

The Research on the Key Equipment for 750kV Fixed Series Compensation in 3000m a.s.l.

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SUMMARY

The Qinghai 750kV fixed series compensation is officially put into operation in December 2018, it is located in the Qaidam area of China where the altitude is 3000m. In this paper, the high-altitude insulation calculation of the main equipment is carried out, and the power frequency withstand voltage, lightning impulse voltage, dry arc distance and creepage distance of each main equipment are proposed. Based on the project, we researched the key equipment such as spark gap and measurement system. According to the ANSYS simulation, the structure of the main electrode of the spark gap is optimized from ball-ball electrode to ball-plate electrode to make the self-trigger voltage be more stable. Considering the self-trigger voltage of the trigatron is up to 60kV_{peak}, the electrode structure of the trigatron is optimized to the structure with large curvature spherical design. The new trigatron has a better linearity and the maximum standard deviation is less than 0.6. In order to research the triggering characteristics, we completed the self-trigger test in the laboratory where the altitude is 0m, and fit the curve of the main gap air distance and the self-trigger voltage. Considering the altitude correction, we calculate the theoretical value of the main gap air distance according to the self-trigger curve. In order to verify the correctness of the revised calculation method, we carried out the triggering test on the site where the altitude is 2900m. Considering the first use of the spark gap in high altitude 750kV systems, a gap trigger test system was built on the site. The test system can supply the power frequency voltage at both ends of the main gap and collect the actual voltage across the gap. And the value of the voltage can be sent to the FSC protection device by IEC60044-8 protocol. If the spark gap is triggered, the engineer can get the triggering voltage value from the protection device by the waveform during the test. Compared with the measured value and the theoretical value of the triggering voltage, it shows that the revised calculation method is right. In addition to the spark gap, the measurement system is also researched. The system consists of windows CT, optic signal column, and merging unit, and can collect the capacitor current, MOV current, capacitor unbalance current, line current, gap current and platform flash current. The windows CT have strong anti-EMI ability, because the A/D converters are integrated with it and the power supply is provided by optical laser from the merging unit on the ground level. And the measurement system has been proved to have good anti-electromagnetic interference capability by open and close the disconnector when the FSC is charged. Finally, the single-phase-to-earth fault is carried out to prove that the series capacitor protective equipment and the line protection relays operate correctly. The logic of the protection device action is analyzed according to the protection device recording. The analysis results show that the action of the spark gap is right. So the performance of the series compensation set is verified by the test.

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KEYWORDS

spark gap; series compensation; high altitude; measuring system; single-line-to-ground test

I. INTRODUCTION

With the development of China's economy and society, the demand for power transmission capacity of the power grid is increasing. Fixed series compensation capacitors (FSC) as a method to improve long-distance line transmission capacity have attracted more and more attention in China's power grid planning. In recent years, China has increased the application of FSC in ultra-high voltage power grids. Related research shows that the installation of 750kV FSC on Qinghai Power Grid can effectively improve the power transmission capacity and ensure the safe and stable operation of the Northwest Power Grid. However, the altitude of Qinghai is relatively high, and the altitude of the installation site has reached 3,000 meters. According to the existing research results and operational experience at home and abroad, the relative density of air in high altitude areas is low, and the discharge voltage will be reduced in both insulators and air gaps.

In this paper, the high-altitude insulation calculation of the main equipment is carried out relying on the Qaidam FSC. Considering the fact that the self-triggering occurred frequently in the past, the spark gap was studied. And the electrode structure was optimized. At the same time, the measuring system is introduced, which has strong anti-electromagnetic interference capability. Finally, the action waveform of the single-line-to-ground test is analyzed.

II. INTRODUCTION of 750kV SERIES COMPENSATION SYSTEM

The main purpose of using series compensation in a power system is virtual reduction of line reactance in order to enhance power system stability and increase load ability of transmission corridors. The principle is based on the compensation of distributed line reactance by inserting series capacitor (SC). The protection mode of MOV paralleled with gap is adopted in this project. The main equipment include: capacitor bank, MOV (metal oxide varistor), spark gap, damping device, bypass switch, optical signal column, measuring system, post insulator, inclined suspension insulator. Among them, MOV is the main protection device of the capacitor bank, limiting the capacitor voltage within the protection level; the spark gap is the backup protection device of the MOV and the capacitor bank. Bypass switch can help spark gap extinguishing, and also it is necessary for system maintenance and dispatching. The damping circuit rapidly attenuates the discharge current of the capacitor to prevent capacitors, spark gaps, and bypass switch from being damaged during discharge^{[1][2]}. The single line diagram of this project is shown in Fig. 1.

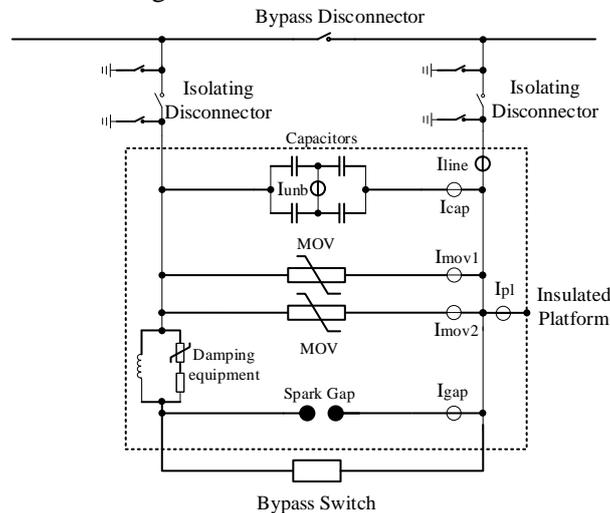


Fig. 1 750kV FSC Single Line Diagram

A. Basic Parameters

The Qaidam FSC is installed in the 750kV line of Qaidam-Haixi double-circuit, and the rated capacity of the single set is 597Mvar. The basic parameters are shown in Tab. 1.

Tab. 1 Basic Parameters

basic parameters	FSC
rated voltage of system (kVrms)	750
rated capacity (Mvar)	597
degree of compensation	20%

rated current (Arms)	3000
rated capacitance (μF)	143.96
rated impedance (Ω/phase)	22.11
rated voltage of the bank (kVrms)	66.3
protective level (kVpeak)	213.87

III. THE RESEARCH of INSULATION LEVEL

The study of insulation level is the premise of the overall design of the series compensation, and it is the requirement that must be met when the equipment is selected. For the series compensation, the insulation requirements are mainly included with the insulation of the series compensation platform to ground (evaluating the insulation performance of the post insulator, inclined suspension insulator, and the optical signal column), the insulation between the equipment on the series compensation platform and the platform (evaluating the insulation performance of capacitor bank, MOV, damping resistance, damping reactor, spark gap), and the insulation of the equipment outside the platform (evaluating the insulation performance of bypass switch, isolation switch). The insulation distribution is shown in Fig. 2.

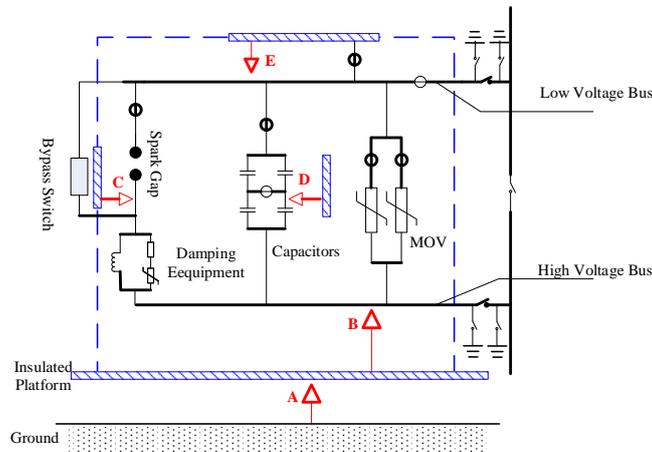


Fig. 2 Distributions of Insulation Level

The insulation distributions shown in Fig. 2 have the following meanings.

Level A: platform to ground.

Level B: high voltage bus to platform.

Level C: the post insulators of spark gap and damping equipment to platform.

Level D: the post insulators of capacitor bank to platform.

Level E: low voltage bus to platform.

A. Voltage Withstand Requirements

The rated withstand voltage of the isolating switch, bypass switch, optical signal column, platform post insulator, and inclined suspension insulator shall be selected according to the system voltage considering with the corresponding altitude correction.

To select the insulation levels for the various components on the bank assembly, IEC 60143 was used. The power frequency withstand voltage (U_{ipf}) of the insulation is calculated using the equation (1).

$$U_{ipf} = 1.2 \times \frac{U_{pl}}{\sqrt{2}} \times (\text{AltitudeCorrectionFactor}) \quad (1)$$

This formula applies to the insulation that spans the entire segment, which is the level of protection used in this segment. This formula also applies to the insulation inside the segment, such as the insulation between the capacitor units and the insulation of the capacitor terminals. The higher of equations (2) and (3) shall apply.

$$U_{ipf(n)} = U_{ipf} \times \frac{n}{s} \quad (2)$$

$$U_{ipf(n)} = 2.5 \times n \times U_n \quad (3)$$

Where n is the number of series section for which the insulation is being applied, s is the total number of series sections, $U_{ipf(n)}$ is the section power frequency withstand voltage, U_n is the nominal rms section voltage and U_{pl} is magnitude of the maximum peak of the power frequency voltage appearing across the overvoltage protector during a power system fault.

B. Altitude Correction

In GB/T 311.2-2013, it is stipulated that the effects of ambient temperature and humidity can cancel each other out when determining the atmospheric correction factor. Therefore, only the altitude where the equipment installed is considered whether it is dry insulation or wet insulation during insulation coordination.

Appendix B "Elevation Correction Factor" of GB 311.1-2012 stipulates: the insulation specified by the standard needs to be corrected according to the following equation (4) when equipment is operating at altitudes above 1000m.

$$K_a = e^{q \left(\frac{H-1000}{8150} \right)} \quad (4)$$

Where H is the altitude above sea level (in meters) ; q is the index and the value is as follows :
 $q=1.0$ for lightning impulse withstand voltage ; $q=1.0$ for short-duration power-frequency withstand voltage of air clearances and clean insulators ; The q value is selected as shown in Fig. 3 for switching impulse withstand voltage.

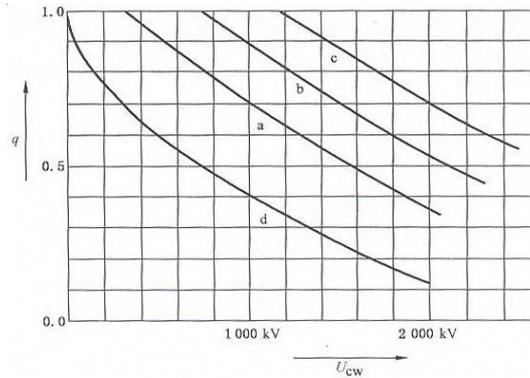


Fig. 3 the Ration between the q And the Impulse Withstand Voltage

In Fig. 3, curve a is for phase-to-earth insulation ; curve b is for longitudinal insulation ; curve c is for phase to phase insulation ; curve d is for rod-plane gap.

When the insulation coordination is performed on the Qaidam FSC, the altitude is 3000m. For lightning impulse and power frequency withstand voltage, the altitude correction factor K_a is 1.28; for switching impulse withstand voltage, take $q=0.6$ according to curve a, so the altitude correction factor K_a is 1.16.

C. Insulation Creepage Distance Requirements

The creepage ratio is the ratio of the creepage distance of the external insulation of the power equipment to the highest voltage of the equipment, in mm/kV. The pollution level of Qaidam FSC station is e grade, so its minimum nominal creepage ratio is 31mm/kV.

The minimum creepage distances were calculated according to the equation (5) :

$$L_{\min} = U_m \times \sqrt{3} L_{\text{spec}} \times \frac{I_{30}}{1.35} \times K_a \quad (5)$$

Where L_{spec} is minimum nominal specific creepage distance and the pollution level of Qaidam FSC station is e grade, which the minimum nominal creepage ratio is 31mm/kV. Where $(I_{30} / 1.35)$ is a scaling factor used when the 30 min overload current I_{30} , exceeds 1.35 p.u. and U_m is highest nominal voltage continually appearing across the insulation. K_a is for short-duration power-frequency withstand voltage, and it is 1.28.

D. Air Clearances

The FSC is installed in the AC system, the appropriate air clearances should be calculated according to the equation in Appendix F of GB/T 311.2-2013. The formula is as shown in equation (6).

$$U_{ipf(n)} = 0.9 \times 750 \times \ln(1 + 0.55d^{1.2}) \quad (6)$$

Where $U_{ipf(n)}$ is the power frequency withstand voltage ; d is the air clearance.

E. Calculation of Insulation Level

The insulation requirements of the equipment can be calculated by the above-mentioned insulation coordination analysis method. And the insulation requirements of each level can be obtained, as shown in Tab. 2.

Tab. 2 Insulation Requirement

Level	Power frequency withstand voltage(kV)	Lightning impulse withstand voltage(kV)	Creepage distance(mm)	Air Clearances (mm)
A	1230	2685	30937	6487
B	275	650	4443	783
C	275	650	4443	783
D	140	325	2222	408
E	28	95	687	118

IV. THE RESEARCH of SPARK GAP

The FSC is generally equipped with a spark gap, which is connected in series with the damping circuit in parallel with metal oxide varistors (MOV) to quickly bypass the MOV during the internal fault within 1ms to make sure the energy absorbed by MOV don't exceed the design rating.

At present, the spark gap commonly used in China is open, including a trigatron and a main gap [3]. Since the main gap is open, its discharge characteristics are susceptible to environmental factors. The typical structure of the spark gap is shown in Fig. 4.

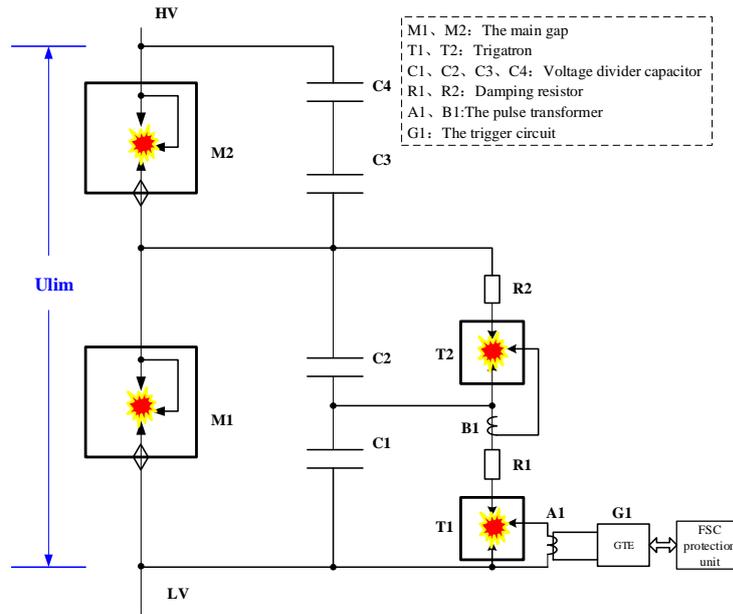


Fig. 4 the Spark Gap System

A. Main Gap

According to the protection level of the capacitor bank, the self-trigger voltage of the single main gap in the double-stage spark gap of the Qaidam FSC project is 156.13kVpeak. Considering the influence of the altitude correction, the distance between the main gaps will be adjusted to about 90mm. In the research process, in order to improve the stability of the spark gap and reduce the self-triggering probability affected by the environment. We optimize the electrode structure of the main gap compared to the spark gap used in the 500kV FSC project. The ball-ball electrode structure was changed to a ball-plate electrode structure as shown in Fig. 5.

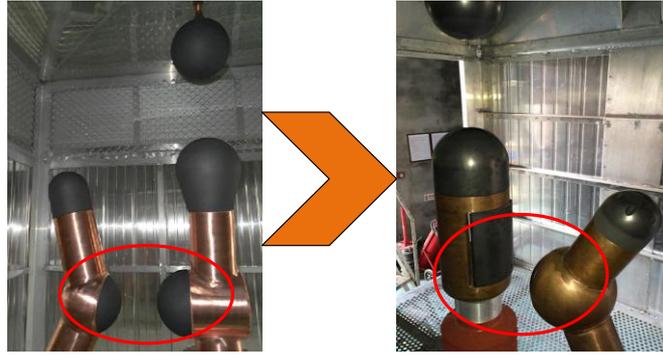
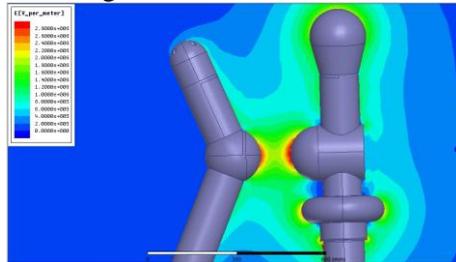
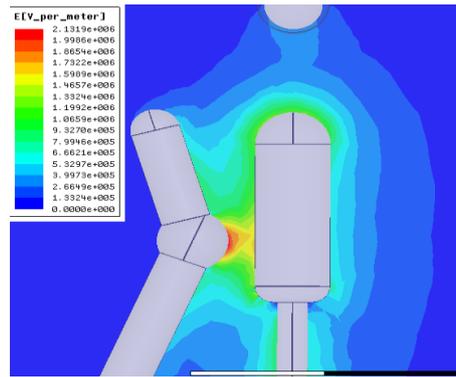


Fig. 5 Optimization of Electrode Structure

During the research process, the electric field strength of the gap is simulated and analyzed. The simulation cloud diagram is shown in Fig. 6.



(a)



(b)

Fig. 6 the Simulation of Electric Field Intensity

In order to analyze the unevenness of the electric field of the main electrode, a non-uniform coefficient is introduced, which is the ratio of the maximum field intensity to the average field intensity.

$$f = E_{max} / E_{av} = E_{max} / (U/d) \quad (7)$$

Where E_{max} is the maximum field strength between electrodes; E_{av} is the average field intensity; U is the voltage applied across the electrode; d is the distance between electrodes.

The non-uniformity coefficient of field intensity decreases from 2.3 to 1.33 according to the simulation result, while the voltage and the gap distance are the same. It effectively improves the discharge stability of the spark gap. When $f < 2$, the electric field is a slightly uneven electric field. So the discharge characteristics of the spark gap can be analyzed with reference to the breakdown principle of the uniform electric field [4].

For the spark gap of the ball-plate electrode structure, the self-discharge voltages were tested at gap distances of 50 mm, 55 mm, 60 mm, 65 mm, and 70 mm. The altitude of the test site is 0m. The test data is shown in Tab. 3.

Tab. 3 the Discharge Voltage of Main Gap

No.	Discharge voltage /kV				
	50mm	55mm	60mm	65mm	70mm
1	135.14	144.69	155	166.68	176.42
2	135	146.3	156.65	166	176.8

3	134.57	145.83	156.69	166.73	178.37
4	134.22	145.79	157	167.18	177.36
5	134.9	145.44	156.72	166.92	177.08
6	135.14	145.39	157.75	167.29	177.17
7	136.36	145.6	155.54	167.88	177.76
8	134.29	146.35	156.92	167.57	178.58
9	134.08	146.32	157.35	166	179.14
10	134.08	145.53	156.69	166.29	177.87
average value	134.78	145.72	156.63	166.85	177.66
Standard deviation	0.66	0.49	0.77	0.61	0.80

From the Tab. 3, it can be seen that the standard deviation of the self-trigger voltage of the gap of the ball plate electrode does not exceed 0.8, which also shows that the trigger voltage of the optimized gap is more stable.

B. Trigratron

According to the protection level of the capacitor bank, the maximum self-discharge voltage of the two-stage spark gap (main gap + trigratron) of the Qaidam FSC project is 235.26 kV_{peak}, so the self-trigger voltage of the trigratron is 58.82 kV_{peak}. The common electrode of the original trigratron is a global electrode, and the radius of the ball electrode is 40 mm. The historical test data indicates that the self-trigger voltage of the trigratron of the structure is unstable, and the standard deviation is greater than 1. In order to improve the reliability of the forced triggering of the trigratron, the electrode structure inside the trigratron was optimized during the research, as shown in Fig. 7.

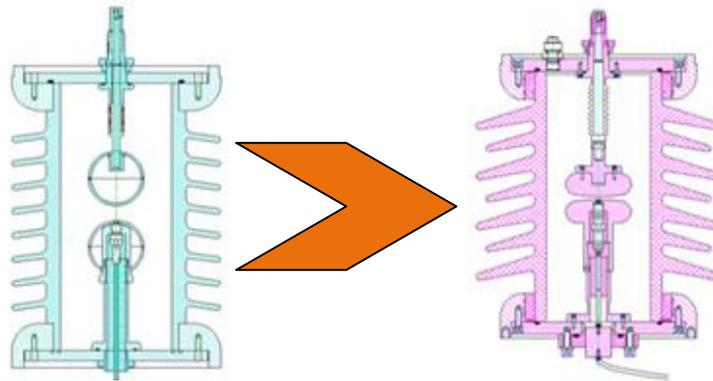


Fig. 7 the Optimization of Trigratron

The optimized trigratron electrode is a spherical electrode with large curvature, and a micro-positive pressure nitrogen gas is charged into the trigratron. The trigger tests are carried out on the optimized trigratron. The results are shown in Table 4.

Tab. 4 the Discharge Voltage of Trigratron

No.	Discharge voltage /kV				
	13.14mm	10mm	15mm	20mm	25mm
1	56.59	45.89	61.39	78.4	95.17
2	56.59	45.76	61.83	78.92	95.88
3	56.99	45.98	62.08	79.71	95.39
4	56.52	45.69	61.16	78.19	94.88
5	56.97	44.62	61.62	79.19	96.61
6	56.62	46.14	62.07	79.09	95.25
7	57.17	45.78	61.94	79.84	95.19
8	56.78	44.81	62.83	79.18	96.29
9	57.75	46.16	62.37	78.69	95.41
10	56.92	46.06	62.5	79.54	95.82
average value	56.89	45.689	61.979	79.075	95.589
standard deviation	0.35	0.51	0.48	0.51	0.52

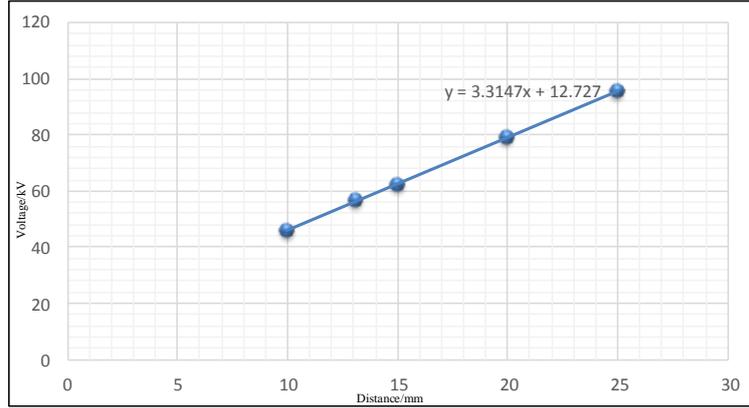


Fig. 8 the Self-Discharge Voltage Curve of Trigratron

It can be seen from Tab. 4 that the standard deviation of the trigratron does not exceed 0.6. It can be found from Fig. 8 that the linearity of the self-trigger voltage of the trigratron is better. And the self-triggering voltage is more stable.

For the trigratron, the performance of the forced trigger determines the reliability of the spark gap forced to conduct in the event of a system failure. During the study, 65% of self-triggering voltage was applied across the trigratron. And it was 100% reliable triggering in both peaks and troughs.

C. Study on the Triggering Characteristics of Gaps at High Altitude

For the conventional FSC project, since the altitude is generally below 1000 meters, the field generally only tests the trigratron by self-triggering and forced triggering through the DC booster.

In this project, considering the altitude of the spark gap application area is 2900 meters, in order to ensure reliable operation of the spark gap, the spark gap should be tested on the whole, and the test circuit is shown in Fig. 9.

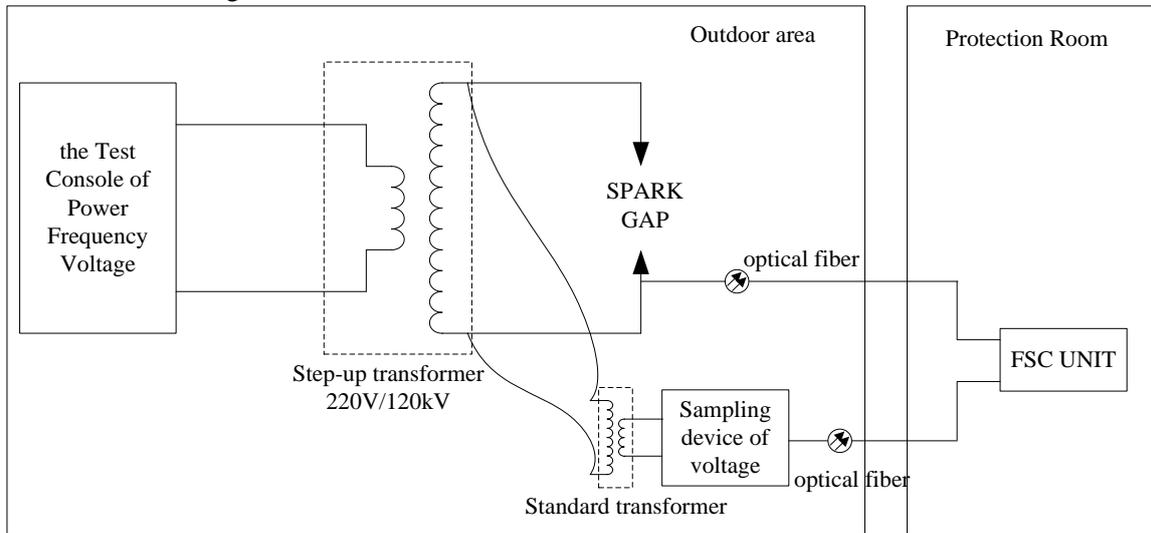


Fig. 9 the Test Circuit of the Spark Gap

As shown in Fig. 9, the frequency voltage is processed at both ends of the gap by the AC booster, and the real-time voltage signal is sampled by the standard transformer and sampling device, and the sampled value is transmitted by the fiber channel through the IEC60044-88 protocol to the FSC UNIT in protection room during the test. If the peak value of the sampling voltage is greater than the forced trigger voltage setting of 169kV, the FSC UNIT will issue a gap trigger command. If the booster voltage drops quickly, it indicates that the spark gap forced trigger is successful.

According to the data in Tab. 3, the discharge voltage curve of the main gap at altitude of 0 m can be fitted as follows:

$$U = -0.001d^2 + 2.258d + 24.44 \quad (8)$$

Where U is the instantaneous value of the voltage at the time of the main gap discharge ; d is the distance between the electrodes of the arcing gap.

The self-trigger voltage of the single main gap in this project is 156.13kV. The voltage value can be corrected from 0 meter to 2900 meters above sea by the equation (9), the correction coefficient $K=1.43$. so the corrected trigger voltage is 223.26kV.

$$K = e^{\frac{H}{8150}} \quad (9)$$

Substituting the corrected voltage into equation (8), it is found that $d=91.79$ mm. So the distance of the main gap is adjusted to 92mm at the site. When the frequency voltage value of 110kV (155.54kVpeak) is applied at both ends of the main gap, the main gap is self-triggered. Then the test loop of Fig. 9 is used to perform a forced trigger test on the spark gap. When the voltage across the main gap rises to 169kV, the gap triggers successfully and the voltage drops. The trigger waveform is shown in Fig. 10.

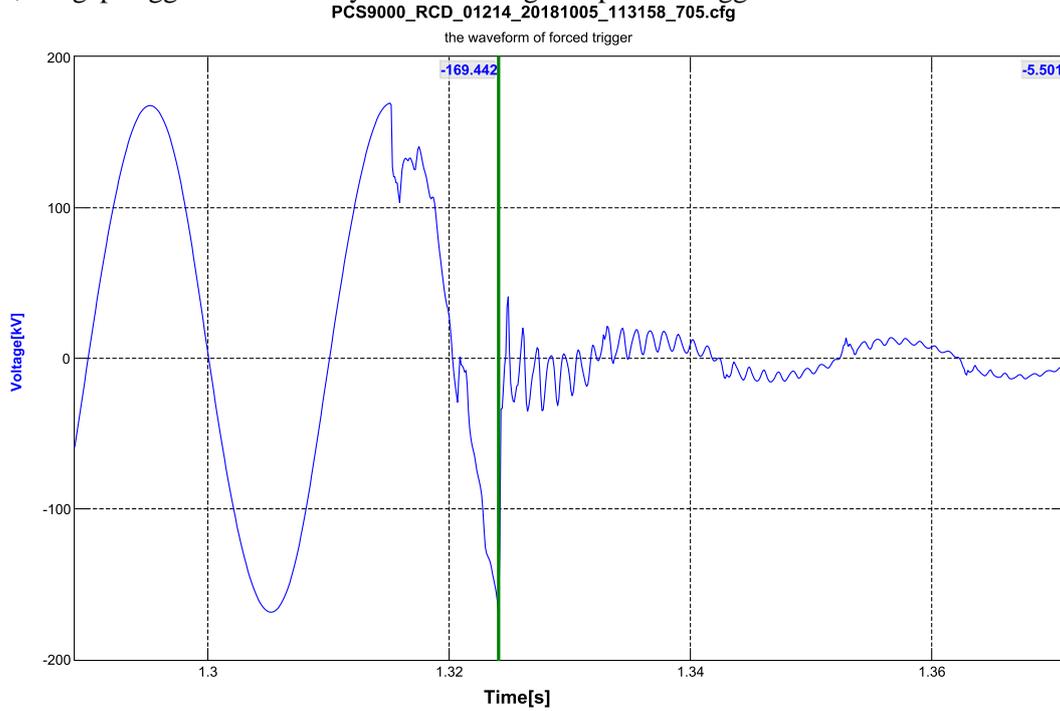


Fig. 10 the Forced Trigger Waveform

V. MEASURING SYSTEM

For the original measuring system of FSC installation, the A/D converters connect with the secondary windings of electromagnetic CTs through long cables.

While the spark gap is flashing over or the disconnect switch is operating, there are very strong EMI (electromagnetic interference) on the insulated platform. So the A/D converters may be affected if there are no other protective measures.

In the project, NR apply the ECT which is shown in Fig. 11 to reduce the electromagnetic interference. The ECT is designed as a window type and the primary conductor is installed across the window. There are two LPCT (low power current transformer) coils in a single ECT, and the analog data are converted to digital data by the A/D converter. The A/D converter is connected with LPCT through very short cable (only about 10 cm). There are two A/D circuits in an A/D converter, and the sampling data are respectively used by pick up and protection DSP modules.

The ECT has strong ability to anti EMI, because the cable connecting the current transform to the A/D converter is very short, and the power supply of ECT is only provided by optical laser from the MU on the ground level^[5].

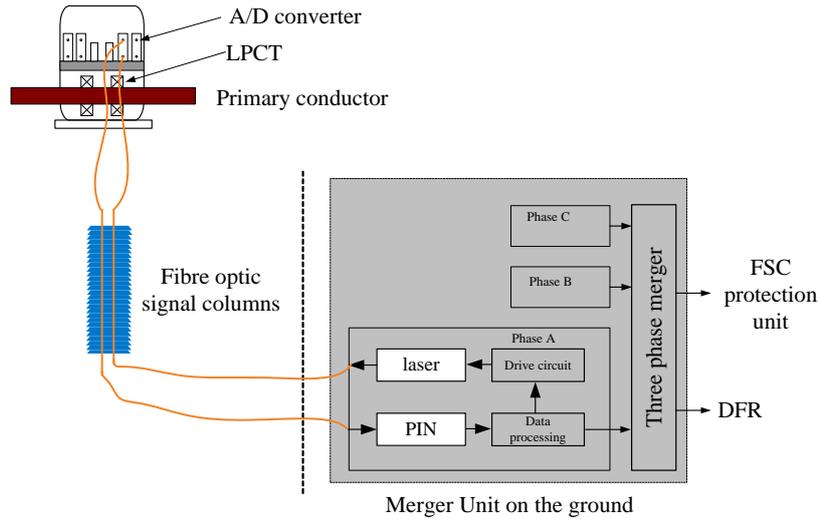


Fig. 11 Principle of an Electronic CT Measuring System

In order to study the actual anti-interference performance of the measuring system, the recording device is used in the operation test to record the waveform of each CT on the platform when the isolating disconnector is operating. The waveform is shown in Fig. 12.

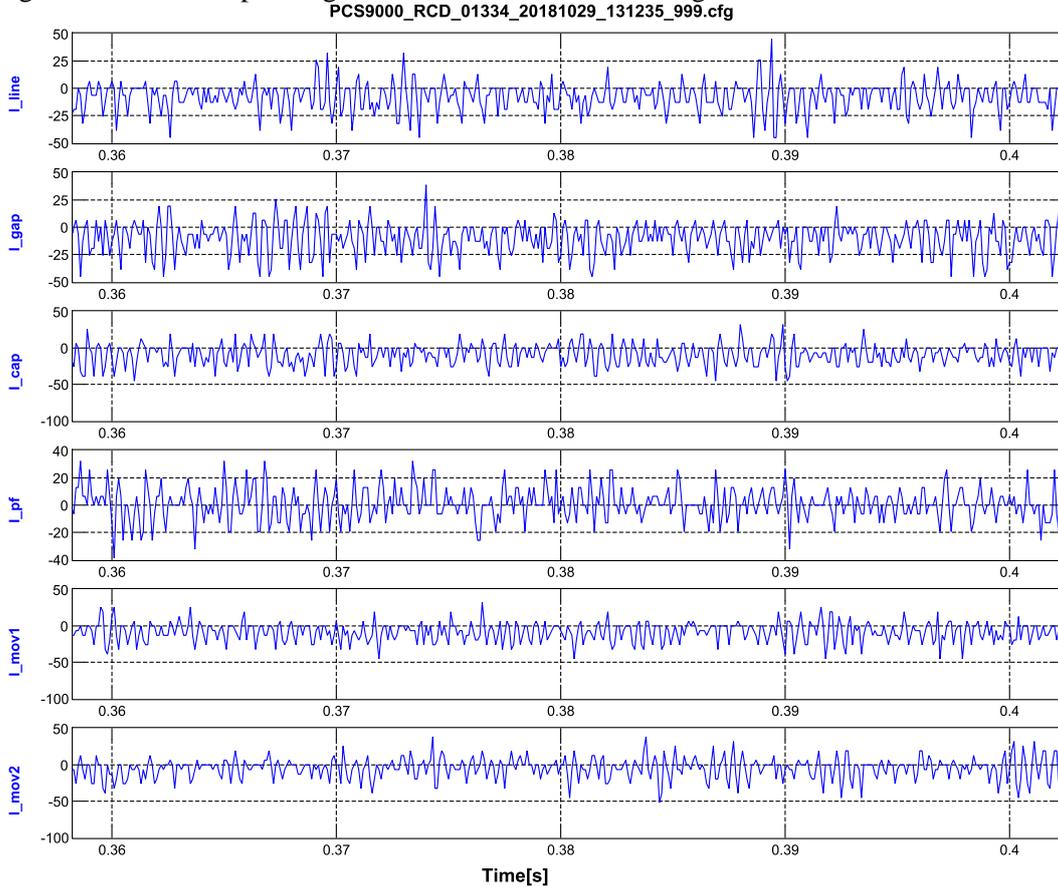


Fig. 12 Waveform during Closing Insulating Disconnector

It can be seen from Fig. 12 that when the platform is energized, the interference current measured by each CT is below 50A, indicating that the measuring system has strong anti-interference ability.

VI. ARTIFICIAL SINGLE LINE TO GROUND TEST

After completing all the routine test items of the SC P&C system, the artificial SLG (single-line-to-ground) test was done in the transmission line about 3 km away from the SC installation. The infrared camera is used to record the moment of the short-circuit test when the spark gap conduct, as shown in

Fig. 13.



Fig. 13 the Infrared Photo of Spark Gap

The related current waveform is shown in Fig. 14, and when the spark gap is flashing over, the bypass switch current and flashover to platform current are almost not affected.

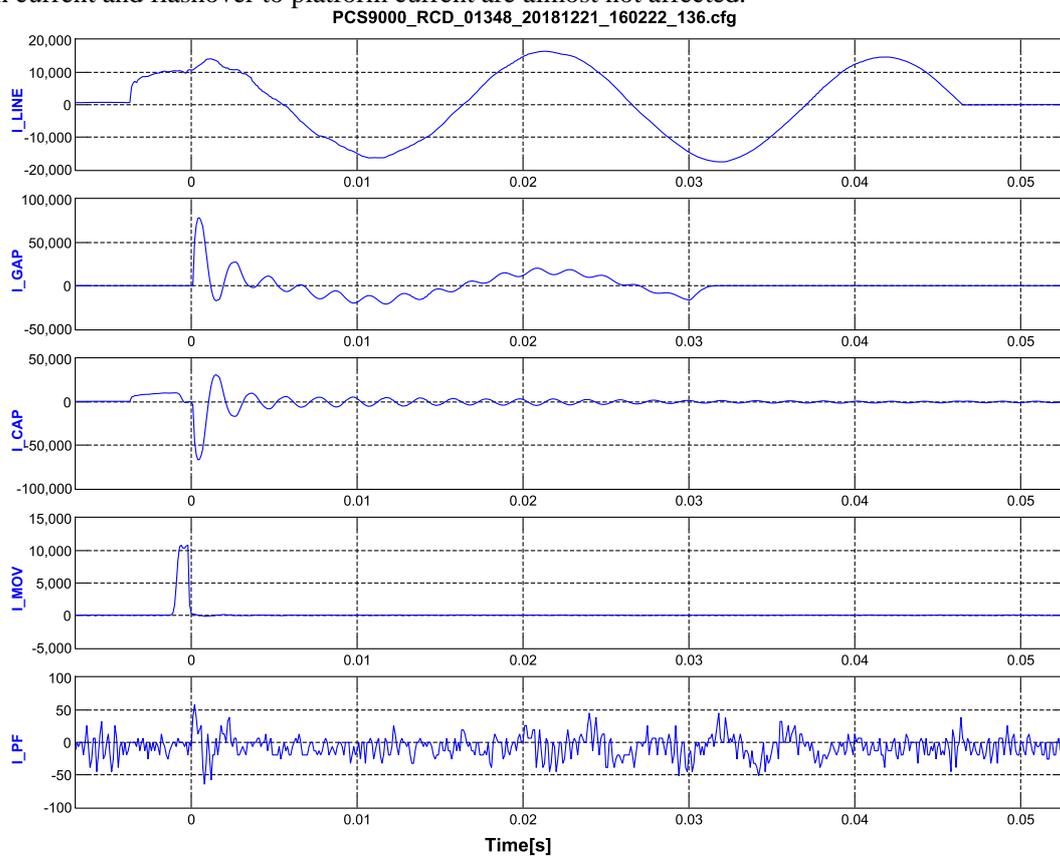


Fig. 14 Current Waveform in Artificial SLG

As shown in Fig. 15, from the varistor current starting to reach the setting until the spark gap starting to conduct, the time delay is about $700\mu\text{s}$. The varistor high current protection setting is 9990A, and the fixed delay is 3 samples (the sampling rate is 10 kHz, 3 samples that is $200\mu\text{s}$).

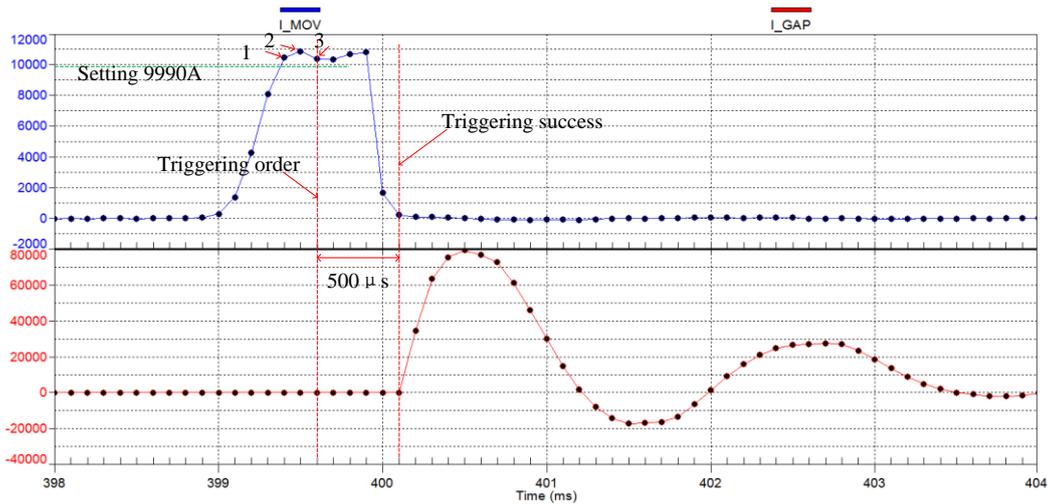


Fig. 15 .MOV Current and Spark Gap Current

VII. CONCLUSIONS

- 1) The high altitude correction equation $K_a = e^{q(\frac{H-1000}{8150})}$ can be used to calculate the correction factor. The design of FSC platform is based on the insulation requirements calculated in the paper, such as the power frequency withstand voltage, lightning impulse voltage, dry arc distance and creepage distance. And the commission test results indicate that the FSC meets the high altitude requirements.
- 2) The main gap electrode adopts a ball-plate electrode with a standard deviation of less than 0.8; the trigatron electrode adopts a spherical electrode with large curvature, and the standard deviation is less than 0.6. The triggering performance of the spark gap is reliable.
- 3) The application of ECT significantly enhances the anti-EMI ability of A/D converter.
- 4) The results of artificial single line to ground fault show that the coordination between the SC P&C system and the primary equipments is very well, the spark gap can reliably and fast be forced triggered to flashover, the time delay from the point at which the varistor current reaches the protection setting until spark gap conduction is about 500μs, and the ECT has strong ability to anti electromagnetic interference.

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