Experimental Research on Strong Transient Electromagnetic Interference in Substation

Cheng Lin, Wang Naiyong, Ma Xuejie and Bi Chuang

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Lin Cheng
State Grid Shaanxi Electric Power
Research Institute of Electric Power
Xi'an, China
chaplin138@163.com

Naiyong Wang
State Grid Shaanxi Electric Power
Research Institute of Electric Power
Xi'an, China
172377199@qq.com

Xuejie Ma
School of Aeronautics and Astronautics
University of Electronic and Technology of China
Chengdu, China
1592635810@qq.com

Chuang Bi
School of Aeronautics and Astronautics/Aircraft Swarm Intelligent Sensing and Cooperative Control Key Laboratory of Sichuan Province
University of Electronic and Technology of China
chuang.bi@uestc.edu.cn

***Abstract*—This paper proposes an experimental method to study strong transient electromagnetic interference in substation. A circuit breaker is used to control the turn-on and -off of the sphere gap arc to generate continuous multi-pulses to simulate the process of opening and closing strong transient electromagnetic interference of 330kV Air Insulated Switchgear (AIS) and Gas Insulated Switchgear (GIS). The electromagnetic interference is measured under different voltage levels, different load conditions and different positions, which is used to evaluate the immunity characteristics of the secondary equipment. The experimental method in this paper can also be applied for the electromagnetic compatibility performance evalulation of electronic transformer, where the isolation switch is used to simulate the electromagnetic interference source.**

Keywords—Isolation switch, AIS, electromagnetic interference, GIS

I. Introduction

The development of smart grid technology has radically changed the construction form of substations, and the secondary equipment will face a more severe electromagnetic environment than conventional substations[1-2]. Electronic transformers, which is the intelligent equipment in the power system, have electromagnetic compatibility faults in the engineering applications[3], due to the existing standards for intelligent equipment are based on the electromagnetic environment of traditional substations, which cannot fully meet the actual working conditions of the smart substation. In the electromagnetic compatibility standard[4], the voltage amplitude of the electrical fast transient pulse group immunity is 4kV, the frequency is 10MHz, and the duration is 15ms. However, the measured voltage amplitude on site can reach 20kV, and the frequency can reach 30MHz and the duration is 100~300ms. Therefore, although the electronic devices have passed the electromagnetic compatibility test specified in the standard, there is still a high failure rate on site [5].

It is very important to carry out research on system-level strong electromagnetic environment simulation technology for substations. In [6], the very fast transient over-voltage (VFTO) of 800 kV GIS substation is measured, and the results include the influence of arcing time and the number of breakdowns on the disturbance level. In [7], various isolation switch operations in 1000 kV substation is evaluated, and the electro-magnetic transient program (EMTP) simulation results show that the maximum over-voltage of VFTO is 1.58 p.u., and the main frequency is between 840 kHz and 30 MHz. In [8], the VFTO radiated electric field generated by the operation of a three-phase circuit breaker in a 220k V GIS is measured. The experimental results show that the amplitude of the pulse electric field, generated by the circuit breaker's closing operation of the no-load transformer, is 7kV/m, the leading edge is 5ns, and the leading edge steepness is 1.2(kV/m)/ns.

Aiming at the 330kV AIS and GIS systems of the substation, this paper uses a circuit breaker to finely control the on-off of the moving ball gap arc to simulate the strong transient electromagnetic process of the on-site isolating switch. And obtains the electromagnetic interference characteristics under different electrical conditions.

The main structure of the paper is as follows: Section II describes the experimental principle of the isolation switch to simulate the electromagnetic interference sources. Section III explains the experimental equipments and experimental methods. Section IV analyzes the electromagnetic interference of AIS and GIS. Section VI gives the conclusion.

II. Experimental Principle of Transient Electromagnetic Interference in Substation

A. Air Insulated Switchgear

The experimental diagram of electromagnetic interference in isolating switch is shown in Fig.1. The transformer control system T is used to control the power frequency voltage level of the transformer output, the power-side capacitive voltage divider C_1 is used to monitor the voltage of the test transformer; the power-side capacitor C_2 is used to simulate the total capacitance of the live blade side of the isolation switch in the actual field; the vacuum circuit breaker switch B is used to simulate the on-off process of the electromagnetic interference source; the discharge ball gap D is used to simulate the on-off arc process of the actual isolation switch; the load-side capacitor C_3 is used to simulate the sum of the load blade-side capacitance of the isolation switch and the sum of the no-load long-line capacitance in the actual field; L is ground inductance.

When the AIS isolating switch is opened and closed, the disconnection voltage U_g of the isolating switch changes with the power-frequency voltage. When U_g is higher than the breakdown voltage U_c between the moving and static contacts, the dielectric gap will be broken down, and the gap arc will pass through the high-frequency transient current to form an electrical loop. Because there are a large number of energy storage components in the system, each breakdown will produce a transient high-frequency oscillation process. Electric current forms an electrical circuit. Because there are a large number of energy storage elements in the system, each breakdown will produce a transient high-frequency oscillation process, the oscillation frequency is:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - (\frac{R}{2L})^2} \quad (1)$$

where R, L, C is the equivalent total resistance, total inductance, total capacitance in the circuit during the operation of the isolating switch.

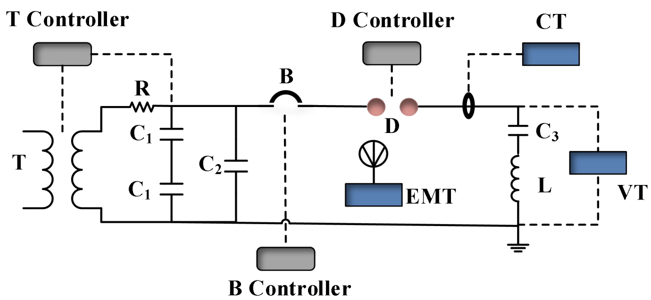

Fig.1. Equivalent circuit diagram of experimental system.

During the oscillation process, if the values of the loop parameters L and C are small, a transient over-voltage with a high frequency is generated. Under the action of high-frequency over-voltage, an arc reignition occurs between the contacts of the isolating switch, and a series of high-frequency oscillations will be formed in the loop, which interferes with the secondary system of the power grid through coupling methods such as conduction, electric field, magnetic field, and radiation, causing various failures of the secondary system.

B. Gas Insulated Switchgear

During the opening and closing of the isolating switch, the traveling wave generated by the SF_6 gas breakdown of the switch fracture spreads and develops on the GIS and its adjacent devices, and triggers a high-frequency oscillation process. Each breakdown causes the switch fracture voltage to drop within a few nanoseconds, resulting in a very steep voltage traveling wave. Under the same conditions, the insulation performance of SF_6 gas is several times that of air, which greatly shortens the electrical distance between adjacent GIS equipment. On the one hand, the travel of the traveling wave during the transmission process is shortened, and the oscillation frequency is much higher than that of the isolation switch operation in the air-insulated substation. On the other hand, as the traveling wave transmission distance is shortened, the damping effects such as transmission loss and skin effect in the propagation process are also reduced, which makes the high-frequency oscillation last longer. This also explains why the phenomenon of extremely fast transients in GIS is far more serious than in air-insulated substations.

III. EXPERIMENTAL EQUIPMENTS AND METHODS

A. Experimental System

According to the circuit diagram in Fig. 1, the outdoor experimental system built is shown in Fig. 2. The equipment included in the system is shown in TABLE I. It contains primary equipments, secondary equipments and their parameters.


(a) (b)

Fig.2. Outdoor experimental system structure (a) Outdoor test site of substation (b) System control room

TABLE I. EXPERIMENTAL SYSTEM EQUIPMENTS

Equipment classification	Equipment Description	
	Equipment name	***Parameter Description***
Primary Equipment	Test transformer T	Simulate the industrial frequency high voltage power supply
	Protection resistance R	100 Ω
	Power-side capacitive voltage divider C_1	Monitor the voltage of the test transformer
	Power and load side capacitance C_2,C_3	Two sets of 1000pF, 2000pF , 5000pF
	Breaker switch B	Control the on-off and the duration of disturbance source
	Discharge ball gap D	Diameter : 10cm Adjustable distance: 0cm-5cm
	Ground inductance L	Adjustable inductance
Secondary Equipment	Load side voltage measuring device VT	Measuring range: 5kV and above, 50Hz～250MHz
	High frequency electromagnetic field measuring device EMT	Bandwidth is not less than 500MHz
	Load side current measuring device CT	Measuring range: 0~3kA, 200kHz～100MHz

If an isolating switch is used as an electromagnetic interference source, the arcing process is highly dispersed, the on-off time is unstable, and the experimental process time is long, the operation is complicated, and the efficiency is low, which cause the experiment to be unable to truly simulate the on-site electromagnetic environment of the electronic transformer. Therefore, this experiment uses a combination of a 330kV vacuum circuit breaker and a discharge ball gap-simulated isolating switch, and the circuit breaker is used to control the on and off of the simulated interference source.

B. Experiment procedure

- Step 1:

Connect the test transformer, capacitive voltage divider, grounding inductance, power-side analog capacitor, circuit breaker, discharge ball gap, and load-side analog capacitor.

- Step 2:

Connect the high-frequency current acquisition device in series between the discharge ball gap and the load-side capacitance to measure the load-side current; connect the high-frequency voltage acquisition device in parallel at both ends of the load, and use the insulator to raise the insulation distance required by the primary voltage to be tested to measure the load side voltage; use an electromagnetic field probe to measure the electric and magnetic fields in the space near the spherical gap.

- Step 3:

Start-up debugging related control device, high-frequency voltage current, electromagnetic field acquisition device.

- Step 4:

In the open state of the circuit breaker, the transformer high-voltage output rated working voltage.

- Step 5:

By operating the circuit breaker to operate the control device, set the discharge mode and discharge delay time, which can be "single opening" or "single closing", or "close-delay t-open" mode.

- Step 6:

Record and measure high-frequency voltage and current, electromagnetic field waveform data .

- Step 7:

After waiting for 2 minutes, repeat the operation of 3 to 4 mode 9 times, a total of 10 combined operations.

- Step 8:

The high-voltage transformer is reduced to zero and the test is over.

If the output parameters of the equipment differ greatly from the expected value, change the ball gap distance to adjust; if the electric field amplitude needs to be changed, it can be achieved by moving the measuring probe close to the experimental circuit or changing the power supply capacitance or changing the load capacitance; if the transient state needs to be changed, it can be realized by changing the “close-delay t-minute” time of the circuit breaker. After adjusting the device parameters, repeat the operation until the output parameters meet the requirements.

IV. Analysis of Experimental Results

A. *Over-voltage and over-current*

According to the experiment procedure in Section III, the over-voltage and over-current on the load side of AIS is measured. The single pulse waveform of the instantaneous current and voltage measured under the conditions of power frequency voltage of 100 kV, input capacitance of 1000 pF and output capacitance of 3000 pF is shown in Fig. 3. It can be seen from Fig. 3. that the peak value of the voltage pulse at the moment of breakdown can reach about 156 kV, and the peak value of the current pulse can reach about 204 A, and the single breakdown is a process of oscillation attenuation.

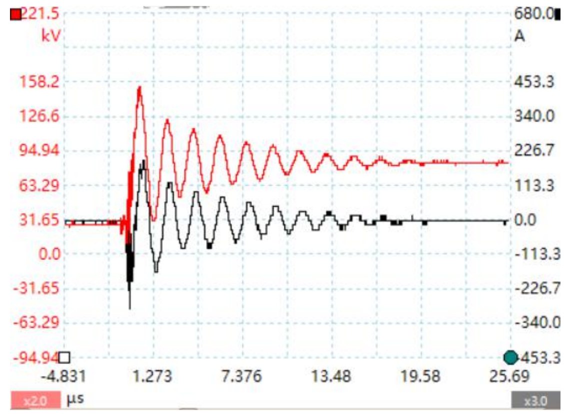

Fig.3. Single pulse measured waveform of voltage and current at the moment of breakdown

In addition, Fig. 4. shows the variation of over-voltage and over-current with different load capacitances at a voltage level of 50 kV. In Fig. 4 (a)，the selected output capacitance is 3000 pF, and the input capacitance is 1000 pF, 4000 pF, 7000 pF, and 10000 pF. It can be seen that as the input capacitance increases, the peak values of the over-voltage and over-current single pulses both increase. In Fig. 4 (b), the input capacitance is 4000 pF, and the output capacitance is 1000 pF, 3000 pF, 5000 pF, 10000 pF. Over-voltage and over-current also increase with the increase of output voltage. The same conclusion can be obtained for a voltage level of 100 kV, except that the peak value is increased compared to 50 kV. The specific data is shown in TABLE II and TABLE III.

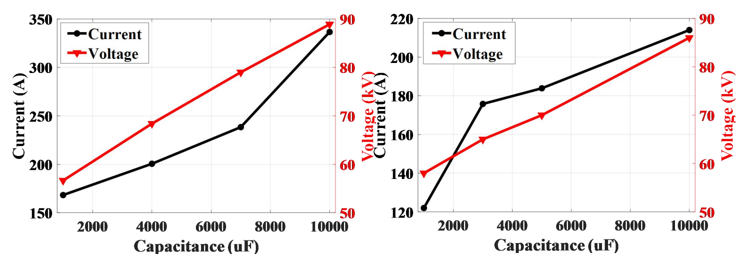

Fig.4. Over-voltage and over-current under different capacitance conditions.

TABLE II. Transient Interference under Different Output Capacitance Conditions

Output capacitance (pF)	Fixed input capacitance	
	Over-voltage (kV)	Over-current (A)
1000	112.2	275.2
3000	135.4	298.1
5000	169.1	321.0
10000	180.5	389.0

TABLE III. TRANSIENT INTERFERENCE UNDER DIFFERENT INPUT CAPACITANCE CONDITIONS

Input capacitance (pF)	Fixed output capacitance	
	Over-voltage (kV)	*Over-current (A)*
1000	108.1	275.9
4000	123.3	298.5
7000	168.1	520.0
10000	172.0	540.0

B. *Electromagnetic field*

In this experiment, the radiated electromagnetic field of AIS at the input-side and output-side of the line was measured. Place the measuring equipment on the ground at a distance of 1 m, 2 m, 3 m, and 4 m from the insulating column, and measure the three directions of X, Y, and Z. Under the condition of a voltage level of 50kV, a given input capacitance of 4000 pF and an output capacitance of 10000 pF. The results are shown in Fig. 5. As can be seen in Fig. 5, the electric and magnetic fields received in the X-direction are higher than those in the Y-direction and Z-direction, and as the measurement distance increases, the electromagnetic field intensity gradually decreases.

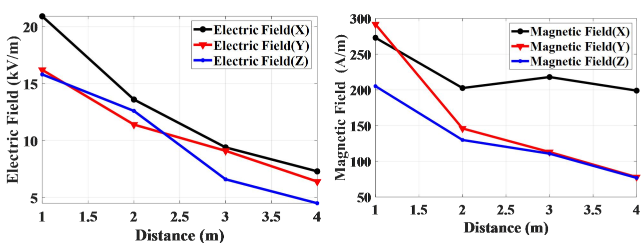

Fig.5. Electromagnetic field at different positions (a) Electric field strength (b) Magnetic field strength

C. *VFTO of GIS*

Apply the experimental procedure of Section III to the GIS system, set the input capacitance of the system to 4000 pF, the output capacitance to 3000 pF, and the voltage level to 50 kV, the measured VFTO waveform is shown in Fig. 6, where the peak value of VFTO can reach 63.78kV. Before reaching the steady state, the voltage waveform appears stepped as a whole, with partial waveform distortion. It is consistent with the theoretical analysis results.

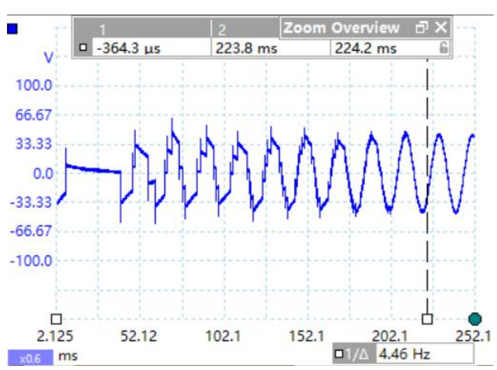

Fig.6. VFTO measured waveform at the output side of GIS system

V. CONCLUSIONS

In this paper, the combined control of the circuit breaker and the ball gap is used to simulate the electromagnetic transient phenomenon caused by the operation of the isolating switch of the substation. The over-voltage, over-current, and electromagnetic radiation of the AIS system, as well as the VFTO in the GIS system are analyzed. The conclusion is that: different load capacitance has a greater impact on the transient current voltage and electromagnetic field, over-voltage and over-current increase with the increase of input and output capacitance, and the electromagnetic field decreases with the increase of measuring distance, which is consistent with the theoretical analysis.

VI. ACKNOWLEDGMENT

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