Investigation on Very Fast Transient Overvoltage Caused by Incomplete Separation of Air-Insulated Switches

Yongjie Zhang, Yong Xu, Ming Gao, Ji Sheng, Danhua Chen, Jie Yuan, and Wentao Yang

Abstract The air-insulated isolation switch has the ability to interrupt small capacitive currents, but it does not have the function of extinguishing arcs. In the event of incomplete Break of Three-Phase, severe arcs can occur, and the capacitive voltage and arc current on the power side will produce a large pulse wave, which poses a great threat to the equipment insulation. Based on the actual spatial structure and electrical characteristics of the substation, each component underwent reasonable equivalence processing. Using ATP-EMTP simulation, the situation of gap discharge in the isolation switch during incomplete Break was analyzed. The transitory process of repeated breakdown of the gap was studied, and the causes of accidents caused by incomplete Break of Three-Phase were summarized. Measures and ideas for suppressing transitory overvoltage were proposed. The results indicate that incomplete Break of the isolating switch can cause a significant decrease in insulation voltage at the disconnection gap, and long-term intermittent repetitive discharge can cause high-frequency oscillations that generate rapid overvoltage with amplitudes and steepness higher than normal values. This phenomenon can easily cause damage to adjacent equipment insulation, resulting in huge hazards. In large power systems, most cases of incomplete Break of Three-Phase switch are caused by long-term overvoltage shocks that lead to equipment insulation breakdown. Appropriate line lengths and reducing residual charges can help to reduce overvoltage.

Keywords Air-insulated substation · Incomplete separation · Disconnect switch · Very fast transient overvoltage · Electromagnetic transient program

Y. Zhang · Y. Xu · M. Gao · J. Sheng
STATE Grid Yangzhou Power Supply Company, Yangzhou 225001, China

D. Chen (✉) · J. Yuan · W. Yang
College of Electrical and Information Engineering, Hunan University, Changsha 410082, China
e-mail: danielchen@hnu.edu.cn

J. Yuan
e-mail: yuanjie@hnu.edu.cn

W. Yang
e-mail: yangwt@hnu.edu.cn

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1 Introduction

With the continuous construction and expansion of power grids, high-voltage AC air-insulated isolation switches are widely used in power systems because of their small footprint, high reliability and low cost. The isolation switch has no arc extinguishing function and generally does not undertake the function of short-circuit and load currents, but as it is usually connected to lightning arresters, transformers, no-load transformers et cetera, the isolation switch needs to have a certain small current disconnection capability [1–5]. The electromagnetic transient issues such as overvoltage and overcurrent caused by operating isolation switches are becoming increasingly serious, and the number of accidents they trigger is gradually increasing [6].

Currently, research on the ultra-fast transient overvoltage is mainly focused on GIS disconnect switches (DSes) [6–12]. Research on air-insulated DS is relatively few, and there is currently no research on the incomplete disconnection conditions of air-insulated DS. Kai [6] investigates the ultra-fast transient overvoltage induced by CBs under incomplete breaking conditions, but there is a significant difference between the overvoltage induced by CB breakdowns under GIS conditions and those under air isolation switch conditions. Though [13] proposed a breaking model for air-insulated isolating switches, it did not consider the impact of incomplete three-phase breaking on overvoltage. In the long process of arc discharge, weather and other physical factors, as well as the coupling effect between fault phase and non-fault phase, may lead to multiple reignitions of the arc caused by small currents. Therefore, its simulation model is difficult to achieve ideal results.

This paper selects the air-insulated isolating switch of a 220 kV substation in Jiangsu as the research object. The electromagnetic transient program (EMTP) is used to compute the overvoltage of the air-insulated disconnect switch under incomplete breaking conditions; the effects of parameters such as transformer incoming line length and residual charge are discussed.

2 Description of Failure Caused by Incomplete Separation of DS

A conventional substation in Jiangsu has 220 kV bus operation as shown in Fig. 1, and its operation status before the fault is described below. 220 kV A substation has two 220/110/10 kV main transformers. According to the dispatching command, all equipment connected to bus I needs to be transferred to bus II, and No. 4616 switch is changed to run on 220 kV bus I, through bus couple 2610 and 4616 switch to 4616 line impact, after the impact is normal, the dispatching order is executed to turn 220 kV female switch to cold standby, the accident process as shown in Table 1.

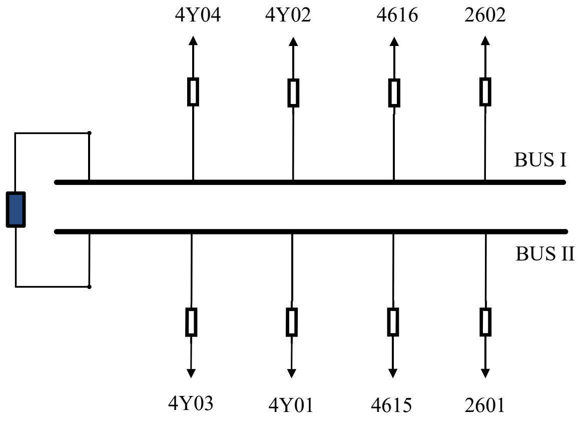


Fig. 1 Single-line diagram of 220 kV substation

Table 1 SOE of the fault

Time	Event
2020.9.16 20:45	Switch 2610 splitter
2020.9.16 21:00	Disconnect switch 26,101 incomplete separation
2020.9.16 21:49	Current transformer B phase explosion

On September 16, 2020, the No. 2610 CB, as illustrated in Fig. 1, was switched to standby state and the console SOE signal showed that No. 2610 switch was tripped at 20:45:10, confirming that the 220 kV switch was disconnected at 20:45.

While separating the busbar I DS 26,101 at around 21:00, phases B and C DSes were not in place, and the contacts were only separated by about 10 cm. After the manual operation was invalid, the isolation switch was in discharge state, and the DS was divided as shown in Fig. 2.

At 21:49, an explosion occurred in the 220 kV busbar No. 2610 branch together, 220 kV busbar protection I busbar differential action, all switches of 220 kV busbar are tripped, loss of power of No.1 main transformer, total loss of load 35,000 kW, affecting a total of 6820 users.

According to the investigation and failure analysis, 220 kV busbar 2610 current transformer B-phase short-circuit fault, resulting in busbar protection tripping, the cause of the fault is 26101 isolation switch is not in place to generate arc, small current arc by external influences in the long time discharge process constantly reignited to generate overvoltage, a longer impact leads to the insulation breakdown of current transformer.

Fig. 2 Photo of DS under incomplete isolating state in the field

3 Mathematical Model

According to the actual spatial structure and operation mode of the substation line, appropriate line branches are selected to model the isolation switch overvoltage model, and the 220 kV bus operation mode of the substation is shown in Fig. 3.

The establishment of a proper equivalent model and the selection of appropriate parameters will have an important impact on the simulation results. Each phase in the three-phase incomplete division process has differences, and the influence of factors such as inter-phase coupling needs to be considered, so a three-phase independent division and closing model of the disconnecting switch should be established. In the modeling of substation air-insulated switches, the parameter selection of components needs to be taken into account the influence of multiple relationships such as size, shape and mutual position on the parameters, mainly considering those factors that have a greater impact on the results, such as transformers, busbars, overhead lines, CBs, DSes, PTs, etc. Factors such as grounding cutter, bushing and arrester that have less impact on the simulation can be ignored [14]. Transformer equivalent inlet capacitance is 2500 pF, equivalent inductance is 25 pF, AC voltage source provides stable excitation of transformer voltage level [15, 16]. The busbar is equated with a parametric model with a wave speed of light and a wave impedance of 350 Ω. The overhead line is equated with a distributed parametric model with a wave speed of light and a wave impedance of 300 Ω. The potential transformer can be represented by the equivalent capacitance to ground. The disconnecting switch can be equated

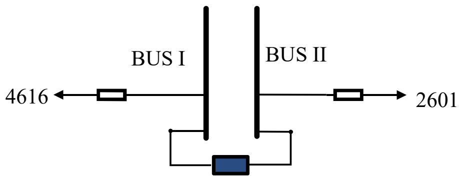


Fig. 3 Single-line diagram of 220 kV substation under study

Table 2 Main parameters for substation

Parameter	Value	Unit
Transformer	2500	pF
Busbar	350	Ω
Overhead line	300	Ω
Circuit breaker opening status	450	pF
Circuit breaker closing status	Equivalent to part of the busbar	pF
DS opening status	150	pF
DS closing status	80	pF
PT	200	pF
Wavespeed	3 × 108	m/s

to the ground capacitance in the divide-and-close state, and can be equated to the series model of inductance and resistance in the arc-burning state. The CB and in the closed state can be equated as a part of the overhead line, and in the split state the switch break can be replaced by a series capacitance. The distance between the transformer and the isolating cutter is 20 m, the length of the double-ended busbar is 50 m, and the length between the rest of the components is 5 m (Table 2; Fig. 4).

4 Simulations Study

This simulation sets the first closing at the peak of phase B, which makes the maximum overvoltage generated, and the overvoltage magnitude on its main equipment is shown in Table 3.

As can be seen from Table 3, while operating the DS, the transformer, the DS, the CB and the busbar has different peak values. The overvoltage amplitude at busbar I is the largest and the overvoltage amplitude at the transformer side is the smallest, The overvoltage at the value of transformer side is much smaller than t others. the maximum value of overvoltage at each point is smaller than the lightning surge withstand voltage of 2.32 p.u. [17], the overvoltage of the transformer is also less than the rated withstand voltage of the winding 2.0 p.u. [18–20]. So, the CT in the accident between the middle of the DS and CB is not directly pierced by the overvoltage, and Fig. 5 shows the overvoltage waveforms on both sides of DS.

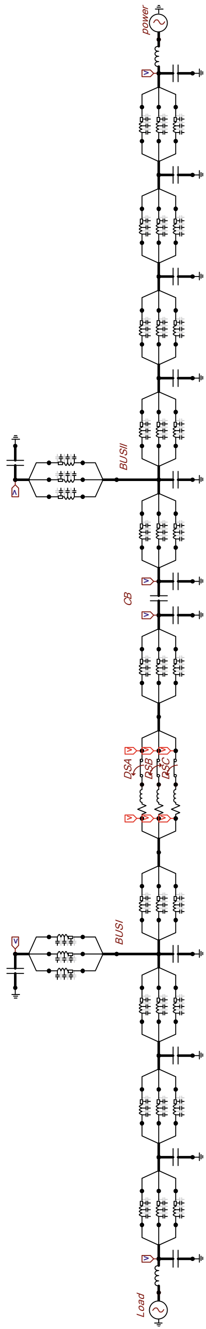


Fig. 4 Circuit diagram for simulation under DS incomplete breaking overvoltage model

Table 3 Overvoltages of power equipment within substation

Main test components	Peak value	Peak value (p.u.)
Transformer	442	1.42
Load side of DS	600	1.93
Power side of DS	602	1.94
CB	510	1.61
Busbar I terminal	670	2.15
Busbar II terminal	639	2.05
Load side	601	1.93

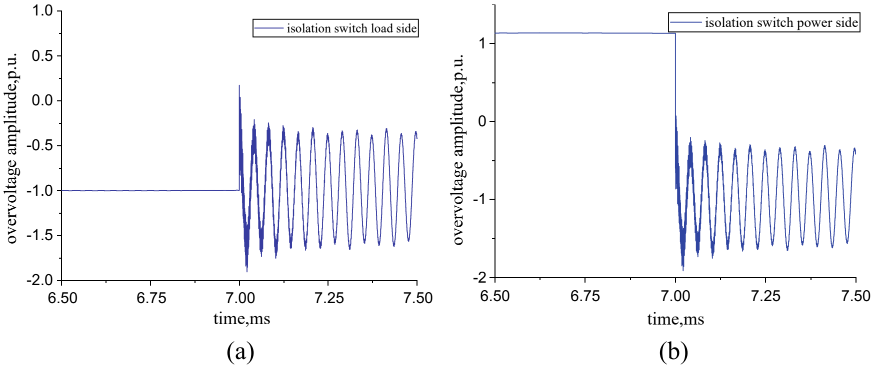


Fig. 5 Waveform of overvoltage around the DS. **a** Load side of DS; **b** Load side of power

5 Results and Discussion

5.1 Influence of Main Transformer Inlet Line

Branch circuit length is one of the main factors affecting overvoltage, in some cases, a small change in bus length can cause a large change in node voltage [21], Considering the different spatial structure of each substation, the length of the main transformer inlet to the transformer also varies greatly. Integrating the spatial structure of several substations, six different lengths were selected for simulation, and the parameters were obtained as shown in Table 4.

As the length of the main transformer inlet line increases, within the length range of 5–20 m, the change law of overvoltage magnitude of each device has obvious differences, mainly divided into 3 categories, busbar, load-side equipment and power-side equipment. In the bus end position, with the length increase, the overvoltage amplitude shows an overall decreasing trend, for the isolated switch load side equipment, its overvoltage has an obvious decreasing trend with the increase of the main transformer inlet length, while for the isolated switch power side equipment, its overvoltage basically does not change, only the transformer outlet voltage increases, but

Table 4 Effect of main transformer inlet line length on the equipment overvoltage (p.u.)

Main test equipments	5 m	10 m	15 m	20 m	25 m	30 m
Transformer	1.42	1.44	1.45	1.45	1.43	1.44
Load side of DS	2.29	2.14	2.18	1.88	1.93	2.03
Power side of DS	1.93	1.94	1.92	1.93	2.32	2.27
Terminal of busbar I	2.57	2.56	2.51	2.18	2.64	2.73
Terminal of busbar II	2.28	1.96	2.05	2.05	2.49	2.51
Load side	2.29	2.14	2.03	1.95	2.29	2.40

the increase magnitude is very small and can be considered to remain unchanged. As the inlet length of the main transformer continues to increase, the overvoltage of equipment at other locations besides the transformer has a tendency to increase significantly, while the overvoltage at the transformer decreases slightly, but it basically considered to remain unchanged. The reason for this phenomenon is that due to the short wavefront time of overvoltage, it propagates in the form of traveling waves within the overhead line. Complex refraction and reflection phenomena occur at the wave impedance mutation, and the branch length determines the overvoltage after folding and reflection, and the subsequent generation of overvoltage superimposed to enhance or weaken the overvoltage amplitude. Due to the extremely fast propagation speed and short wavelength of the traveling wave, a small change in the branch length will have a great impact on the overvoltage waveform. Figure 6 shows the overvoltage waveform when the main transformer feed line length is 5 and 20 m.

From Fig. 6, it can be seen that the overvoltage generated at the isolation switch at the main transformer feed line length of 5 m is much higher than that at the feed line length of 20 m. Therefore, choosing a suitable branch length will help suppress overvoltages at the equipment within the substation.

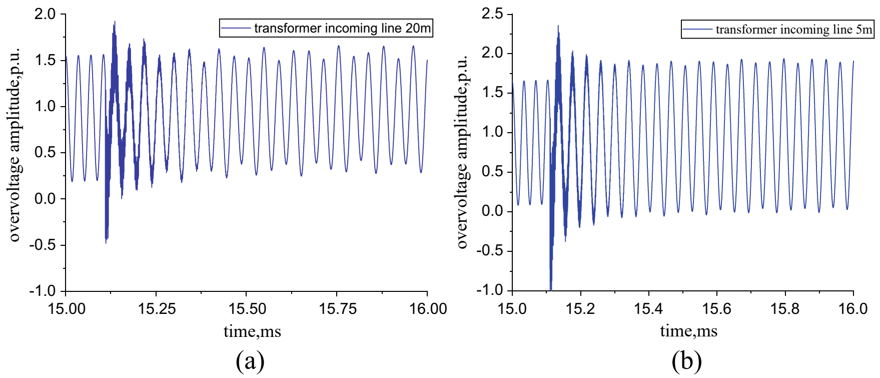


Fig. 6 Overvoltage waveforms at the DS. **a** Inlet line length of main transformer is 20 m. **b** Inlet line length of main transformer is 5 m

5.2 *Influence of Residual Charge*

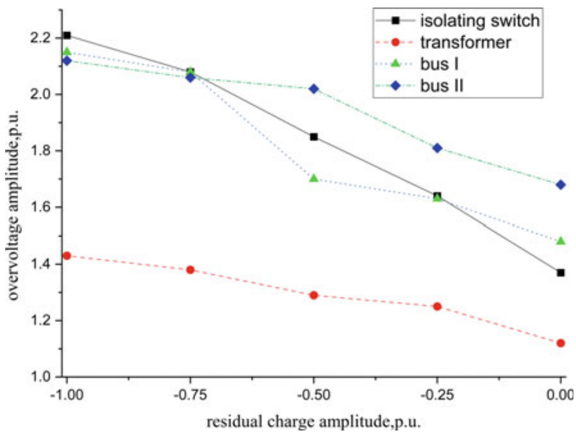
After the isolation switch gap is broken, due to the small current passing through the isolation switch gap, resulting in different magnitudes of residual charge on the load side of the isolation switch after the arc is broken. In order to study the effect of different residual charges on the overvoltage of each device, five groups of residual charges are selected for simulation in this paper, which are 0, −0.25, −0.5, −0.75, −1.0 times the voltage value (Table 5).

As can be seen from Fig. 7, as the residual voltage of the line rises, the overvoltage magnitude of each device is also increasing, where the overvoltage of the transformer reacts more slowly to the residual voltage, while the maximum overvoltage at the disconnector switch break reacts more violently to the magnitude of the residual voltage, which shows that the overvoltage at the disconnector switch break rises faster under the same residual voltage change, while the characteristics of the bus overvoltage are in the middle of the transformer and the DS. This shows that the residual charge has a greater influence on the overvoltage at the disconnector switch.

Table 5 Overv Effect of residual charge on overvoltage

Residual voltage (p.u.)	DS	Transformer	Busbar I	Busbar II
0	1.07	1.12	1.48	1.68
−0.25	1.64	1.25	1.23	1.81
−0.5	1.85	1.29	1.70	2.02
−0.75	2.08	1.38	2.18	2.06
−1.0	2.21	1.43	2.15	2.12

Fig. 7 Effect of residual charge on overvoltage



6 Introduction

The conclusions are as follows:

- The simulation data found that even in the most serious case of overvoltage, the overvoltage of the equipment at each location did not exceed the set value of insulation breakdown, and the disconnecting switch three phases incompletely divided to the final explosion of the current transformer for a longer period of time, so the possibility of direct destruction of insulation by overvoltage is ruled out. But the data show that the overvoltage generated at the isolation switch is large, in a complex external environment, small current discharge process for a long time, must be accompanied by the reignition of the isolation switch gap arc, overvoltage will impact the adjacent equipment again and again, continuous discharge will also lead to the surrounding temperature rise, and compared to other equipment, the current transformer nearest to the isolation switch and more fragile, again and again the overvoltage impact and temperature rise The insulation of the current transformer is gradually aging, and eventually the insulation is destroyed, which leads to more serious accidents.
- The length of the main transformer inlet line has different degrees of influence on the overvoltage at each location of the substation, among which the overvoltage at the exit of the transformer is the smallest, and the overall influence on the equipment at other locations shows a trend of first decreasing and then increasing. Therefore, choosing the appropriate length of the main transformer inlet line has a certain role in reducing the overvoltage generated by the incomplete separation of the three phases of the disconnecting switch.
- The residual charge has an overall positive correlation to the overvoltage generated by the substation. As the residual charge increases, the greater the overvoltage generated by each device in the case of incomplete three-phase separation of the disconnecting switch. Rapid removal of residual charge is of some significance to eliminate this type of overvoltage.

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