On Fusing Mechanism Involving the Fuses at Secondary Winding of PT Induced by VFTO

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Abstract. The impact of very fast transient over-voltage(VFTO) on the primary and secondary equipment in gas insulated station(GIS) should not be ignored. In this paper, the research on fusing mechanism involving the fuses at secondary winding of PT induced by VFTO is carried out based on an actual case from the 500kV GIS substation belonged to Guizhou Tianshengqiao No.2 hydro power plant. As for the high voltage side, the transfer function about over-voltage can be formed in order to analyse the characteristics about high frequency over-voltage. As for the low voltage side, a three-phase equivalent model for secondary circuit of PT with the parallel arrangement at the A, B and C phases may be built for simulating the current distribution of the low voltage fuses in the situation of high frequency voltage and current. The results show that the maximum allowable current of fuse might be reduced greatly in the high-frequency circumstance due to skin effect and proximity effect, in comparison with nominal frequency condition.

1.Introduction

Gas-Insulated Switchgear (GIS) have been found a broad range of applications in power system over the last three decades because of their high reliability, easy maintenance, small space requirement, etc. There are also more and more GIS equipment in the power systems of China such as Guizhou Power Grid. Very Fast Transient Overvoltage (VFTO) may be generated in GIS due to voltage breakdowns (flashovers) in SF6 gas. They primarily occur during the operation of disconnector in GIS substation and can be hardly avoided. Due to the physical properties of breakdown in SF6 gas [1], the typical rise time of front VFTO is substantially smaller than the transient time of the associated electromagnetic wave through the components of GIS. This causes that each of the voltage breakdowns generates the travelling waves that could propagate back and forth in the GIS. They would be reflected and transmitted at the discontinued points of surge impedance, and eventually be superimposed to constitute the VFTO in the particular component of GIS. The induced VFTO would have impacts on primary equipment and secondary equipment as well [2].

For example, in the recent five years, there have been 7 abnormal events about the blown fuse at the secondary side of the potential transformer (PT) of 500kV # 2M bus in the 500kV GIS Switching Station of Tianshengqiao No.2 hydropower station. In fact, the protection devices at the 500kV bus usually acquire the voltage values from the PT. Therefore, it will lead to the malfunction of protection device and certainly jeopardize the power supply reliability of
power plant once if the secondary circuit goes abnormal. The abnormal events were likely caused by VFTO. Thus it is necessary to study on modeling, assessment, monitoring and control technology for VFTO in GIS substation.

As for the product design of GIS, it was started in the 1980s that some foreign manufacturers launched a lot of research on VFTO phenomenon resulted from switch operating in GIS involving the measurement system for VFTO, analogy experiment and digital simulation for analyzing the characteristics of VFTO, the effect of VFTO on insulation and the electromagnetic interference on secondary equipment, etc. Moreover, the suppression measures such as the switch with damping resistor for VFTO were proposed. However, the studies on the destructive effects of VFTO in the recent years were mainly focused on the primary electrical equipment such as transformer [3] or other insulation-level evaluation issues. The main contribution from those works focused on the component model suitable for VFTO analysis including arrester model [4], arc model of switch [5-7], potential transformer model [8], the computing method for fast transient overvoltage [9] and so on. Recently, reference [10] conducted a test for transferring voltage between primary side and secondary side of the potential transformer in GIS utilizing a set of equipment capable of generating, controlling and measuring class B shock wave, which concludes that VFTO can pass through PT with the linear transferring characteristic. Nevertheless, it seems that there are few papers have been published so far, addressing the secondary-side high-frequency overvoltage hazards of PT in GIS. Thus this paper carried out a study on the fusing mechanism involving the fuses at secondary winding of PT induced by VFTO based on a case of 500kV substation of Tianshengqiao hydropower plant in China.

2. The transferring characteristics of high frequency overvoltage in PT

![Fig.1 The equivalent circuit of PT](image-url)

Referring to the principle that T-type equivalent circuit for single-phase transformer can be converted to Γ-type equivalent circuit, the equivalent model of potential transformer can be also converted into the equivalent circuit shown in Fig. 1 [11-12]. In Fig. 1, the resistance, inductance and capacitance of potential transformer are represented by R, L, and CPS, respectively. CP and CS stands for the capacitor at primary side and secondary side, respectively. Rh and Lh separately denote ferromagnetic loss resistance and excitation inductance. k stands for transformer ratio. Apparently, \( V_s = kV_p \), \( R = R_p + kR_s \), \( L = L_p + kL_s \), \( C_s = kC' \). As a result of the equivalent circuit of PT displayed in Fig. 1, the transfer function of PT can be expressed as

\[
H(s) = \frac{V_p}{V_s} = \frac{1}{sC_s} \left[ \frac{R + sL}{1 + sRC_p + s^2LC_p} + \frac{1}{sC_s} \right] = \frac{1 + sR(C_s + C_p) + s^2L(C_s + C_p)}{1 + sR(C_s + C_p) + s^2LC_p}
\]

(1)
If a high-frequency signal is inputted in the primary side, especially at the megahertz level, $s$ in the Equation (1) will be very large. At that time, the item with the highest exponent of $s$ can be only considered. Consequently, Equation (1) might be simplified into (2) as follows.

$$H(s) = \frac{C_m}{C_m + C_p}$$  (2)

It can be seen from the transfer function that the signal transfer function of PT may be just related with the capacitor parameters at primary and secondary sides for the high-frequency signal. Therefore, if VFTO transmitted in the GIS encounters PT, those components with high-frequency physical characteristics would capacitively couple to the secondary wire cable through the distributed capacitance at primary and secondary sides, and then interfere with the secondary devices by the means of conduction [13].

3. The current distribution simulation in low-voltage fuse

When the high-frequency current caused by VFTO passes to the secondary side, the device on the secondary side mainly affected by its skin effect and proximity effect.

3.1 Skin effect and proximity effect. Skin effect is the tendency of an alternating electric current (AC) to become distributed within a conductor such that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor. The electric current flows mainly at the "skin" of the conductor, between the outer surface and a level called the skin depth. The skin effect causes the effective resistance of the conductor to increase at higher frequencies where the skin depth is smaller, thus reducing the effective cross-section of the conductor. The skin effect is due to opposing eddy currents induced by the changing magnetic field resulting from the alternating current. So each branch will establish an alternating magnetic field on other branches if a high-frequency alternating current flows through a set of parallel wires. Then the magnetic field would induce an electromotive force for preventing the electric current in each wire [14]. Among these wires, the wire in the middle has the largest induced electromotive force and also endures the greatest flux. As a consequence, the current flowing through the line may be minimum one.

Moreover, in a conductor carrying alternating current, if currents are flowing through one or more other nearby conductors, such as within a closely wound coil of wire, the distribution of current within the first conductor will be constrained to smaller regions. The resulting current crowding is termed as the proximity effect. This crowding gives an increase in the effective resistance of the circuit, which increases with frequency. A changing magnetic field will influence the distribution of an electric current flowing within an electrical conductor, by electromagnetic induction. When an alternating current (AC) flows through a conductor, it creates an associated alternating magnetic field around it. The alternating magnetic field induces eddy currents in adjacent conductors, altering the overall distribution of current flowing through them. The result is that the current is concentrated in the areas of the conductor furthest away from nearby conductors carrying current in the same direction. The proximity effect can significantly increase the AC resistance of adjacent conductors with frequency [15]. At higher frequencies, the AC resistance of a conductor can easily exceed ten times its DC resistance.

The high-frequency characteristics of VFTO can be conducted to the secondary side of PT, so that there is an uneven distribution of current. At that time, the inductance effect in this wire and the increased resistance caused by heat generated would be very small so as to be negligible [16-17]. However the thermal effect on the fuse is very sensitive. Hence high-frequency current play an inevitable role on the fusing. The part of fuse link would be overloaded and consequently blown out even if in the case with the current less than the rated value.

3.2 The distribution of current within the conductor based on the mechanisms of skin effect and proximity effect. It is supposed that a parallel arrangement of A, B, C three-phase line and return line could be depicted in Fig. 2. The parallel lines are equipped with the low voltage fuses with the same specifications and length.
When there is a high-frequency current in the line, the total flux $\psi_{DA}$ for the loop AD according to an electric field theory could be calculated by the following Equation.

$$\psi_{DA} = \frac{\mu_0 L}{2\pi} \left( I_A \ln \frac{d_{AA}}{d_{AA}} + I_B \ln \frac{d_{AB}}{d_{AB}} + I_C \ln \frac{d_{AC}}{d_{AC}} - I_D \ln \frac{d_{AD}}{d_{AD}} \right)$$

(3)

where $\mu_0$ stands for the permeability of wire, $L$ stands for the length of wire, the three-phase currents and the current of back line may be denoted by $I_A$, $I_B$, $I_C$ and $I_D$, respectively. $d_{AA}$ and $d_{DD}$ represent the radius of A line and D line respectively, $d_{AD}$, $d_{BD}$, $d_{BA}$, $d_{CD}$, $d_{CA}$ and $d_{DA}$ represent the distance between A line and D line, B line and D line, B line and A line, C line and D line, C line and A line, D line and A line, respectively.

Similarly, the total flux $\psi_{DB}$ for the loop BD can be listed as (4).

$$\psi_{DB} = \frac{\mu_0 L}{2\pi} \left( I_A \ln \frac{d_{AD}}{d_{AD}} + I_B \ln \frac{d_{BD}}{d_{BD}} + I_C \ln \frac{d_{BC}}{d_{BC}} - I_D \ln \frac{d_{CD}}{d_{CD}} \right)$$

(4)

Meanwhile $\psi_{DC}$ for the loop BD can be also derived as (5).

$$\psi_{DC} = \frac{\mu_0 L}{2\pi} \left( I_A \ln \frac{d_{AC}}{d_{AC}} + I_B \ln \frac{d_{BC}}{d_{BC}} + I_C \ln \frac{d_{CD}}{d_{CD}} - I_D \ln \frac{d_{AD}}{d_{AD}} \right)$$

(5)

Based on the equivalent circuit depicted in Fig. 3, the induced voltage in the loop AD could be attained as (6).

$$V_A = -j \omega \psi_{DA}$$

(6)

It can be clearly seen from Fig.3 that $I_D = I_A + I_B + I_C$. Therefore, Equation (6) can be rewritten in another form as (7).

$$V_A = \beta_{AI} I_A + \beta_{BI} I_B + \beta_{CI} I_C$$

(7)
where

\[ \beta_{AA} = \frac{j \omega \mu_0 L}{2\pi} \begin{pmatrix} \ln \frac{d_{ab}}{d_{cd}} \\ \ln \frac{d_{ac}}{d_{cd}} \end{pmatrix}; \]

\[ \beta_{AB} = \frac{j \omega \mu_0 L}{2\pi} \begin{pmatrix} \ln \frac{d_{ab}}{d_{cd}} \\ \ln \frac{d_{bc}}{d_{cd}} \end{pmatrix}; \]

\[ \beta_{AC} = \frac{j \omega \mu_0 L}{2\pi} \begin{pmatrix} \ln \frac{d_{ab}}{d_{cd}} \\ \ln \frac{d_{bc}}{d_{cd}} \end{pmatrix}. \]

Then VB and VC might be also gotten in the same way.

It may be observed from Fig.3 that

\[ V = V_s - I_s Z_s = V_a - I_a Z_a = V_c - I_c Z_c \]  

in which ZA, ZB and ZC separately represent the total impedance of each branch.

\[ V = (I_a + I_b + I_c)(Z_a + Z_b + Z_c) - V_s \]  

Substituting (7) into (8), we obtain (10) as follows

\[ V = (\beta_{AA} - Z_s)I_a + \beta_{AB}I_b + \beta_{AC}I_c = -V_s + (I_a + I_b + I_c)Z \]  

where \( Z = Z_a + Z_b + Z_c \).

The corresponding equations for the other two loops are presented as follows.

\[ V = \beta_{BA}I_a + (\beta_{BB} - Z_b)I_b + \beta_{BC}I_c \]

\[ V = \beta_{CA}I_a + (\beta_{CB} - Z_c)I_b + (\beta_{CC} - Z_c)I_c \]

\[ = -V_s + (I_a + I_b + I_c)Z \]  

Then these equations can be expressed in the form of a matrix as (13).

\[
\begin{bmatrix}
(Z + Z_s - \beta_{aa}) & (Z - \beta_{ab}) & (Z - \beta_{ac}) \\
(Z - \beta_{ba}) & (Z + Z_s - \beta_{bb}) & (Z - \beta_{bc}) \\
(Z - \beta_{ca}) & (Z - \beta_{cb}) & (Z + Z_s - \beta_{cc})
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}
=
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]  

According to the different distance from the three-phase line to return line, the current through the line can be transformed into the values with per unit. The matrix in (13) can be transformed into a function involving the distance between center line and back line and the rated current of fuse, which may be fitted into a curve, as shown in Fig. 4.

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3.3 The analysis about fusing mechanism on the high frequency condition. When low-voltage fuses work at the low frequency condition, the distribution of current in the three-phase lines could be affected by their impedances. Nevertheless, when the operating frequency rises up to
100kHz, the current distribution is totally different. As shown in Fig. 2, the current flowed through phase C line will be only 0.43 times rated current if the spacing distance between phase C line and the return line is only 30mm. But the phase A line will undertake the greatest impact since it is closest to the return line. It also means that its current could reach 1.5 times rated current. In other words, the reduced current in phase C line flows to the other two phases so that there is an excessive current in phase A line. Consequently, the heat productivity of fuse is greater than its heat release. Meanwhile its temperature rapidly rises so as to be blown out.

Therefore, in the case of high frequency, the maximum allowable current of fuse would be obviously decreased due to skin effect and proximity effect so that the reasonable arrangement of the distance between low-voltage fuses is critical in this working condition. Thus it should be noted that the distance between the low voltage fuses at the secondary side of PT should be increased as much as possible. Since most of low voltage fuses are currently designed without considering the VFTO working condition and are usually verified in the nominal frequency or the setting frequency less than MHz [18], the unpredictable consequences will happen once if they are used in the high-frequency circuits. Hence it should be suggested that the fuse for high-frequency working condition may be customized according to the additionally standard.

4. Case study

An actual case study has been carried on 500kV GIS substation belonged to Guizhou Tianshengqiao No.2 hydropower plant. There have been six events about blown fuse at secondary winding side of No.52YH PT at the No.2M 500kV bus in the five-year period from 2007 to 2011. The detailed data about these abnormal events are listed in Table 1.

Table 1: The operation mode of 500kV GIS substation in Tianshengqiao No.2 hydro power plant

| No. | Fuse   | Operation Description | Operation Order          | The status of 500kV GIS before the fuse is fused                                                                 |
|-----|--------|-----------------------|--------------------------|---------------------------------------------------------------------------------------------------------------|
| 1   | 52YH   | Open Switch 50132     | No.5013 breaker runs from SB to OOS | No.5012 and 5013 breakers and No.50122, 50121, 50132 and 50131 switches open, others close.               |
|     | Phase B | Close Switch 50132    | No.5013 breaker runs from OOS to SB | No.5011, 5012 and 5013 breakers and No.50132, 50111 and 50112 switches open, others close.               |
|     | PF2    | Close Breaker 5013    | No.5013 breaker runs from SB to IS | No.5013, 5023, 5033 and 5043 breakers open, others close.                                                     |
| 2   | 52YH   | Open Switch 50122     | No.5012 breaker runs from SB to OOS | No.5012 breakers and No. 50121 switch open, others close.                                                   |
|     | Phase B | Open Switch 50132     | No.5013 breaker runs from SB to OOS | No.5012, 5013 breakers and No.50122, 50121 and 50131 switches open, others close.                        |
|     | PF2    | Open Switch 50222     | No.5022 breaker runs from SB to OOS | No.5021, 5022 breakers, No.50221 switch open, others close.                                                |

Note: OOS denotes ‘out of service’, SB denotes ‘standby’, IS denotes ‘in service’.

PSCAD/EMTDC has been taken as the simulation platform. The simulation time step is selected as 45μs and the calculation step is selected as 50ns. The model data comes from the specific
parameters of major electrical components provided by the hydropower plant and the operational and planning database of China Southern Power Grid. A simulation model is built as Fig. 5 where the model of PT is described in Fig. 6.

Fig. 5 The VFTO analysis model for 500kV GIS substation in No.2 Tianshengqiao hydropower plant

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(a) The model of PT with conventional opening delta connection
The first event in Table 1 is taken as an example for the VFTO analysis model. In this case, No.5012, No.5013 No.50122, No.50121, No.50132, No.50131 disconnectors are opened, and other breakers as well as switches are closed. There is a typical serious transient voltage case obtained in the numerous VFTO simulations, displayed as follows.

(b) The model of PT for Tianshengqiao No.2 hydro power plant

Fig. 6 The model of PT

Fig. 7 The VFTO curves for Phase A at primary winding of 52YH

Fig. 8 The VFTO curves for Phase A at secondary winding of 52YH
As seen from Figure 7, the peak value of phase voltage at the primary side of No. 52YH PT may rise up to 1168 kV ~ 1172 kV, i.e., about 2.60 p.u. ~ 2.61 p.u.. Furthermore, the peak value of the phase voltage at its secondary side displayed in Figure 8 can attain 215 V, which might belong to the operational over-voltage. According to the reports from field survey, there is a 2 mm air gap between B phase of the first winding of No. 52YH PT and the connected part for phase A and phase B involving the third winding which is also the opening triangle winding. Meanwhile, the related wires are arranged in parallel. As a result, it can be inferred that the gap between the fuses at the ends is also 2 mm. The breakdown voltage resulted from surge overvoltage at the primary side can be ranged from 670 V to 760 V for root-mean-square value with 960 V to 1060 V for peak value. Considering the possible existence of impurities in the gap between the two fuses, the equivalent distance of air gap may be appropriately reduced to 1.5 mm. In this way, the peak value of the discharge breakdown voltage could drop to 720 V ~ 795 V. Figure 9 shows that the peak overvoltage between B phase of the first winding and B phase of the third winding with opening delta connection of No. 52YH PT may move up to about 585 V that would be close to the breakdown voltage of air gap. If VFTO becomes more severe, it is possible for the fuses at both ends to breakdown. Consequently, it will be able to result in the malfunction of protection devices, which could make a serious threat to reliable operation in the power plant.

5. Electronic submission of the full paper

In this paper, the research on fusing mechanism involving the fuses at secondary winding of PT induced by VFTO has been carried out based on an actual case from the 500 kV GIS substation belonged to Tianshengqiao No. 2 hydropower plant in China. There are several findings and conclusions as follows.

1) As for the high voltage side of PT, the transfer function about over-voltage has been formed in order to analyze the characteristics about high frequency over-voltage.

2) As for the low voltage side of PT, a three-phase equivalent model for secondary circuit of PT with the parallel arrangement at the A, B and C phases may be built for simulating the current distribution of the low voltage fuses in the situation of high frequency voltage and current. The results show that the maximum allowable current of fuse might be reduced greatly in the high-frequency circumstance due to skin effect and proximity effect, in comparison with nominal frequency condition.

3) The results from this case study indicate that the impact of VFTO on the primary and secondary equipment in gas insulated station should not be ignored. In the next step, a case study on 500 kV Liupanshui substation would be done for proving the conclusions again.
6. Acknowledgements

This work was supported in part by Science & Technology Program of Guizhou Power Grid Co., Guizhou Science & Technology Collaboration Foundation (No. 20157635) and the Training Program for Outstanding Young Scientists and Educators of Guizhou (No. 2012151).

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