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Study on Very Fast Transient Overvoltage of Closing No-load China UHV Transmission Demonstration Project Jindongnan-Nanyang-Jingmen 1000 kV Transmission Lines

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Abstract

When the ultra high voltage (UHV) substation used the gas insulated switchgear (GIS) system to switch lines with capacitive current, the pre-breakdown and multiple reignition will occur between switching contacts. Because of discharge characteristics of SF_6 and special structures of GIS system, the variations of the electromagnetic transient process and very fast transient overvoltage (VFTO) are very fast and extremely complex. The development process and characteristics of VFTO remain to be dealt with to seek effective suppression measures. The overvoltage of closing no-load long lines on GIS system is analyzed in detail. The simulation model of the very fast transient process of closing no-load long lines on UHV GIS system is established. The VFTO of closing no-load China UHV transmission demonstration project Jindongnan-Nanyang-Jingmen 1000 kV transmission lines is analyzed using electromagnetic transient simulation software ATP-EMTP. The VFTO of closing no-load long lines on UHV GIS system is simulated and calculated, when the system has no additional closing resistors and lightning arresters, additional single stage closing resistors, additional multistage closing resistors, lightning arresters in two terminals of lines, lightning arresters in two terminals and the middle of lines, and additional multistage closing resistors and lightning arresters in two terminals and the middle of lines. The simulation results show that the additional multistage closing resistors and lightning arresters in two terminals and the middle of lines can effectively restrain the VFTO of closing no-load long lines on UHV GIS system.

Keywords: *ultra high voltage, gas insulated switchgear system, closing no-load long lines, very fast transient overvoltage, ATP-EMTP*

1. Introduction

Gas Insulated Switchgear (GIS) system owns the advantages of small footprint, high reliability, long life cycle of operation and maintenance, ease of maintenance, *etc.*, It is widely used in the 110 kV and above transmission system, especially in the Ultra-high Voltage (UHV) transmission system [1, 2]. The GIS system closing no-load long lines will occur the pre-breakdown and multiple reignition between switching contacts, and produce Very Fast Transient Overvoltage (VFTO). VFTO has the characteristics of fast, steep wave front, high peak overvoltage, frequency. It has significant influence of insulation to GIS system and its connected winding equipment. Meanwhile, VFTO may also cause secondary equipment insulation and personal safety issues, and may generate electromagnetic

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interference to measurement and control equipment, then resulting of secondary equipment malfunction. Therefore, it is urgent to carry out research and come up with effective suppression measures of the Ultra-high Voltage (UHV) Gas Insulated Switchgear (GIS) system closing no-load long lines Very Fast Transient Overvoltage (VFTO) [3-7].

Before the research of UHV transmission technology in our country, only a few countries have built 1,000 kV UHV AC Transmission Line. However, due to the load growth slow, the operation of the transmission line has to be reduced to 500 kV. It shows the lacks on GIS system design, key technology research and actual operating experience of deep understanding on UHV GIS extremely fast transient over-voltage. In recent years, China's UHV transmission technology testing capacity and engineering practice level has been comprehensive upgraded. Currently, the 1000 kV southeastern Jindongnan-Nanyang-Jingmen UHV AC pilot project has been officially put into operation. Its GIS system layout and the actual operating voltage different from the former Soviet Union and Japan, therefore, it is important to research closing no-load long lines VFTO problem based on the actual situation of China's GIS system, and provide some theoretical basis for the design, construction and operation of the UHV transmission line [8-10].

This paper studies the UHV GIS system overvoltage generation mechanism and propagation characteristics, produces a detailed analysis of the GIS system closing no-load long lines. Then, based on these, it uses ATP-EMTP electromagnetic transient simulation software to model the very fast transient process of closing no-load long lines on UHV GIS system. The VFTO of closing no-load long lines on UHV GIS system is simulated and calculated, when the system has no additional closing resistors and lightning arresters, 100 Ω additional single stage closing resistors, 400 Ω additional multistage closing resistors, lightning arresters in two terminals of lines, lightning arresters in two terminals and the middle of lines, and 400 Ω additional multistage closing resistors and lightning arresters in two terminals and the middle of lines. Through comparative analysis of simulation results, it proposes efficient measures on effectively restraining the VFTO of closing no-load long lines on UHV GIS system.

2. GIS System Closing No-load Long Lines Overvoltage Analysis

GIS system over-voltage from isolation switch, the routine operation of the circuit breaker and ground fault, it is caused by operation or malfunction recognition [11]. Closing no-load long lines is one of the common operations in power system. As the mutations happened before and after in the line voltage closing, it may cause closing no-load long lines overvoltage in the transition process of this change. This over-voltage is the main operation voltage in UHV system [12, 13].

There are two different situations of closing no-load long lines: First is the normal operation of the planned closing, over-voltage that caused by oscillation, which may superimposed composition by the power frequency steady component and an unlimited number of rapid decay of the harmonic components. The overvoltage coefficient is generally less than 2 times of the steady-state frequency voltage amplitude. Second is the automatic reclosing after line fault excision. Because of different starting conditions, reclosing overvoltage is much more serious than planned closing overvoltage. In the closing overvoltage, the most serious one is three-phase reclosing, its amplitude can be up to three times rated voltage.

Supposing the wire cutter can synchronized operation completely in three-phase, then, the sum of forced component and transient component is zero of three-phase in the line. The voltage during transient process only depends on positive-sequence parameters, which can be analysed by single phase circuit. It is assuming power equivalent potential $e(t)=E_m\cos(\omega t+\theta)$, pickup voltage E_m, time t=1/ω, line impedance Z is a reference value. And ωt=τ, p=d/dτ, steady state p=j:

$$e(\tau) = \cos(\tau + \theta) = e(p) = \frac{p\cos\theta - \sin\theta}{1 + p^2} \tag{1}$$

The transition process operation voltage $u(p, x)$ of any point x (distance that calculated from the end of the line) in closing line, can use the principle of superposition to calculate a same size and opposite direction electric potential $e(p)+U_0/p$ ($U_0$is per-unit vale) in the circuit breaker. Let the line instead by entrance impedance, then obtained the line first terminal voltage. Let the first terminal voltage multiplied by the voltage transfer coefficient, then obtained the point x voltage on the line:

$$u(p,x) = \frac{e(p) + \frac{U_0}{p}}{pL_s + Z_R(p)} Z_R(p) K_{1x} - \frac{U_0}{p} \tag{2}$$

In the formula, L_s is Power Leakage Inductance; $Z_R(p)=Z_C$th$p\lambda$ is the computing entrance impedance, which look through first end to end; $\lambda=\omega l/v$; K_{1x}=ch$p\eta$/ch$p\lambda$ is the point x, which is the operating voltage transfer coefficient to the first end, $\eta=\omega x/v$.

After substituting, it can obtain:

$$u(p,\eta) = \frac{\frac{p\cos\theta - \sin\theta}{1 + p^2} + \frac{U_0}{p}}{\mathrm{ch}p\lambda + pL_s\mathrm{sh}p\lambda}\mathrm{ch}p\eta - \frac{U_0}{p} \tag{3}$$

Using decomposition theorem, the above original function is solved. Then the obtained transition process voltage of the point x in the closing line is:

$$\begin{aligned} u(\tau,\eta) &= U_2\cos\eta\cos(\tau+\theta) - \sum_{i=1}^{\infty} K_i(U_0 + S_i\cos\theta)\cos w_i\eta\cos w_i\tau + \sum_{i=1}^{\infty} K_i S_i \frac{\sin\theta}{w_i}\cos w_i\eta\sin w_i\tau \\ &= U_2\cos\eta\cos(\tau+\theta) - \sum_{i=1}^{\infty} K_i \frac{U_0 + S_i\cos\theta}{\cos\delta_i}\cos w_i\eta\cos(w_i\tau + \delta_i) \end{aligned} \tag{4}$$

In the formula, $U_2=1/(\cos\lambda-K_L\lambda\sin\lambda)$ is the steady-state voltage amplitude of the end of the line, l is length of the line, $S_i=\omega_i^2/(\omega_i^2-1)$, $\delta_i=\mathrm{tg}^{-1}(S_i\sin\theta/(\omega_iU_0+\omega_iS_i\cos\theta))$, $K_L= L_s/L_0l$, L_0 is line inductance per km, $K_i=2/(\omega_i\lambda\sin(\omega_i\lambda)+\omega_i\lambda\sin(\omega_i\lambda)K_L+\omega_i\lambda\sin(\omega_i\lambda)K_L^2\omega_i^2\lambda^2)$, ω_i is every self-oscillation angular frequency of system.

If remember damping effect of line resistance to free oscillation, the Eq. (4) can be written as:

$$u(\tau,\eta) = U_2\cos\eta\cos(\tau+\theta) - \sum_{i=1}^{\infty} K_i \frac{U_0 + S_i\cos\theta}{\cos\delta_i} e^{-a_i\tau}\cos w_i\eta \cdot \cos(w_i\tau + \delta_i) \tag{5}$$

In the formula, $\alpha_i=(R_l/2\omega L_0l)/(1-2K_L/(1+K_L+K_L^2\omega_i^2\lambda^2))$.

Before closing, when there is no residual voltage on the line, end line voltage is:

$$u_2(\tau) = U_2\cos(\tau+\theta) - \sum_{i=1}^{\infty} K_i \frac{U_0 + S_i\cos\theta}{\cos\delta_i} e^{-a_i\tau}\cos(w_i\tau + \delta_i) \tag{6}$$

When there is residual voltage, and closing in the maximum (θ=0°) supply voltage, end line voltage is:

$$u_2(\tau) = U_2\cos\tau - \sum_{i=1}^{\infty} K_i(U_0 + S_i)e^{-a_i\tau}\cos w_i\tau \tag{7}$$

When there is no residual voltage (U_0=0) on the line, and closing in the maximum (θ=0°) supply voltage, end line voltage is:

$$u_2(\tau) = U_2 \cos\tau - \sum_{i=1}^{\infty} K_i S_i e^{-a_i\tau} \cos w_i\tau \qquad (8)$$

Therefore, the size when closing no-load long lines going through voltage is mainly depends on components of free oscillations; every oscillation amplitude of each harmonic is related with coefficient K_i, S_i, that is to say, coefficient K_L is related with harmonic angular frequency ω_i. Seen by the relationship of K_i and K_L, K_L larger, the faster the convergence of free oscillations, usually the value of K is quite small, so in general calculation, it is sufficiently precise to get value of the first three items on free oscillation.

3. UHV GIS System Closing No-load Long Lines Very Fast Electromagnetic Transient Process Modeling

ATP-EMTP was first advanced by Professor H. W. Dommel in his electromagnetic transient analysis software [13, 14]. It owns the advantages of multi-function analysis, full element model and accurate calculation. The ATP-EMTP has standard user interface window, its main window interface is showing in Figure 1:

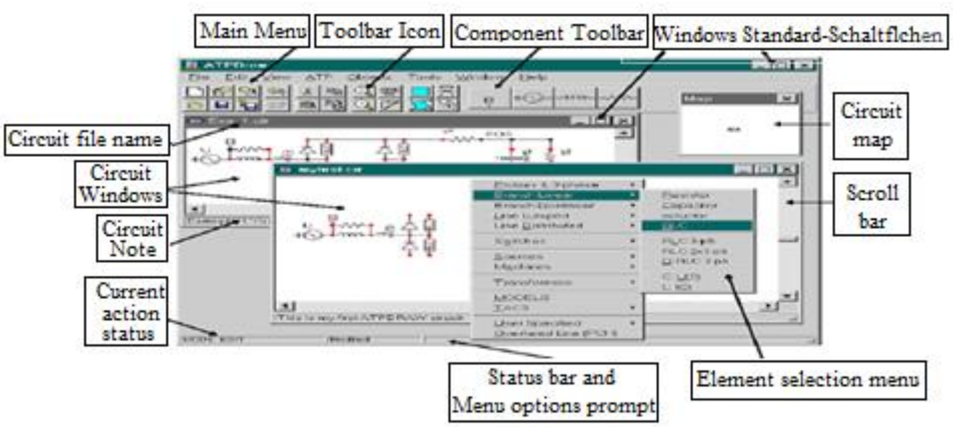

Figure 1. The Main Window

The following will detailed descript the power model, linear lumped element model, measuring instrument model, circuit breaker additional closing resistor model, zinc oxide arrester model, 1000kV line JMarti model and each parameter sets.

3.1. Model Selection And Parameter Settings

(1) Power Model

The power model is shown in Figure 2.

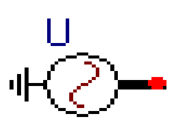

Figure 2. Power Model

By analysis of 1000 kV transmission line actual power functions and parameters of 1000 kV UHV demonstration project in south-eastern Shanxi-Nanyang-Jingmen UHV AC transmission project, ATP-EMTP power model set the parameter is 1100√2/√3 kV.

(2) Linear Central Component Model

The linear central component is resistor, the model shown in Figure 3, specific parameters may set according to need.

Figure 3. Linear Lumped Element Model

(3) Gauge Model

The setting parameters of Gauge are 3 phase. The model shows in Figure 4.

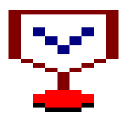

Figure 4. Measurement Model

(4) The Circuit Breaker Additional 100 Ω Single-stage Closing Resistors Model

The circuit breaker additional 100 Ω single-stage closing resistors model is shown in Figure 5. When closing, auxiliary contact K1 first closed, access 100 Ω single-stage closing resistors, over a period of time (called the closing resistor connecting time), the main contact K closed. By doing these, it can achieve purpose of limit closing overvoltage [15, 16].

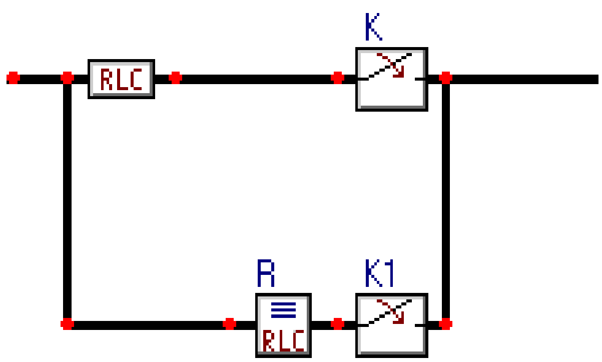

Figure 5. Circuit Breaker Attached Additional Single Stage Closing Resistors

(5) Circuit Breaker Additional Multistage Closing Resistor Model

Circuit breaker additional multistage closing resistor model shown in Figure 6, the principle is similar to circuit breaker additional single-stage closing resistor. First, joint auxiliary contact accesses all closing resistors. Then, short circuit the closing resistors level after level. But closed two adjacent auxiliary contacts must go through a period of time, which is closing resistors access time. And finally close the main contacts. As shown in Figure 6, closing K1, K2, K3, K sequentially.

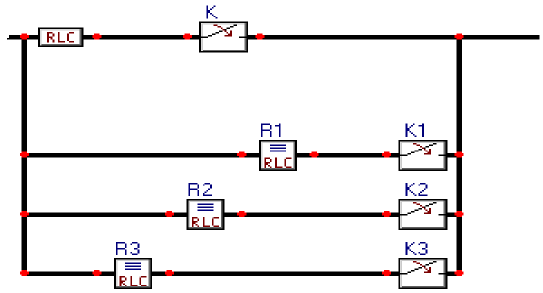

Figure 6. Circuit Breaker Attached Additional Multi-Stage Closing Resistors

The resistance value of the circuit breaker closing is generally among 200 ~ 900 Ω, under different system operation modes and line length, the closing overvoltage level of closing resistor may different. Some related studies have shown that when the closing resistor values between 300 ~ 400 Ω, overvoltage is relatively low. But lower resistance value may require more energy. After comparing comprehensively, this paper considers take closing resistor value of 400 Ω.

Practice has proved that additional closing resistors role is obvious. In order to give full play to the effect of closing resistor, it requires sufficient time for accessing closing resistor, which means when closing the main contact K of circuit breaker, the previous stage of the transition process has largely end, and may no longer affect the second stage.

The accessing time of 5000 kV circuit breaker united closing resistor in China is generally 10 ~ 15 ms. Continue to increase the closing resistors access time may reduce closing statistics voltage. Its effect is related with transmission system operating methods. Some methods have obvious effect, some are not, but energy of resistance is significantly increased. Combined all of the factors, it can identify 1000kV circuit breaker closing resistor may get the value of 400 Ω, access time may take 9.5 ± 1.5 ms.

(6) The Zinc Oxide Arrester Model

With the improvement of the level of metal oxide surge arresters manufacturing in recent years, its ability of limiting voltage operation has improved continuously, and become one of the key equipment of the UHV system overvoltage protection. Its excellent performance can limit various transient overvoltages of UHV transmission lines effectively; can protect electrical equipment from hazard. It is widely used now. It sets parameter of zinc oxide arrester based on overvoltage characteristics of zinc oxide arrester. Zinc oxide model is shown in Figure 7 [17, 18].

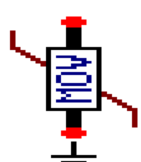

Figure 7. Zinc Oxide Arrester Model

(7) JMarti Model of 1000kV Line

This paper sets the parameter according to the 1000 kV UHV AC transmission pilot demonstration project in southeastern Shanxi - Nanyang - Jingmen UHV AC Transmission Tower parameter and the actual wire parameters. Select 1000kV overhead line, JMarti model as shown in Figure 8:

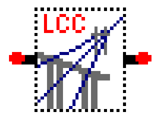

Figure 8. 1000 kV Overhead Line Model

3.2. UHV GIS System Model

Combining the above models, it can obtain the desired simulation system model, shown in Figure 9.

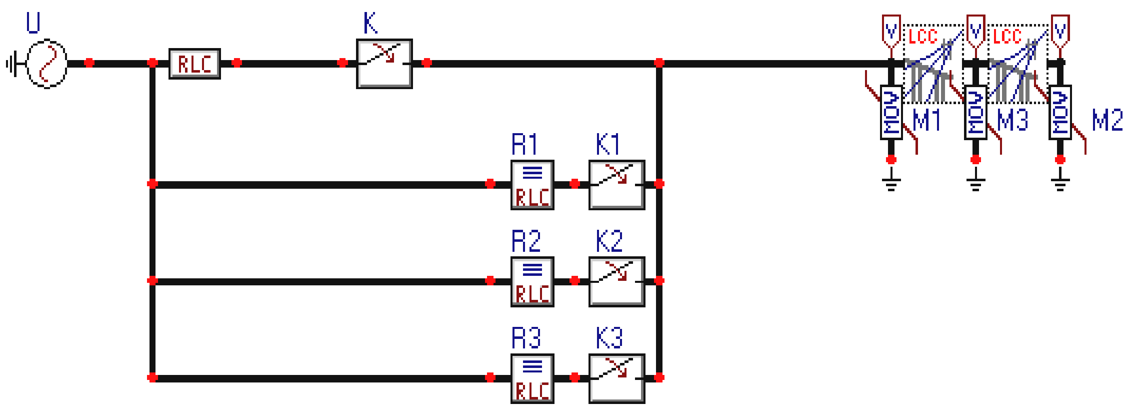

Figure 9. ATP-EMTP Simulation System Model

International Council on Large Electric Systems (CIGRE) recommendations line to use 12 pi-type equivalent circuit equivalents. It has proved actually that the result is very satisfied when use 12 pi-type equivalent circuit equivalent. Therefore, the above models have totally used 12 pi-type equivalent circuit equivalents. Jindong switching station to Nanyang switching station line use 6 pi-type equivalent circuit equivalent and Nanyang switching station to Jingmen switching station line use 6 pi-type equivalent circuit equivalent. Power voltage $u = 1100\sqrt{2}/\sqrt{3}\cos\alpha$ kV, frequency f=50 Hz, when α=0°, bus voltage is $u = 1100\sqrt{2}/\sqrt{3}$ kV, closing resistor R1=100 Ω, R2=100 Ω, R3=200 Ω, R=R1+R2+R3=400 Ω; K1, K2, K3, K closing time is t_1, t_2, t_3, t, separately t_1=0 ms, t_2=10 ms, t_3=20 ms, t=30 ms.

4. The No-load Long Line Closing Voltage Simulation Calculation

Under the same initial conditions, this paper has done three-phase same period closing operation to no-load line of this model. It has measured in the absence of the additional closing resistors and arresters, adding 100 Ω single stage closing resistor, adding 400 Ω multistage closing resistor, adding surge arresters in both sides of the line, adding surge arresters in both sides of the line and the middle side, adding 400 Ω multistage closing resistor and adding surge arresters in both sides of the line and the middle side. Power voltage, overvoltage of Nanyang switching station and Jingmen switching station (all phase A) waveforms are shown in Figure 10-15. The waveforms in these figures, X0005A is waveform of power turned half around voltage, X0006A is waveform of Nanyang switching station voltage, X0007A is waveform of Jingmen switching station voltage.

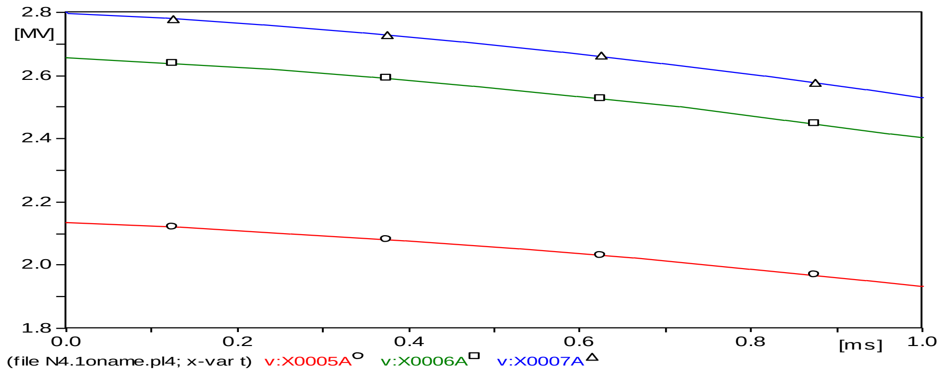

Figure 10. The VFTO Waveform (No Additional Closing Resistors and Lighting Arresters)

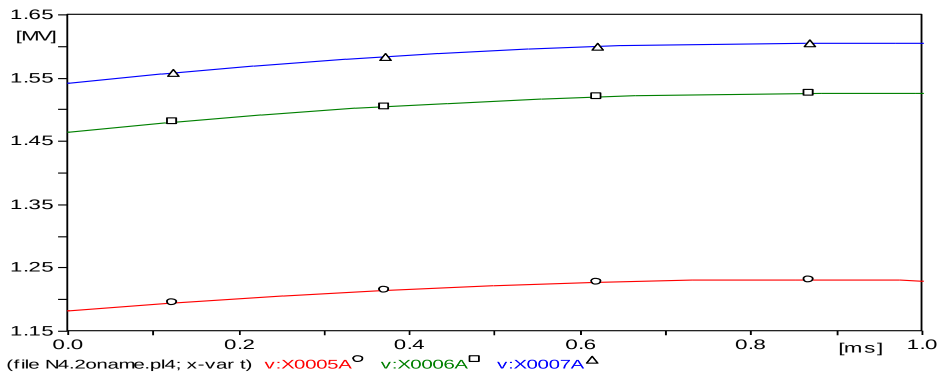

Figure 11. The VFTO Waveform (Additional 100 Ω Single Stage Closing Resistors)

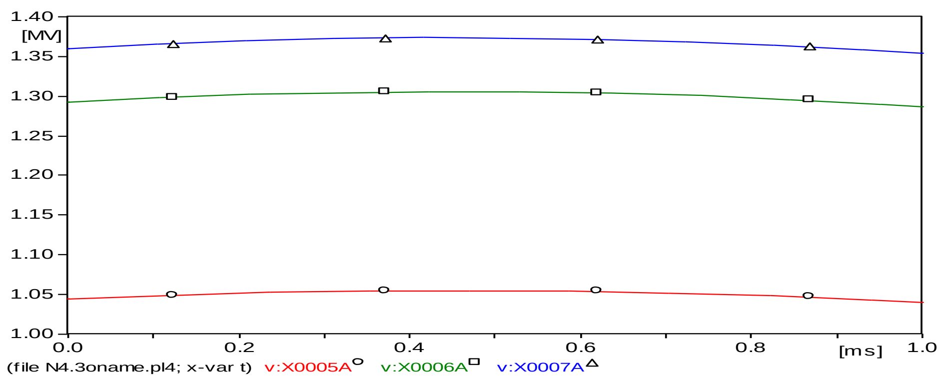

Figure 12. The VFTO Waveform (Additional 400 Ω Multistage Closing Resistors)

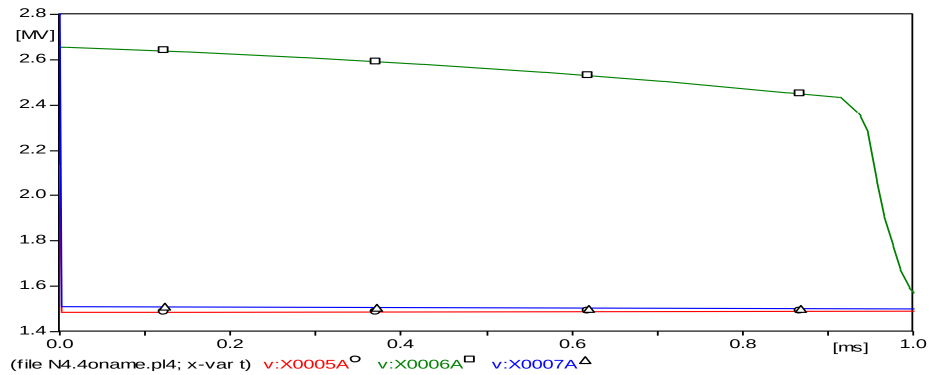

Figure 13. The VFTO Waveform, (Lightning Arresters in Two Terminals of Lines)

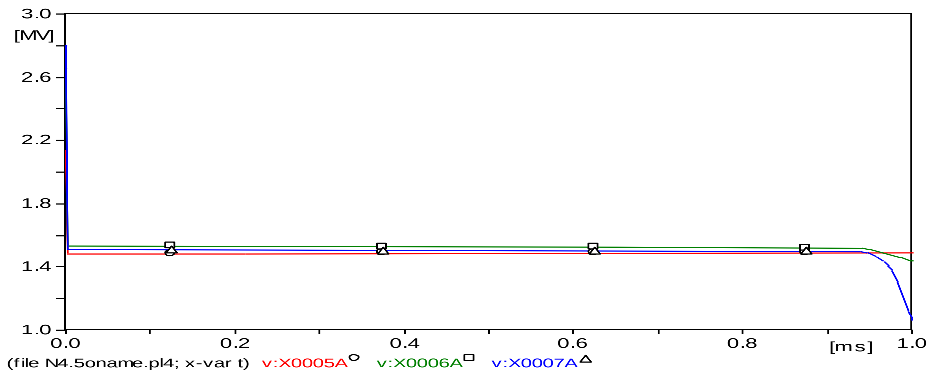

Figure 14. The VFTO Waveform (Lightning Arresters in Two Terminals and the Middle of Lines)

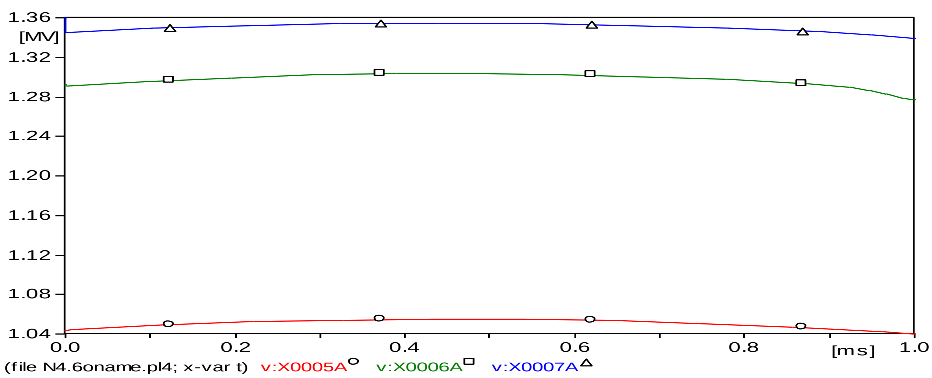

Figure 15. The VFTO Waveform (Additional 400 Ω Multistage Closing Resistors and Lightning Arresters in Two Terminals and the Middle of Lines)

Through comparing simulation calculation with Figure 10-15, it can be seen that when there are no measures taken to limit the three-phase same period closing over-voltage, the maximum value is 2.13 pu of 1000kV no-load long-term Jindongnan turned half around voltage, the maximum value is 2.65 pu of Nanyang switching station voltage, the maximum value is 2.8 pu of Jingmen switching station voltage. The overvoltage condition is serious.

When adding 100 Ω single stage closing resistor limits the three-phase same period closing overvoltage, the maximum value is 1.25 pu of 1000kV no-load long-term Jindongnan turned half around voltage, the maximum value is 1.55 pu of Nanyang switching station voltage, the maximum value is 1.63 pu of Jingmen switching station voltage. Although voltage spikes are decreased than take any measures, the overvoltage condition is also serious.

When adding 400 Ω multistage closing resistor limits the three-phase same period closing overvoltage, the maximum value is 1.07 pu of 1000kV no-load long-term Jindongnan turned half around voltage, the maximum value is 1.33 pu of Nanyang switching station voltage, the maximum value is 1.38 pu of Jingmen switching station voltage. It can be seen that voltage peak has declined than only use single-stage closing resistor.

When retrofitting 828kV rated voltage metal oxide surge arresters in Jingdongnan switching station and Jingmen switching station to limit the three-phase same period closing overvoltage, the maximum value is 1.5 pu of 1000kV no-load long-term Jindongnan turned half around voltage, the maximum value is 1.51 pu of Nanyang switching station voltage, the maximum value is 2.68 pu of Jingmen switching station voltage. Although the maximum peak is significantly reduced, the waveform has severe distortion.

When retrofitting 828kV rated voltage metal oxide surge arresters in Jingdongnan switching station, Nanyang switching station and Jingmen switching station to limit the three-phase same period closing overvoltage, the maximum value is 1.5 pu of 1000kV no-load long-term Jindongnan turned half around voltage, the maximum value is 1.51 pu of Nanyang switching station voltage, the maximum value is 1.53 pu of Jingmen switching station voltage. This limits the maximum over-voltage of line in Jingmen switching station. The maximum overvoltage has completely achieved requirements. Although the waveform has a moment oscillation after auxiliary contact closing, waveforms basically close to sine wave.

When adding 400 Ω multistage closing resistor in Jingdongnan switching station, and retrofitting 828kV rated voltage metal oxide surge arresters in Nanyang switching station and Jingmen switching station to limit the three-phase same period closing overvoltage, the maximum value is 1.06 pu of 1000kV no-load long-term Jindongnan turned half around voltage, the maximum value is 1.30 pu of Nanyang switching station voltage, the maximum value is 1. 35 pu of Jingmen switching station voltage. There is no distortion.

5. UHV GIS System No-load Long-term Closing Very Fast Transient Overvoltage Suppression Measures

Over-voltage amplitude can decided UHV power grid insulation design and insulation level, can relate to the cost and reliability of the power system directly, can through reduce the amplitude of voltage to reduce the insulation level of the UHV transmission system, thereby saving investment. Through previous analysis and simulation calculation, it can be seen the UHV GIS system no-load long-term closing very fast transient overvoltage suppression measures are as follows.

(1) The Circuit Breaker Adding Single-stage Closing Resistors

Operation switch of the power system transmission lines, unless appropriate damping, otherwise it will produce high overvoltage on transmission lines and its connected devices. Over the years, the ultra-high pressure system is equipped with a circuit breaker, which owns closing resistor. This can be seen as a measure of controlling system closing or reclosing operation voltage. When circuit breaker closing, before closure of the main contacts closed, we series with a closing resistor in load circuit short-time. This can reduce UHV GIS system no-load long-term closing very fast transient overvoltage. Through simulation calculation, it can be seen that after adding 100 Ω single stage closing resistor, the value of 1000kV no-load long-term Jindongnan turned half around voltage has reduced 0.88 pu, the value of Nanyang switching station voltage has reduced 1.1 pu, the value of Jingmen switching station voltage has reduced 1.17 pu.

(2) Circuit Breaker Adding Multi-stage Closing Resistors

In the low voltage level of the grid, circuit breaker adding single-stage closing resistor can limit over-voltage limit to low level. It is an effective measure of limiting closing over-voltage. But with the improvement of the grid voltage level, particularly in the UHV grid, circuit breaker adding single-stage closing resistor has been more difficult to meet the requirement of limiting over-voltage. Adding multi-level closing resistor to limit UHV GIS system no-load long-term closing very fast transient overvoltage has got significant effect. It is a very effective measure to limit UHV GIS system no-load long-term closing very fast transient overvoltage. Through simulation calculation, it can be seen that after adding 400 Ω multistage closing resistors, the value of 1000kV no-load long-term Jindongnan turned half around voltage has reduced 1.06 pu, the value of Nanyang switching station voltage has reduced 1.32 pu, the value of Jingmen switching station voltage has reduced 1.42 pu.

(3) Adding Zinc Oxide Surge Arresters In Both Sides And The Middle Side Of The Line

Adding zinc oxide surge arresters in both sides and the middle side of the line is another very effective measure to limit UHV GIS system no-load long-term closing very fast transient overvoltage. In China, the requirement of arrester can have reliably action when circuit breaker parallel resistance failure or other unforeseen circumstances occur a higher overvoltage, limit over-voltage in an allowable range, which means arrester is configured as a backup protection. Through simulation calculation, it can be seen that after adding zinc oxide surge arresters in both sides and the middle side of the line, the value of 1000kV no-load long-term Jindongnan turned half around voltage has reduced 0.63 pu, the value of Nanyang switching station voltage has reduced 1.14 pu, the value of Jingmen switching station voltage has reduced 1.29 pu.

In summary, the best effect is both adding 400 Ω multistage closing resistor and adding zinc oxide surge arresters in both sides and the middle side of the line to limit UHV GIS system no-load long-term closing very fast transient overvoltage. Through simulation calculation, it can be seen that after adding 400 Ω multistage closing resistor and adding zinc oxide surge arresters in both sides and the middle side of the line, the value of 1000kV no-load long-term Jindongnan turned half around voltage has reduced 1.07 pu, the value of Nanyang switching station voltage has reduced 1.35 pu, the value of Jingmen switching station voltage has reduced 1.45 pu.

6. Conclusion

This paper analyzes the generation mechanism and propagation characteristics of GIS system no-load long-term closing voltage in detail. Then use ATP-EMTP electromagnetic transient simulation software to model UHV GIS system no-load long-term closing very fast electromagnetic transient process, select the desired model and carry through parameter settings, and build simulation calculation model of UHV GIS system no-load long-term closing very fast transient overvoltage. Using this model to do simulation calculation of the absence of the additional closing resistors and arresters, adding 100 Ω single stage closing resistor, adding 400 Ω multistage closing resistor, adding surge arresters in both sides of the line, adding surge arresters in both sides of the line and the middle side, adding 400 Ω multistage closing resistor and adding surge arresters in both sides of the line and the middle side. Power voltage of Nanyang switching station and Jingmen switching station (all phase A) are bigger than the limited value. Through comparative analysis, it offers some suppression measures of the UHV GIS system no-load long-term closing very fast transient overvoltage. Through simulation calculation comparative analysis, the measures of adding 100 Ω single stage closing resistor, adding 400 Ω multistage closing resistor, adding surge arresters in both sides of the line, adding surge arresters in both sides of the line and the middle side can certain extent limit the largest over-voltage of line closing over the same period. But all of these unable to meet the requirements of the UHV transmission line pressure limiting and distortion are existing in waveform. Adding multistage closing resistor and retrofitting 828kV rated voltage metal oxide surge arresters in both sides of the line and the middle side can limit UHV GIS system no-load long-term closing very fast transient overvoltage effectively. It can damp wave oscillation, which may have some practical value.

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