The Configuration Effect of SCSR on VFTO and Its Inhibitory Effect Analysis

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Abstract. The very fast transient overvoltage (VFTO) is changed when stepped controllable shunt reactor (SCSR) is installed in substation, this paper simulates and analyzes the closing sequence of the disconnector (DS) and voltage transformer (PT) installation location’s influence on VFTO with Dommel transmission line, and establishes the VFTO suppression equivalent impedance model in frequency domain, and analyzes the effect of various measures to suppress VFTO time-frequency amplitude. The results show that the VFTO dominant frequency and the corresponding amplitude can be reduced by reasonable choice of DS closing sequence and PT installation site. Compared to the closing resistor, ferrite has advantages in suppressing VFTO. The peak of VFTO increases first then decreases with the increase of the length of the ferrite.

1. Introduction
With compact structures, easily assemble, strong supply stability, less frequency electromagnetic radiation and many other advantages, Gas insulated substation (GIS) with is widely used in power system. In the closing process of disconnector, the step voltage wave produced between the moving and static contacts will transmit in GIS. When equipment resistance changes suddenly, the refraction and reflection of the voltage wave will take place which makes the voltage waveform distortion and then produces the very fast transient overvoltage (VFTO). With the increasing level of power line voltage, the effect of VFTO is stronger and may threaten the insulation of the equipment in the substation[1-4]. The peak, the maximum rate of change, rise time and the amplitude in main frequency of the VFTO waveform are determined by the internal structure and switch operation mode of GIS.

Much research work of formation mechanism, influencing factors and its suppressing has been carried out at country and abroad. Reference [5] summarizes achievements in terms of VFTO simulation and measurement, and new study directions are proposed for further researching VFTO in GIS. Reference [6] completes the measurement on the interferences of the secondary cable produced by electromagnetic field and also establishes the simulation model by using the theory of transmission line and electromagnetic coupling. During the characteristics computation and simulation of the high frequency wave transmission, the model of transmission line, in a certain extent, affects the accuracy of the results. At present, there is no report about the VFTO amplitude frequency characteristics based on the theory of the transmission line. This paper gives full consideration of the VFTO transmission properties, and obtains VFTO amplitude-frequency curve of different GIS structures by using the Dommel transmission line model based on frequency-dependent characteristics [7], and by using electromagnetic transient state simulation software, the validity of the calculation has been verified. At present, there is not any report about the configuration effect on VFTO and its inhibitory effect.
analysis on the theory of transmission line. This paper simulates and analyzes the closing sequence of the disconnector (DS) and voltage transformer (PT) installation location’s influence on VFTO with Dommel transmission line, and establishes the VFTO suppression equivalent impedance model in frequency domain, and analyzes the effect of various measures to suppress VFTO time-frequency amplitude.

2. The effect of DS closing sequence and PT position on VFTO

2.1 The simplification model of GIS physical structure

Three-phase insulated GIS bus-bar system is mainly consisted of GIS conductor, shell, high voltage equipment and SF$_6$ gas. It adopts enclosed structure, and the electromagnetic field is mostly shielded by the shell, and it can be simplified as a single phase system for analysis. The disconnector has no ability to extinguish arc so the breakdown process can be analyzed independently every time. GIS bus-bar system simplified physical model is shown in figure 1.

![Figure 1](image)

**Figure 1** The simplified model of the three-phase insulated GIS bus-bar’s physical structure

2.2 The theory of transmission line

Based on the distributed parameter equivalent circuit of GIS bus-bar system, the bus can be equivalent to the lossless lines with concentrated resistor by using Dommel transmission line theory as shown in figure 2.

![Figure 2](image)

**Figure 2.** A line model with lumped resistance

As figure 2 shows, the concentrated resistor is divided into three parts including the resistor of two ports R/4, the middle section is R/2 which should be much smaller than wave impedance z. For the convenience of calculation, the transmission lines can be further simplified as equivalent model as shown in figure 3.

![Figure 3](image)

**Figure 3.** The model
Based on the Dommel transmission theory, we segment the bus, and then solve the problem by using node voltage method. The equivalent impedance and equivalent admittance between are respectively $Z_C$ and $Y_C$ as equation 1.

$$
Z_C = \cos^2(\omega r)R - R\left(\frac{1}{2} + \frac{R^2}{32\zeta^2}\right)\sin(\omega r)
$$

$$
+ jR^2\cos(\omega r)\left(\frac{3R^2}{8\zeta} + 2\zeta\right)
$$

$$
Y_C = \frac{-2 - \frac{R^2}{4\zeta^2}\sin^2(\omega r) + jR}{Z_C}
$$

(1)

2.3 DS closing sequence and PT position on VFTO

In the process of GIS bus system transient overvoltage analysis, transformer, circuit breaker and voltage transformer are replaced by capacitors[8]. The equivalent wave impedance of the other electrical equipment in the system, such as current transformer, insulator, grounding switch and so on, which is similar to bus, can be equivalent to a constant length of bus. In order to guarantee the accuracy of line model, all the parallel conductor of the bus is omitted, the resistors are assembled somewhere and the remaining part is taken as a nondestructive circuit to simulate. The simplified equivalent model of GIS bus-bar system and the nondestructive line with resistors are shown in figure 4 respectively.

**Figure 4** the equivalent model of GIS bus-bar system with distributed parameter

Supposing the disconnector is an ideal switch and the voltage between $U_S$ and $U_L$ is step change, the power supply voltage with disconnector and the voltage with off-load can conduct Laplace transform respectively as follows:

$$
U_S(s) = \frac{e(s)Z_S(s)}{Z_L(s) + Z_S(s)}
$$

$$
U_L(s) = \frac{-e(s)Z_L(s)}{Z_L(s) + Z_S(s)}
$$

(2)

There, $s$ is the Laplacian operator, $Z_S(s)$ and $Z_L(s)$ represent respectively the source impedance, impedance of off-load, $e(s)$ is the initial voltage difference transformation which can be expressed as

$$
e(s) = \frac{U_{S0} - U_{L0}}{s}
$$

(3)

Where $U_{S0}$ and $U_{L0}$ respectively represent the voltage of the disconnector in power supply side before being closed and the residual voltage of off-load.

By using the mentioned expression(1), the impedance value $Z_L(s)$ of the off-load side is obtained. Taking view of the end of the bus, transformer node 5 in figure 3, we can also get the equivalent impedance $Z_S(s)$ of the power supply side, and we can obtain the voltage between the disconnector of
the power supply side and the voltage of off-load side respectively as follows by putting it into the formula (1)

\[ U_S(s) = \frac{e(s)Z_{Sm}(s)Z_{Ln}(s)}{Z_{Lm}(s)Z_{Sn}(s) + Z_{Sm}(s)Z_{Ln}(s)} \]

\[ U_L(s) = \frac{e(s)Z_{Sm}(s)Z_{Sn}(s)}{Z_{Lm}(s)Z_{Sn}(s) + Z_{Sm}(s)Z_{Ln}(s)} \]  (4)

Where, \( Z_{Lm}(s), Z_{Ln}(s), Z_{Sm}(s) \) and \( Z_{Sn}(s) \) respectively represent the polynomial of the numerator and the denominator impedance in the off-load side as well as the numerator and the denominator impedance in the power supply side.

\[ Z_{Lm}(s)Z_{Sn}(s) + Z_{Sm}(s)Z_{Ln}(s) = 0 \]  (5)

In the formula (5), there are a large number of trigonometric functions. And by using infinite series expansion approximation, we can solve the equation in the complex frequency and the frequency domain solution is \( p_i \) (i = 1... n). The method how to evaluate the limit can determine the undetermined coefficient of the disconnector voltage in power supply side.

\[ K_i = \frac{N(s)}{D(s)} \bigg|_{s=p_i} \quad (i = 1,2,3...n) \]  (6)

Where, \( N(s) \) and \( D(s) \) respectively represent the derivative of the numerator and denominator of the disconnector voltage \( U_S(s) \) in power supply side. The corresponding disconnector voltage in the power supply side can be expressed in time domain as the following function

\[ U_i(t) = \sum_{i=1}^{n} K_i e^{p_i t} = \sum_{i=1}^{n} \frac{N(p_i)}{D(p_i)} e^{p_i t} \]  (7)

Using the method above can calculate respectively the disconnector voltage with off-load \( U_i(t) \), the transformer port voltage \( U_f(t) \) and voltage transformer port voltage \( U_{pt}(t) \).

The closing order of the two disconnector groups has an effect on VFTO which is shown in figure 5. The VFTO peak generated on the SCSR by the disconnector action at position 2 is about 0.39 p.u., and the VFTO peak of DS close at position 1 is slightly smaller, approximately 0.28p.u., but its oscillation is more intense.

![Figure 5. The VFTO waveform of different DS closing sequence](image)

The results show that when DS in the off-load side closes, its end of the bus-bar is shorter, compared with the disconnector action in the power supply side, the reflection is more complex, and the voltage wave oscillation frequency of the breaker increases.

Except for DS closing order, the installation position of PT also has an important influence on VFTO. Compare the four types working conditions respectively: no installing PT, installing PT in position 1, 2 and 3, we can get the voltage wave shown in figure 6.

The figure 6 shows that the VFTO peak value and oscillation amplitude at SCSR port obtained by installing shunt capacitor at position 1 are smaller than that without shunt capacitor. the VFTO peak and oscillation amplitude at SCSR port slightly increase when installed at locations 2. the VFTO peak
at the SCSR port rises and the oscillation frequency decreases when the shunt capacitor is installed at three locations.

3. Analysis of the effect on restraining VFTO

If the VFTO transient over-voltage peak is too high, when transmitted to the electromagnetic device, it will produce an over-voltage distributed unevenly on the winding coils which may lead to the partial resonance on the high voltage winding coils[9], and then it makes power equipment fault occur in GIS system. To solve the problem above, it’s common to install closing resistors, shunt capacitors, ferrite and other methods in engineering to suppress VFTO, where the ferrite and closing resistor are generally installed near the disconnector and the shunt capacitors are mainly installed at the end of the bus-bar system.

We study all kinds of equivalent impedance models based on GIS Simplified model, where the closing resistors and parallel capacitors equivalent impedance model in high frequency can be expressed by constant capacitance or reactance, and the most important thing is the analysis of the ferrite equivalent model. the ferrite equivalent impedance and the ferrite complex permeability can be expressed as follows

$$\mu = \mu' - j\mu''$$

(8)

$\mu'$ is the real component for permeability, denoting the stored magnetic, $\mu''$ is the imaginary part of permeability, denoting the consumption of magnetic energy, and the permeability is nonlinear to the voltage wave frequency[10]. To facilitate the computation and analysis, we use the first-order piecewise function to fit the complex magnetic spectrum, and the piecewise linear complex magnetic conductance spectrum can be shown in figure 7. The equivalent impedance of ferrite can be expressed as

$$Z_F(s) = \frac{\mu_0 s (\mu' - j\mu'') A_F}{l_F}$$

$$A_F = \frac{l_F (\ln \frac{D_F}{d_F}) (D_F \cdot d_F)}{D_F - d_F}$$

$$l_F = \frac{2\pi (\ln \frac{D_F}{d_F}) (D_F \cdot d_F)}{D_F - d_F}$$

(9)

Where $A_F$, $l_F$ are respectively the equivalent area and equivalent magnetic circuit of the magnetic circle, $l_F$ is the axial length of ferrite circ, $D_F$ and $d_F$ respectively are the circular outer diameter and inner diameter. Changing the shunt capacitance of GIS system cannot suppress VFTO effectively, in engineering, we usually use closing resistors to suppress VFTO, but the problem of its complex
structure, high manufacturing cost and low reliability lead to its unreasonable economy. Using the ferrite circle to suppress VFTO has certain theory and the principle of the method is simple, easy to implement, and also has no effects nearly on the equipment structure and its reliability, at the same time, the cost is lower, but the problem is there hasn’t been any apply to the high voltage system. By comparing the two methods above, analyzing the suppression effect of VFTO waveform can provide more perfect theory for the feasibility of the ferrite used in extra-high voltage system.

From figure 8, it can be seen that both the closing resistance and ferrite show good suppression effect. The VFTO peak value of SCSR port under ferrite suppression is 0.53p.u., and the VFTO amplitude tends to be stable at 0.7μs. The VFTO peak value under closing resistance suppression is only 0.2p.u. and there is no oscillation. In order to understand the inhibiting effect of ferrite and closing resistance on VFTO, closing resistance R0=200Ω, ferrite length lF=7cm, external diameter DF=24cm, inner diameter dF=12cm are selected as the base values. The peak values of VFTO on SCSR ports under different ratio of closing resistance and ferrite are given respectively as shown in Figure 9.

From figure 9, it can be seen that the VFTO peak value on SCSR port decreases as the increase of the value of the closing resistance and ferrite. the VFTO peak value basically stops declining when the closing resistance increases to the base value. The further analyses the restraining effect of ferrite in Fig. 10.

![Figure 9. The peak values of VFTO on SCSR ports under different ratio of closing resistance and ferrite](image)

![Figure 10. The effect of different ferrite on VFTO peak](image)

Figure 10 shows that when the ferrite’s diameter is greater than 15 cm of a certain value, VFTO peak reduces first and increase then with the increasing of the length of the circular; and when the circular length is greater than 3 cm of a fixed value, VFTO peak reduces, along with the rising of the equivalent inductance, and the change is less than the rate of VFTO peak with the influence of circular length. The results show that the length of the magnetic ring is the main factor influencing VFTO peak change. Figure 11 shows the VFTO spectrum under different values of breaking resistance and ferrite .

![Figure 11 the effect of different suppression equipment on VFTO spectrum](image)
4. Conclusion
In this paper, the VFTO amplitude on SCSR port is studied based on Dommel transmission line model through mathematical and simulation analysis on the influence of DS closing sequence and PT installation position on VFTO and the suppression effect of VFTO under different suppression equipment. Conclusions are as follows:

(1) The closing order of switches can affect the VFTO amplitude on SCSR port; When closing DS at no-load side, VFTO peak is smaller, wave oscillates are more violent.

(2) The installation of PT at no-load side can reduce the harmonic oscillation frequency within a certain range and suppress the peak value of VFTO. It’s often to change the position of the PT to adjust the dominant frequency of VFTO in practice.

(3) The closing resistor and ferrite have showed a good effect in suppressing VFTO peak. VFTO would be in a state of under-damped.

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Reference
[1] Jiaomin Liu, Wei Du, Zhenzhou Wang, et al. “A new simulation calculation method for VFTO based on time domain finite element method,” Transations of China Electrotechnical Society, vol. 28, pp. 286-292, November 2013.

[2] Dingxie Gu, Muhong Xiu, Min Dai, et al. “Study on VFTO of 1000 kV GIS Substation,” High Voltage Engineering, vol. 33, pp. 27-32, November 2007.

[3] Zutao Xiang, Weidong Liu, Jiali Qian, et al. “Simulation test and computation of suppressing very fast transient overvoltage in GIS by magnetic rings,” Proceedings of the CSEE, vol. 25, pp. 101-105, July 2005.

[4] Yonggang Guan, Meng Zhang, Gongchang Yue, et al. “Simulation test on suppressing VFTO in UHV GIS with magnetic-rings,” High Voltage Engineering, vol. 37, pp. 651-657, March 2011.

[5] Weijiang Chen, Xianglian Yan, Shaowu Wang, et al.” Recent progress in investigations on very fast transient overvoltage in gas insulated switchgear,” Proceedings of the CSEE, vol. 31, pp. 1-11, October 2011.

[6] Weidong Zhang, Peilong Chen, Weijiang Chen, et al. “Measurement and simulation of disturbance voltage generated by VFTO in UHV GIS substation on the secondary cables,” Proceedings of the CSEE, vol. 33, pp. 187-196, June 2013

[7] Zheng Xu. The extended Bergeron model for “electromagnetic transient analysis in multiphase transmission lines,” Proceedings of the CSEE, vol. 16, pp. 354-357, February 1996

[8] Tao Meng, Xin Lin, Jianyuan Xu. “Calculation of very fast transient overvoltage on the condition of segmental arcing model,” Transactions of China Electrotechnical Society, vol. 25, pp. 69-73, September 2010

[9] Jianyuan Xu, Binge Si, Xin Lin, et al. “Electric field parameter calculation of extra-high voltage GIS disconnector based on dummy dielectric constant method,” Transactions of China Electrotechnical Society, vol. 23, pp. 37-42, May 2008.

[10] Yonggang Guan, Meng Zhang, Gongchang Yue, et al. “Simulation test on suppressing VFTO in UHV GIS with magnetic-rings,” High Voltage Engineering, vol. 37, pp. 651-657, March 2011.