On-Site Standard Lightning Impulse Test for 1,100-kV Gas-Insulated Switchgear With Large Capacitance

Key words: gas-insulated metal-enclosed switchgear (GIS), on-site impulse test, load capacitance, circuit inductance, lightning impulse, insulation detecting effectiveness

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Introduction

Gas-insulated metal-enclosed switchgear (GIS) was developed in the mid-1960s [1]–[5]. Compared with traditional air-insulated switchgear, the GIS concentrates the bus, isolating switch, circuit breaker, lightning arrester, transformer, and many other devices in an enclosed grounding metal case. It has many advantages such as reliability, compactness, long maintenance cycle, and low environmental impact, which have led to it being widely used in electrical power systems [6]–[16]. However, increased operating voltages and more extensive power grids have given rise to increased GIS failure rates [17], [18].

Two main types of insulation defects in GIS equipment may develop in the process of transportation and installation. One arises from unattached conductive particles or dust, and the other from physical damage [19]. On-site withstand voltage and insulation defect detection tests are therefore essential before GIS equipment is put into operation. In recent years, AC withstand voltage and partial discharge tests have become popular. However, they do not detect all types of defects in GIS [20]. It is therefore necessary to develop other tests, to be carried out before GIS equipment is put into operation, which will complement the AC withstand voltage and partial discharge tests.

A new on-site standard lightning impulse test for 1,100-kV GIS with large capacitance is described. It uses a fully enclosed compact standard lightning impulse generator with low inductance.

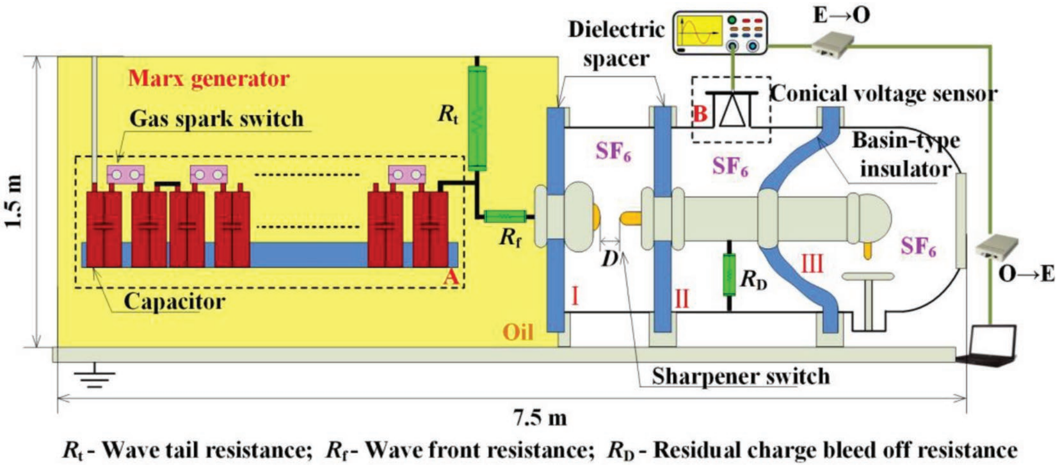

Figure 1. Schematic diagram of impulse voltage generating system.

In this article, the present lightning impulse (LI) test [21], [22], considered as an insulation defect detection test for GIS, is reviewed. Then the influence of various impulse waveform parameters on the discharge characteristics of an SF_6 gas gap is analyzed, in order to evaluate the effectiveness of the LI test in detecting insulation defects. (SF_6 is by far the most frequently used insulating gas in GIS.) Finally, a new on-site LI test, based on a fully enclosed compact standard LI generator, is proposed, and its application in a ultrahigh voltage (UHV) substation is reported.

Limitations of the Standard LI Test for Power Equipment With Large Capacitance

The LI test is particularly sensitive to abnormal field configurations, e.g., damaged electrodes, and is recommended in IEC 62271-203 and GB 7674-2008 for voltage classes of 245 kV and above [23], [24]. Users are recommended to select one of the following two test procedures:

(1) power-frequency voltage test for 1 min and partial discharge measurements at the test voltage specified for the equipment under test, or
(2) power-frequency voltage test for 1 min and LI tests with three impulses of each polarity at the test voltage specified for the equipment under test.

With increasing operating voltage, the capacitance of power equipment increases. In addition, the inductance of the traditional impulse generator is large, possibly as much as 100 μH. The LI wavefront time T_f is defined in (1).

$$T_f = 4.66\sqrt{LC}, \tag{1}$$

where L is the inductance of the generator and C is the capacitance of the equipment under test [21]. Substituting C = 3,000 pF, a typical GIS capacitance, and L = 100 μH yields T_f = 2.55 μs, exceeding the standard LI test upper limit of 1.56 μs.

The Nonstandard LI Test

The IEC has also proposed a nonstandard LI test in which the T_f of the impulse voltage waveform can be as much as 8 μs, or, when using oscillating LI voltages, as much as 15 μs [23]. In order to evaluate the effectiveness of the nonstandard LI test in detecting defects in GIS, we investigated the breakdown characteristics of SF_6 in a highly inhomogeneous electric field.

Experimental

Figure 1 shows our experimental setup schematically. It consists of an oil-immersed Marx generator and simulation GIS bus [21]. A water resistance R_D is used to speed the release of the residual charges when a steep front waveform, e.g., a very fast transient overvoltage, is applied and the sharpener switch is opened. The generator could generate double-exponential impulses with T_f in the range 0.08 to 23.5 μs and tail time around 50 μs, or an oscillating LI with wavefront time around 10 μs and oscillation frequency around 25 kHz, as shown in Figure 2.

The rod-plane electrode system shown in Figure 3 was adopted to simulate local field enhancement in GIS. The high voltage electrode was a 0.5 mm radius hemispherically capped stainless steel rod. The grounded plane was a 300 mm diameter Rogowski stainless steel electrode. In a highly inhomogeneous electric field, the breakdown voltage of SF_6 under positive polarity is lower than that under negative polarity [25], [26]. Positive polarity voltage was therefore used in this study because, at the same absolute value, it is more likely to detect insulation defects than negative polarity voltage. The waveforms were recorded using an oscilloscope (Tektronix DPO4104) with a bandwidth of 1 GHz and a sample rate of 5 Gs/s. Calibration results demonstrated that the response time of the measuring system was less than 5 ns, and the uncertainty in the divider ratio was less than 3%. The voltage-time characteristic of the rod-plane electrode system was obtained by applying impulse voltages of various amplitudes, and its 50% breakdown voltage by using the up-and-down method described in IEC 60060-1 [27]. The 50% breakdown voltage is the voltage at which the probability that a disruptive discharge, i.e., complete insulation breakdown, will occur on the surface or inside the test object is

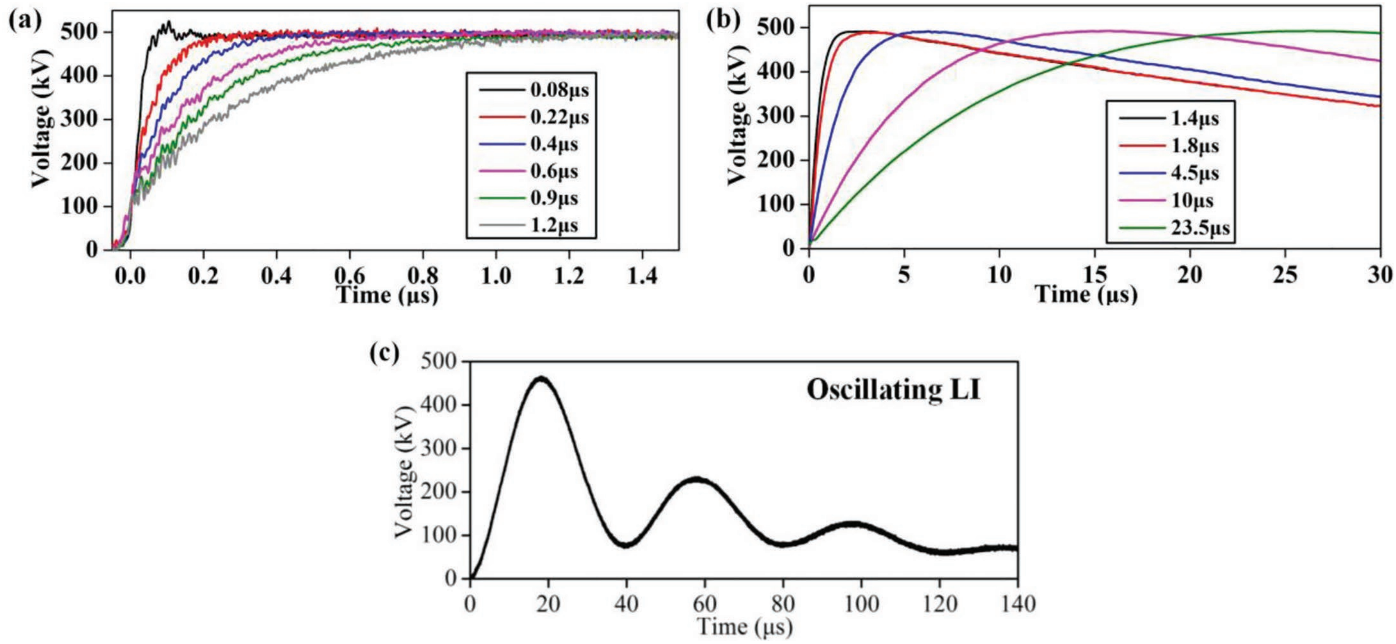

Figure 2. Output impulse voltages with different wavefront times T_f: (a) double-exponential impulses with T_f in the range 0.08 to 1.2 μs, (b) double-exponential impulses with T_f in the range 1.4 to 23.5 μs, and(c) oscillating impulse with T_f around 10 μs. LI = lightning impulse.

50%. The test setup was installed in a chamber filled with SF_6 to absolute pressures in the range 0.3 to 0.6 MPa.

Breakdown Characteristics

Figure 4 shows the measured 50% breakdown voltage as a function of SF_6 gas pressure under standard and oscillating LI. It will be seen that the former are consistently lower than the latter. (Positive impulse polarities were used for both). Thus, particle defects, which can be detected by standard LI, may not be detected by oscillating LI.

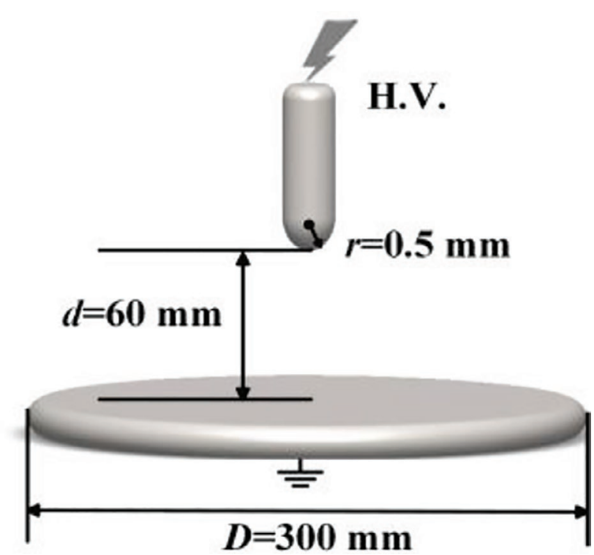

Figure 3. Rod-plane electrode system used to obtain the discharge characteristics of SF_6 in a highly inhomogeneous electric field.

Figure 5 shows the 50% breakdown voltage as a function of double-exponential impulse wavefront time T_f for five SF_6 pressures. (Positive impulse polarities were used.) It can be seen that when T_f >1.2 μs, the 50% breakdown voltage increases monotonically with increasing T_f, at all measured pressures. Furthermore, the 50% breakdown voltage at T_f = 1.2 μs (standard LI) is lower than that for T_f ≥3.0 μs at all measured pressures. It follows that LI testing using double-exponential impulses with T_f ≥3 μs will not be as effective as standard LI testing.

Figure 6 shows breakdown voltage as a function of time-to-breakdown, under positive double-exponential impulses, for four wavefront times T_f. Measurements were made using the rod-plane electrode system at an SF_6 pressure of 0.6 MPa. It will be seen that, for T_f = 0.08 and 1.2 μs, the breakdown voltage decreases as the time-to-breakdown increases. However, the opposite is true for T_f = 10 and 23.5 μs. It is important to note

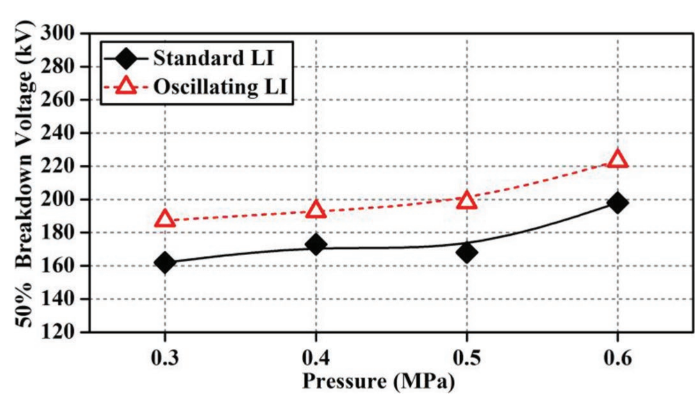

Figure 4. 50% breakdown voltage versus gas pressure under standard and oscillating lightning impulse (LI), both with positive impulse polarities.

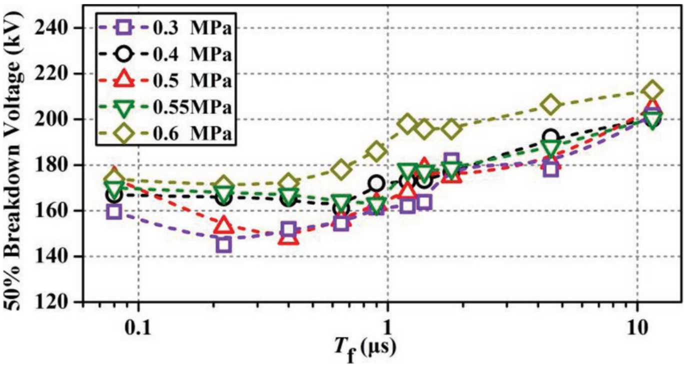

Figure 5. 50% breakdown voltage versus double-exponential impulse wavefront times T_f at five SF_6 gas pressures.

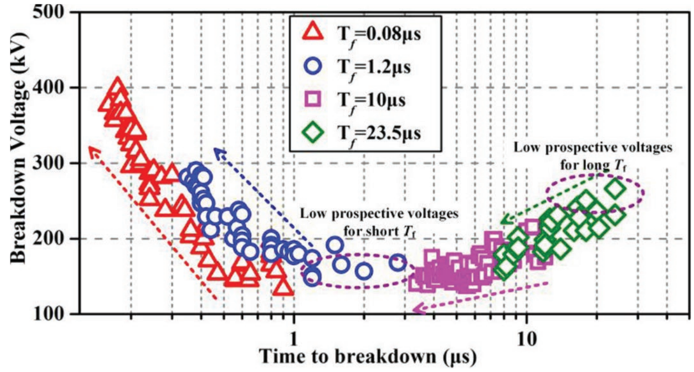

Figure 6. Breakdown voltage as a function of time-to-breakdown, under positive double-exponential impulses with four wavefront times T_f. Measurements were made using the rod-plane electrode system at an SF_6 pressure of 0.6 MPa. The arrows show the direction of increase of the prospective voltage.

that the breakdown voltage here is the maximum value of the recorded breakdown voltage, not the prospective voltage, which is the peak value of the applied impulse waveform, assuming that there is no disruptive discharge under any applied impulse waveform. More than 30 breakdown voltages were measured for each T_f value. The arrows in Figure 6 show the direction of increase of the prospective voltage for impulses with various wavefront times T_f. At short T_f, i.e., $T_f \leq 1.2$ μs, the breakdown voltages increase and the breakdown times shorten when the prospective voltages increase. However, for long T_f, i.e., $T_f \geq 10$ μs, the breakdown voltages increase and the breakdown times lengthen when the prospective voltages decrease. Within the ellipse labeled "Low prospective voltages for long T_f," the time to breakdown is less than or close to T_f, and the prospective voltage ($U_{pv\text{-}Long}$) is greater than or equal to the breakdown voltage ($U_{bv\text{-}Long}$). However, within the ellipse labeled "Low prospective voltages for short T_f," the time to breakdown is greater than or close to T_f, and the prospective voltage ($U_{pv\text{-}Short}$) equals the breakdown voltage ($U_{bv\text{-}Short}$). We can conclude that $U_{pv\text{-}Long} \geq U_{bv\text{-}Long} > U_{bv\text{-}Short} = U_{pv\text{-}Short}$, so that $U_{pv\text{-}Long} > U_{pv\text{-}Short}$. The effectiveness of defect detection using the impulse test is reflected in the value of the prospective voltage, i.e., the higher the prospective voltage, the lower the effectiveness of defect detection. It follows that a defect, e.g., a conductive particle attached to the GIS bus, can be detected more reliably using impulses with short T_f rather than long T_f.

We conclude that, compared with the standard LI test, the nonstandard LI and oscillating LI tests with long T_f are expected to be less effective in detecting insulation defects in GIS. Breakdowns occurring after a piece of GIS equipment is put into service may be due to defects that were not detected during installation testing. Consequently, the standard or impulse LI test with $T_f \leq 1.56$ μs is to be preferred for installation testing, because it offers a greater probability of detecting insulation defects.

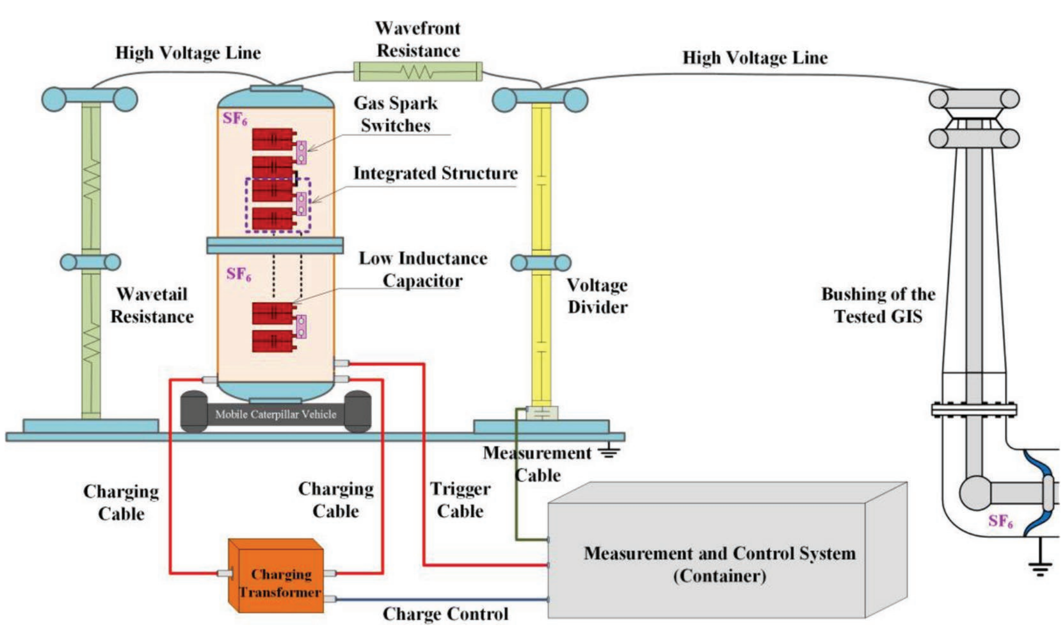

Figure 7. Structure of our compact low inductance impulse generator.

Table 1. Main technical parameters of the impulse generator	
Insulating medium	SF_6
Wavefront time	≥80 ns
Wavetail time	10–2,500 μs
Rated voltage	3,000 kV
Rated capacity	300 kJ
Size	Height = 7.6 m, width = 2.2 m
Weight	<8 tonnes

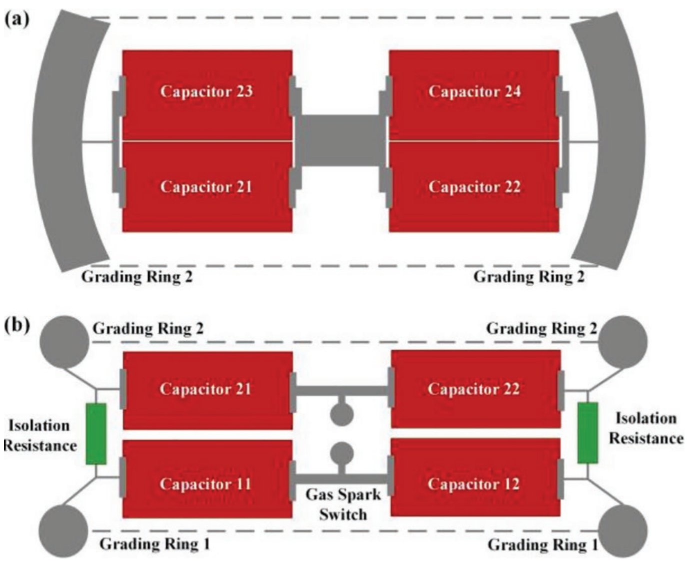

Figure 8. Design of the switch capacitor integration unit: (a) a capacitor group (group 2), (b) a 200-kV discharge unit (unit 1).

Figure 9. Ultrahigh voltage Nanjing substation test site.

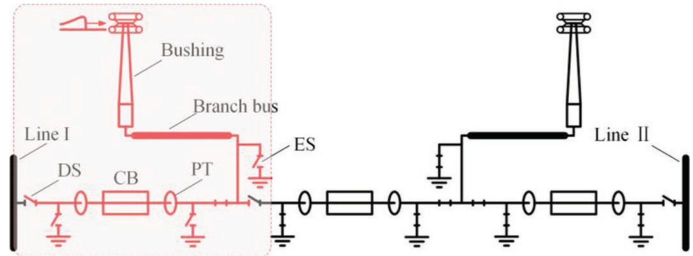

Figure 10. Schematic diagram of 3/2 circuit breaker (CB) connection and section test method. DS = disconnecting switch; ES = earthing switch.

On-Site Standard LI Test Technology

Development of a Compact Low Inductance Impulse Voltage Generator

As stated above, the on-site standard LI test for power equipment with large capacitance cannot be performed using a traditional impulse generator with large inductance (up to about 100 μH). Thus, development of a compact low inductance impulse generator is essential.

We have developed such a generator (Figure 7). The Marx generator is located within a fully enclosed pressure epoxy vessel filled with SF_6, typically to a pressure of 0.3 MPa. The generator consists of thirty 100-kV low-inductance capacitor groups and 15 gas spark switches. The main technical parameters of the generator are given in Table 1. The height of the generator is 7.6 m, much less than the height of the traditional impulse generator with the same rated voltage, typically 12 m. Thus, the circuit inductance is lowered, and the maximum permissible capacitance of the equipment under test is increased.

The generator has three important features, namely:

(a) a low inductance (<50 nF) pulse capacitor;
(b) an SF_6 gas insulating medium, facilitating a compact structure with a single-stage insulation distance only one-third of the corresponding distance in a conventional generator; and

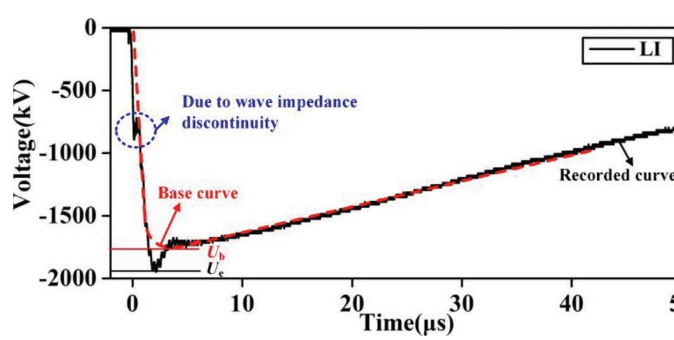

Figure 11. A typical test waveform applied to a load consisting of a circuit breaker and its accessories. The recorded (black) curve is the digital representation of the data measured under the impulse voltage test. The base (red) curve is an approximation impulse voltage of a full lightning-impulse (LI) voltage without a superimposed oscillation.

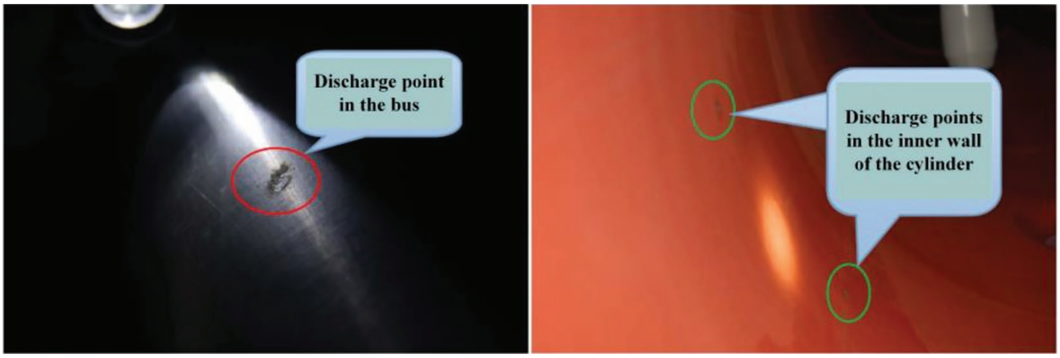

Figure 12. Location of discharges that occurred during testing, under an impulse voltage of +1,800 kV.

(c) the design of the switch capacitor integration unit (Figure 8). Four low-inductance capacitors arranged in parallel meet the requirements of large capacity and low inductance. The capacitor group–gas spark switch–capacitor group integrated structure constitutes a 200-kV discharge unit, and 15 such units are compactly arranged in series to constitute the 3,000-kV Marx generator. The inductance of the single discharge unit is lower than 600 nH, approximately one-tenth of the inductance of the traditional open type impulse voltage generator.

Application in UHV Substation

In August 2015 an on-site standard LI test for a 1,100-kV GIS, using our low inductance impulse generator, was carried out in a UHV substation near Nanjing (Figure 9). This test is believed to have been the world's first on-site standard LI test for UHV GIS.

In order to guarantee an impulse voltage with short wavefront time T_f, one circuit breaker and its accessories were connected as the load for each test (shown in red in Figure 10). The test load could be connected or disconnected using the relevant disconnecting switches and earthing switches; this substation adopts 3/2 circuit breaker connection. Impulses of both polarities and with amplitudes of 1,705, 1,800, and 1,920 kV were applied to the GIS. Figure 11 shows a typical test waveform under load conditions, measured by the voltage divider. The test waveforms, with different test loads, were double-exponential waveforms with front time in the range 1.52 to 2.28 µs, time to 50% of the peak value in the range 48.9 to 59.4 µs, and an overshoot in the range 4.3 to 8.3%. {Percentage overshoot = $100[1 - (U_b/U_e)]$, where U_b and U_e are shown in Figure 11.} The feature during the rise of the waveform (around −750 kV) was due to a discontinuity of the wave impedance Z associated with the high voltage wire, bushing, branch bus, and circuit breaker, etc.

During the test, one insulation defect breakdown occurred under an 1,800-kV positive impulse voltage. One discharge point on the bus and two discharge points on the inner wall of the cylinder were found (Figure 12). There a metal burr (one kind of insulation defect) may have been attached to the bus surface. It seems that, when the impulse was applied, a discharge originated on the bus surface and subsequently branched into two channels.

We conclude that the on-site standard LI test, conducted using our low inductance impulse voltage generator, can detect defects in GIS equipment due to transportation and/or installation more effectively than the nonstandard LI test conducted using the traditional impulse generator.

Conclusions

The following conclusions may be drawn from the work presented above.

(1) The wavefront time T_f of voltage impulses used in LI testing of GIS equipment with large capacitance will usually exceed the standard LI test upper limit of 1.56 µs.
(2) With increasing T_f, the effectiveness of impulse testing of GIS insulation for defects decreases. In particular, the nonstandard LI test, including LI and oscillating LI with long T_f, have lower effectiveness than the standard LI test.
(3) A new fully enclosed and compact standard LI generator with low inductance has been developed, using SF_6 gas as the insulating medium and incorporating novel structural design of the switch capacitor integration unit.
(4) Using the developed generator, an on-site standard LI test for 1,100-kV GIS was successfully carried out in a UHV substation near Nanjing. One circuit breaker and its accessories were connected as the load for each test.

Acknowledgments

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