonic components were basically the same as when the damping bus was not used, but the amplitude of the corresponding harmonic components was also greatly reduced along with the amplitude of the disturbance voltage. The suppression effect was basically the same as the suppression effect on the disturbance voltage at the end of the secondary cable. The spiral tube damping bus significantly suppressed the amplitude of the disturbance voltage caused by the VFTO on the end of the secondary cable. When the VFTO passed, the noninductive resistance $R_n$ absorbed the energy of the overvoltage and increased the corresponding active power. Due to the structure of the spiral tube, the inductance of the damping bus was higher than that of the ordinary bus, which increased the frequency of the transient voltage wave and reduced the voltage at both ends of the noninductive resistance $R_n$, resulting in a loss when the overvoltage wave flowed through, thereby reducing the overvoltage at the end of the secondary cable.

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5.2. Effect of Different Lengths on the End Voltage of the Secondary Cable. The length of the secondary cable determines the distribution of stray capacitance to the ground. This section simulates the secondary cables of different lengths and studies the relationship between the length of the secondary cables and the disturbance voltage. The simulation results are shown in Figure 8, where it can be seen that the disturbance voltage at the end of the secondary cable decreases with increasing cable length and when the cable length is 0~100 m, the effect of reducing the disturbance voltage is significant. Above 100 m, the disturbance voltage can still be reduced by increasing the cable length further, but the effect is greatly reduced. Therefore, in engineering practice, when the length of the secondary cable is less than 100 m, appropriately extending its length reduces the disturbance voltage, while for cable lengths of more than 100 m, the cost–benefit of increasing the cable length is reduced, so other disturbance suppression measures should be considered.

5.3. Effect of Grounding Mode of the Secondary Cable Shield on the Disturbance Voltage. KVVP2-22 type secondary cable was used in this study. The general structure of the secondary cable is shown in Figure 9, which consists of three concentric conductors, a cable core, a shielding layer, a metal sheath, and the insulating layer between them. The shielding layer and the metal sheath play a role in electromagnetic shielding and grounding protection. For anti-interference of the secondary cable, the shielding layer generally has two methods of being grounded at both ends and grounding at one end. The two shielding methods were simulated and analyzed.

By simulating the three methods, nongrounding of the shielding layer, single-end grounding of the shielding layer, and grounding at both ends of the shielding layer, the disturbance voltage at the end of the secondary cable and the amplitude of each harmonic component in the three different grounding modes were obtained. The simulation revealed that the maximum amplitude of the disturbance voltage at the end of the secondary cable could reach as much as 6003 V when the shielding layer was not grounded, the maximum amplitude was 5404 V when the shielding
The parallel grounding of multiple wires greatly reduced the grounding resistance of the wires and the interference to the potential rise from the ground grid. Two-strand, three-strand, and four-strand conductors were used in this study. The simulation revealed that the amplitude of the disturbance voltage at the end of the secondary cable decreased significantly and multistrand wire was used. When two, three, and four conductors were used, the maximum amplitudes of the disturbance voltage at the end of the secondary cable were 3284, 2260, and 1720 V, respectively, which were 45.29%, 62.35%, and 71.35% lower than that of the single conductor, respectively. Fourier analysis was conducted on the terminal voltage of the secondary cable after multistrand wires were used, and the amplitudes of the main harmonic components are listed in Table 5. Following the use of multistrand wires, the main harmonic frequency of the disturbance voltage at the end of the secondary cable did not change, but the amplitude of each harmonic component was greatly reduced. When using a four-strand wire, the amplitude of the disturbance voltage was the lowest, and the amplitude of the harmonic component was also the lowest, which had a good suppression effect on the disturbance voltage.

5.4. Application of Multistrand Conductors. The parallel grounding of multiple wires greatly reduced the grounding resistance of the wires and the interference to the potential rise from the ground grid. Two-strand, three-strand, and four-strand conductors were used in this study. The simulation revealed that the amplitude of the disturbance voltage at the end of the secondary cable decreased significantly and multistrand wire was used. When two, three, and four conductors were used, the maximum amplitudes of the disturbance voltage at the end of the secondary cable were 3284, 2260, and 1720 V, respectively, which were 45.29%, 62.35%, and 71.35% lower than that of the single conductor, respectively. Fourier analysis was conducted on the terminal voltage of the secondary cable after multistrand wires were used, and the amplitudes of the main harmonic components are listed in Table 5. Following the use of multistrand wires, the main harmonic frequency of the disturbance voltage at the end of the secondary cable did not change, but the amplitude of each harmonic component was greatly reduced. When using a four-strand wire, the amplitude of the disturbance voltage was the lowest, and the amplitude of the harmonic component was also the lowest, which had a good suppression effect on the disturbance voltage.

5.5. Effect of Filter Capacitance on the Terminal Voltage of the Secondary Cable. The frequency components of VFTO are very complex, including a large number of high-frequency harmonics. After the shielding layer was grounded, the VFTO amplitude at the end of the secondary cable was still very high, and the harmonic components were still very complex, and even the amplitude portion of the harmonic components had increased. Therefore, it was necessary to install corresponding filtering equipment to reduce the amplitude of the harmonic components and disturbance voltage. Different filter capacitors were added at the end of the secondary cable to simulate filters with different amplitudes. The simulation results are shown in Figure 10.

According to the simulation results, adding a filter capacitor on the secondary side reduced the disturbance voltage on that side, and the disturbance voltage at the end of the secondary cable was inversely proportional to the value of the added filter capacitor. For a filter capacitance of less than 0.01 μF, the amplitude of the secondary side disturbance voltage can be significantly reduced by adding such a filter capacitor. For a filter capacitance greater than 0.01 μF, the inhibitory effect of increasing the filter capacitance amplitude on the secondary cable disturbance voltage decreased.
5.6. Combined Antijamming Measures against Secondary Cable Disturbance Voltage. Sections 5.1–5.5 above, respectively, analyzed the effects of a screw tube damping bus, secondary cable length, shielding layer grounding mode, multiconductor, and filter capacitor installation on the secondary cable end disturbance voltage. The results of the simulation analysis showed that a damping bus greatly reduced the amplitude of the VFTO. For a secondary cable longer than 100 m, the disturbance suppression effect decreased significantly. Grounding at both ends of the shield suppresses the disturbance voltage well, but it increases the amplitude of the main harmonic frequency. For a filter capacitance greater than 0.01 μF, the disturbance suppression effect was greatly reduced. Considering these disturbance suppression measures in general, the suppression effects of combined antijamming measures on the disturbance voltage at the end of the secondary cable were analyzed. The waveform of the disturbance voltage and the amplitude frequency characteristics at the end of the secondary cable following combination with anti-interference measures are shown in Figure 11. The secondary cable employed four-strand conductors, the cable length was set to 100 m, the shielding layer used the method of double-end grounding, and the filter capacitance was 0.01 μF.

According to the simulation results, the maximum disturbance voltage at the end of the secondary cable was 429 V after adopting combined antijamming measures, and the amplitude of its harmonic content was also significantly reduced. The main frequency component was less than 20 MHz, and the high-frequency harmonic component was well filtered.

<table>
<thead>
<tr>
<th>Harmonic component (MHz)</th>
<th>Shielding layer grounding mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage amplitude (V)</td>
</tr>
<tr>
<td></td>
<td>Ungrounded</td>
</tr>
<tr>
<td>1.70</td>
<td>272.9</td>
</tr>
<tr>
<td>3.30</td>
<td>341.7</td>
</tr>
<tr>
<td>6.15</td>
<td>468.3</td>
</tr>
<tr>
<td>8.70</td>
<td>495.2</td>
</tr>
<tr>
<td>9.75</td>
<td>298.7</td>
</tr>
<tr>
<td>12.55</td>
<td>176.8</td>
</tr>
<tr>
<td>18.05</td>
<td>136.9</td>
</tr>
<tr>
<td>24.45</td>
<td>53.93</td>
</tr>
<tr>
<td>30.25</td>
<td>78.19</td>
</tr>
<tr>
<td>41.80</td>
<td>64.11</td>
</tr>
</tbody>
</table>

Table 5: Amplitude of harmonic components of the disturbance voltage at the end of the secondary cable using multistrand conductors.

<table>
<thead>
<tr>
<th>Harmonic component (MHz)</th>
<th>Number of conductor strands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage amplitude (V)</td>
</tr>
<tr>
<td></td>
<td>Single strand</td>
</tr>
<tr>
<td>1.70</td>
<td>272.9</td>
</tr>
<tr>
<td>3.30</td>
<td>341.7</td>
</tr>
<tr>
<td>6.15</td>
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</tr>
<tr>
<td>41.80</td>
<td>64.11</td>
</tr>
</tbody>
</table>

Figure 10: Effect of filter capacitance on the disturbance voltage.
6. Conclusions

In this study, the principles and characteristics of, as well as the best suppression strategies for dealing with, very fast transient overvoltage (VFTO) causing disturbances along the secondary cable in a gas-insulated switchgear (GIS) substation were investigated. A capacitive voltage transformer (CVT) was modeled, and the voltage on the secondary side of the CVT was derived. Using electromagnetic transient simulation software, a simulated model of a 500 kV GIS substation was built according to the CVT equivalent circuit, and the VFTO and secondary side disturbance voltage were simulated and analyzed. A series of measures to suppress the disturbance voltage at the secondary side of the CVT are proposed below.

In this article, a series of anti-interference measures for secondary cables are proposed as a result of simulating the interference of VFTO generated by the switching operation of a 500 kV GIS substation to secondary equipment through a CVT:

1. Using a spiral tube damping bus near the primary side disconnector greatly reduces the amplitude of the VFTO at the end of the secondary cable, and the amplitude of the harmonic component can be suppressed effectively.

2. Grounding at both ends of the shielding layer of the secondary cable can shield the disturbance voltage to a certain extent but may also lead to an increase in the amplitude of each harmonic component. The grounding needs to be used along with filtering equipment.

3. For secondary cable lengths of 0–100 m, increasing the length of the secondary cable appropriately reduces the disturbance voltage at the end of the cable. For cable lengths greater than 100 m, the disturbance suppression effect is significantly reduced.

4. Multistrand grounding can reduce the disturbance voltage on the secondary cable to a large extent, and interference on four-strand cable can be reduced by 71.35% compared to that of single-strand cable.

5. The shunt filter capacitor before the secondary load can both reduce the disturbance voltage of the secondary side and suppress the high-frequency harmonics effectively.

6. Adoption of combined anti-interference measures greatly reduces the terminal voltage of the secondary cable, and the harmonic components are also significantly reduced.

Data Availability

Data are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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