Electromagnetic interference characteristics during switching operation in power distribution network

Wang Chengliang, Shui Weilian, Yang Qingsheng, Ning Yan
Jiangsu Fangtian Power Technology Co., Ltd., Nanjing, Jiangsu Province, 210003, China

Abstract. The disturbance problem caused by the transient electromagnetic field during high-voltage switching operation is the most typical. Electromagnetic interference can be coupled to the secondary circuit in a conductive and radiating manner, then, affects the reliability of the secondary-side circuit. The key to the simulation calculation of the operating switch overvoltage is the judgment and simulation of its opening and closing conditions. The arc current zero-crossing judgment signal, the arc extinguishing and reignition judgment signals are fused, and a control signal is recursively obtained for switching operation. By analyzing the transient process during switch operation, a simplified model for isolating and closing the no-load bus, an overvoltage calculation model, and a fast transient model for overvoltage time-frequency signals are established. The characteristics of the transient electromagnetic field generated when the no-load bus and the circuit breaker of the disconnector are charged to the no-load transformer are simulated. The mechanism of fast transient pulse group generated by switching operation is obtained. The maximum overvoltage amplitude generated during the disconnector’s switching, and the no-load bus is obtained by simulation. Comparing with the measured data, the laws of electromagnetic interference characteristics during switching operation in power distribution network are verified.

1. Introduction
The coexistence of high-voltage equipment and low-voltage equipment in a substation determines the complexity of its electromagnetic interference problems[1,2]. The investigation shows that there are three main sources of electromagnetic interference in the substation: high-voltage switch operation, lightning line faults, and system short-circuit faults. Among them, the disturbance caused by the transient electromagnetic field during switch operation is the most typical[3]. Electromagnetic interference can be coupled into the secondary circuit in a conductive and radiating manner, affecting the reliability of the secondary side circuit.

The primary side of the substation contains a large number of disconnectors and high-voltage circuit breakers. During the operation or maintenance of the power system, the switching operations are very frequent, such as the disconnector cuts off the no-load bus, the circuit breaker cuts off the high voltage line, or the circuit breaker cuts off the capacitor. During this series of operations, there will be dozens or even hundreds of repeated arc breaks and arcings at the switch break[4]. A series of complex transition processes will occur in the oscillation circuit composed of capacitors and inductors in the system. Very fast transient over-voltage (VFTO) signal is formed, and enters the secondary equipment in a conductive manner through the current transformer (CT) and voltage transformer (PT), causing the network protection to malfunction or damage.
2. Transient process during switching operation

When the isolating switch is closed, the dynamic and static contacts are gradually approaching. When the potential difference between the two is so large that it can penetrate the air gap, the first arc is generated, and the potential on the no-load busbar rises from zero after a brief oscillation[5,7]. It is the instantaneous value of the power supply voltage. At this time, the high-frequency current is zero, the arc is extinguished, and the no-load bus voltage is maintained at the instantaneous value when the arc is extinguished.

When the sinusoidal power supply voltage is again greater than the exponentially decreasing breakdown voltage, the arc reignites[6-9], and the number of arc reignitions gradually increases, causing a steep transient wavefront. The transient wave is reflected during the propagation of the circuit due to the mismatch of the characteristic impedance of the circuit, forming a high-frequency damped oscillation wave. From a macro perspective, the entire transient process consists of a very large number of individual pulses, forming a series of pulse groups.

At such high frequencies, the transient process on the primary bus is directly coupled to the secondary equipment in the form of a transient electromagnetic field through the equipment connected to the bus (such as CT, PT, CVT, or carrier-coupled equipment)[10-12]. A very destructive, disturbing and rapidly attenuating oscillating wave is generated in the circuit, so that the voltage and current of the secondary circuit are also attenuating and oscillating[13]. It is precisely due to the existence of these interfering pulse waves that secondary equipment can easily malfunction.

When the isolating switch is switched on and off, the state of the primary equipment of the substation will change from a stable state to a new stable state after a brief oscillation. The oscillation frequency of the oscillation process is obtained by

$$f_l = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2} \approx \frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

(1)

where R is the equivalent resistance, L is inductance, and C is capacitance of the isolation switch circuit.

When the disconnector is closed, the moving contact will move towards the static contact at a certain speed. The first arc occurs when the distance between the dynamic and static contacts reaches that the dielectric gas can be penetrated by the voltage difference across the two ends. When the current crosses zero, the arc is extinguished and the voltage between the switch contacts is established again. Then the voltage rose again and the arc reignited. As the moving contacts of the disconnector continue to move, re-ignition and extinguishment of multiple arcs occur, resulting in a series of electromagnetic disturbances. Each reignition of the arc corresponds to a high-frequency oscillation, and the amplitude of the voltage of the oscillation is equal to the voltage difference between the contacts of the isolating switch immediately before the reignition of the arc.

When the disconnector is opened, the moving contact will move away from the static contact at a certain speed. After the contacts are separated for the first time, the current crosses zero and the arc goes out. With the increase of the voltage difference across the contacts, the switch gap breaks down and the first arc reignition occurs, and the arc is extinguished when the current crosses zero. Repeat the above process until the distance between the moving contacts of the disconnector is sufficiently large, and the voltage difference across the contacts is not enough to penetrate the gas, and the arc no longer reignites.

The maximum voltage amplitude of the oscillation occurred at the reignition time of the last arc is obtained by

$$U_f = \sqrt{\frac{2}{3}} U_{f_l} \left(1 + e^{-1/2f\tau}\right)$$

(2)

where $U_{f_l}$ is the amplitude of the high-frequency oscillating voltage during the last arc re-ignition during the disconnection of the disconnector, $f$ is the power frequency, and $\tau$ is the bus charge leakage time constant.
\[ i_{km}(t) = \left[ u_k(t) - u_m(t) \right] / R \] (3)

\[ u_k(t) - u_m(t) = L \frac{di_{km}(t)}{dt} \] (4)

\[ i_{km}(t) - i_{km}(t - \Delta t) = \frac{1}{L} \int_{t}^{t'} \left[ u_k(t) - u_m(t) \right] dt \] (5)

\[ i_{km}(t) = i_{km}(t - \Delta t) + \frac{\Delta t}{2L} \left\{ \left[ u_k(t) - u_m(t) \right] + u_k(t - \Delta t) - u_m(t - \Delta t) \right\} \] (6)

\[ i_{km}(t) = \frac{\Delta t}{2L} \left[ u_k(t) - u_m(t) \right] + \left\{ i_{km}(t - \Delta t) + \frac{\Delta t}{2L} \left[ u_k(t - \Delta t) - u_m(t - \Delta t) \right] \right\} \] (7)

\[ i_{km}(t - \Delta t) = \frac{1}{R_L} \left[ u_k(t - \Delta t) - u_m(t - \Delta t) \right] + I_L(t - 2\Delta t) \] (8)

The recursive formula of the equivalent current source of the inductor is obtained by

\[ I_L(t - \Delta t) = \frac{2}{R_L} \left[ u_k(t - \Delta t) - u_m(t - \Delta t) \right] + I_L(t - 2\Delta t) \] (9)

According to the voltage value at both ends of the inductor element at the current moment and the current value at the previous moment, an equivalent current source of the inductor element can be obtained.

3. Simulation of switching operation characteristics

In operation, sometimes it is necessary to use the disconnecting switch to open and close a section of the no-load bus, the charging current of the capacitor voltage transformer (CVT) and other equipment. However, the disconnector itself does not have the ability to open and close. The open and close buses of the disconnector are extinguished by the contact lengthening the arc during the movement. During the arc extinguishing process, dozens or even hundreds of re-ignition and re-ignition will occur Ignited, forming a fast transient process with extremely steep front edges.

The electromagnetic process is very complicated during the disconnection of the disconnector. EMTP-ATP is used to establish a calculation model suitable for quantitative analysis of overvoltage. The busbars are uniformly distributed parameters, which can be represented by T-type circuits and centralized parameters. The simulation model uses the TACS switch in ATP to simulate the heavy breakdown of the arc gap dielectric of the isolator. The bus length in the simulation model is 180 m, and the capacitance to ground is 20 pF/m (measured value). The key to the simulation calculation of the operating switch overvoltage is the judgment and simulation of its opening and closing conditions. The switching state of the switch depends on the arc being extinguished and reignited. According to the related theory of AC arc, the quenching and reignition of the arc are determined by two conditions: (1) the AC arc current crosses zero; (2) the relationship between the recovery strength of the isolator switch arc gap medium and its recovery voltage. A switch calculation model is designed based on the judgment of these two conditions.

Take the voltages \( V_3 \) and \( V_4 \) flowing across the standard resistor \( R_1 \), and obtain the direction of the current flowing through the switch \( T \) according to the positive and negative of the subtraction. One of the current signals passes through the delay delay and a calculation step \( \Delta T \) Then, when the direction is compared with the current, if the direction is different or the absolute value of both steps is zero, the model output terminal outputs 1, otherwise it outputs 0.

After the current crosses zero, whether the arc reignites depends on the medium recovery intensity and the recovery voltage between the switch contacts. If the medium recovery intensity is less than the recovery voltage, reignition occurs, otherwise the arc is extinguished. Due to the linear relationship between the medium recovery strength and the electrode distance when the distance is small, [4]
assuming that when the disconnector is closed, the contact leaves are a uniform process, and the medium recovery strength also increases linearly with time.

Obtain the voltages $V_1$ and $V_2$ on both sides of the isolation switch contact at time $t$, use the subtractor to obtain the difference between $V_1$ and $V_2$, and obtain the absolute value processing to obtain the recovery voltage on both sides of the isolation contact, and recover from the medium that increases linearly with time. Intensity difference processing, if the recovery voltage is greater than the medium recovery intensity, output 1, otherwise output 0.

Pass the generated arc current zero-crossing judgment signal, the arc extinguishing and reignition judgment signal through a NAND gate to obtain the control signal of TACS SWITCH. When the control signal is 0, the switch is opened; when the control signal is 1, the switch is closed.

Figure 1. Voltage difference between both sides of the disconnector

Figure 2. Spectrum diagram of electromagnetic interference signal

Figure 1 shows the switching operation model for the closing simulation operation, and the voltage difference between the two sides of the switch is obtained. Figure 2 shows the frequency spectrum of disturbance current during closing operation. At the beginning of the closing operation of the disconnect switch, the distance between the switch contacts is large, and the medium recovery strength is greater than the voltage difference between the two sides of the switch. The voltage difference between the switches is not enough to penetrate the gas medium. As the switch moves, the distance between the dynamic and static contacts becomes smaller and smaller, and the medium recovery strength gradually decreases.

The opening and closing simulation operation is performed through the isolation switch operation model. When the switch is opened, the contacts start to move from the closed state. When the two contacts are separated, the medium between them is broken down. In the late stage of the switch opening, the number of breakdowns is significantly reduced. Until the isolation switch is opened for a certain distance, the dielectric is not enough to be broken down, and the circuit is stable.

4. Conclusions

Based on the mechanism of fast transient pulse group generated by switching operation, a simplified model of disconnecting and closing the no-load bus is established, and the ultra-fast transient overvoltage signal is calculated. The maximum overvoltage amplitude is generated when the disconnector opens and closes the no-load bus. Disturbance waveforms generated by the closing operation of the disconnector show a tapered change from front to back and then from dense to large. The waveform of the opening operation is just the opposite. The overall disturbance signal generated by the switching operation is a periodic function with a discrete frequency spectrum. The disturbance voltage of the disconnector during the opening operation has a larger peak value and a longer duration than the disturbance voltage of the closing operation, and the electromagnetic disturbance caused by the opening operation is more serious.
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