A New Method to Evaluate the Effectiveness of Impulse Voltage for Detecting Insulation Defects in GIS Equipment

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ABSTRACT

Lightning impulse (LI) test is an effective means to detect insulation defects in gas-insulated metal-enclosed switchgear (GIS) equipment. However, the LI test wavefront time T_f will exceed the standard value of 1.2 μs ± 30% for large test load capacitance. Whether extending the T_f will influence defect detection effectiveness should be a concern. In this study, a generating system of impulses with different wavefront parameters was established. The insulation characteristics of a coaxial cylinder structure with an SF_6 gas gap with conductive protrusion in a bus under impulses with different wavefront parameters were studied. Experimental results show that the voltage–time curve of the gap shows a bathtub trend that has a flat part in the range of 1 μs to 5 μs. With a T_f increase, the 50% breakdown voltage increases. Whether extending the T_f will influence defect detection effectiveness is analyzed from the standpoint of the different meaning of the breakdown voltage in voltage-time curve and 50% breakdown voltage. The essence of detection effectiveness under impulse voltages with different wavefront parameters is a comparison of the probability of detecting the same insulation defect. Based on the discharge probability distribution, a new quantitative method to evaluate the insulation defect detection effectiveness of impulse voltages for GIS equipment is proposed. The method, based on the 90% discharge voltage value of an insulation defect under a standard LI, normalizes the discharge probability under different wavefront parameters.

Index Terms — **50% breakdown voltage, detecting effectiveness, discharge probability, lightning impulse, on-site impulse test, voltage–time characteristic, wavefront time T_f**

1 INTRODUCTION

GAS-INSULATED metal-enclosed switchgear (GIS) has been developed rapidly since the mid-1960s. It has many advantages such as reliability, compaction, long maintenance cycle, and small impact on the environment, which have led to it being widely used in electrical power systems [1-3].

Lightning impulse (LI) test, one type of on-site withstand voltage tests, is particularly sensitive to abnormal field configurations in GIS. The test is recommended in IEC 62271-203 for voltage classes of 245 kV and above [4,5]. It should be carried out to ensure enough insulating ability under overvoltage and to detect any defects resulting from transportation, storage, environment, final assembly, and on-site mechanical testing.

According to the IEC 60060-1:2010 "High-voltage test techniques" standard, a standard LI is a smooth, full-lightning impulse voltage with a wavefront time of 1.2 μs ± 30% and a time to half-value of 50 μs ± 20% [6]. However, it is difficult to generate a LI with a wavefront time (T_f) that meets the

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standard. This is due to factors such as the increase in series inductance attributable to the longer and larger test circuit and the increased capacitance of the equipment to be tested. As a result, when an ultrahigh-voltage GIS assembly is tested using existing test facilities to generate a waveform with an overshoot rate β' of 10% or less, the T_f exceeds 2.2 µs or even 3.0 µs [7].

However, there is a concern that a test waveform with an extended T_f may not appropriately verify the insulation performance with respect to wavefront steepness. Okabe designed a series of experiments to research the possibility of extending the T_f [8]. The insulation characteristics of GIS can be broadly classified into those when the GIS is clean and those when metallic particles exist. Okabe used a Φ_1/Φ_2 = 240/340-mm coaxial cylinder structure to simulate a sound GIS system. He found that the longer the T_f (up to 4.8 µs), the lower the 50% breakdown voltage tended to be, but not obviously (less than 6%). Insulation performance is considered to be more conclusively verified if the T_f is extended for the LI voltage test. Meanwhile, a Φ_1/Φ_2 = 42/150-mm coaxial cylinder with a 10 mm needle particle in a high-voltage electrode was used to simulate GIS with insulation defects [9]. They found that the breakdown voltage varied little within the range of 1.0 µs to 10 µs and remained relatively low, as shown by the voltage–time characteristic curve. Hence, it was confirmed that extending the T_f up to approximately 3.6 µs had a minor influence on the breakdown characteristics.

There is a consensus that for a sound GIS system, within a certain range the 50% breakdown voltage changes slightly with an increase in T_f, and the voltage–time characteristic curve is usually flat when the breakdown time extends beyond a certain value [8]. Hence, extending the T_f up to approximately 3.6 µs can be acceptable to verify the reliability of a GIS design. However, the other important role of an LI test in a factory or on-site is to detect insulation defects in an actual GIS assembly. Also, the insulation characteristics of sulfur hexafluoride (SF_6) with a highly inhomogeneous electric field have been found in other studies to be markedly influenced by T_f [10–13].

In this study whether extending the T_f will influence defect detection effectiveness is analyzed. Also, in this paper, based on the breakdown characteristics of SF_6 in a highly inhomogeneous electric field under impulses with different wavefront time parameters, a new evaluation method based on discharge probability is introduced.

2 EXPERIMENTAL SETUP AND METHOD

2.1 EXPERIMENTAL SETUP

An impulse generating system based on a fully enclosed, oil-insulated Marx generator and a simulated GIS bus is established, as shown in Figure 1. The generator and the simulated bus were separated by dielectric spacers and a basin-type insulator. Immersing the Marx generator in oil made it very compact, thereby lowering inductance, which affected the front time of the output waveform [14]. The generator could generate double-exponential impulses with a T_f of a wide range of 0.08 µs to 15 µs and a wave tail time of approximately 50 µs (including a standard LI), as shown in Figure 2.

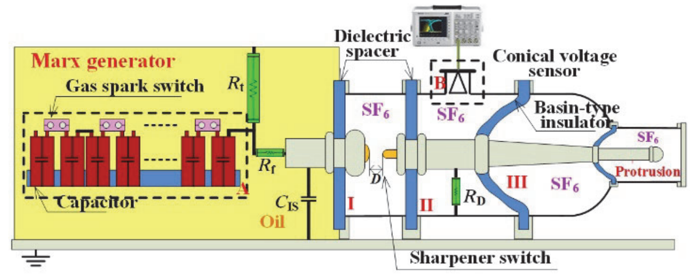


Figure 1. Schematic diagram of the impulse generating system.

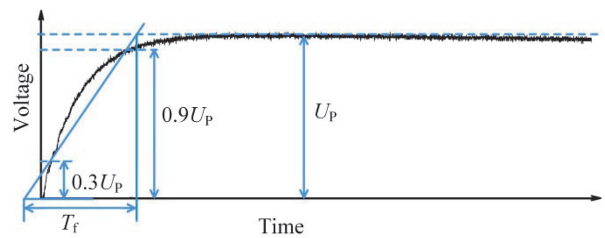


Figure 2. Output impulse voltages from the Marx generator with different waveform parameters.

Coaxial cylinder structures of a 252-kV GIS with Φ_1/Φ_2 = 72/320 mm and a 550-kV GIS with Φ_1/Φ_2 = 170/550 mm were used in the experiment, where a conductive protrusion was used to simulate a defect, as shown in Figure 3. The conductive protrusion was a needle of tens of micrometers in diameter. The length of the protrusion was 3, 5, 10 mm. Considering the ablation of discharge when SF_6 gap breakdown under impulse, the radius of curvature at needle tip will be gradually eroded. So the steel needle was replaced by new ones after every 10 discharges. The parameters of the test gap are shown in Table 1. The test setup was installed in a chamber filled with SF_6 at absolute pressures of 0.6 MPa.

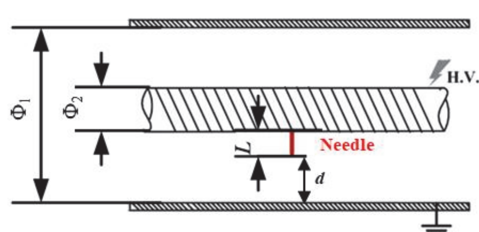


Figure 3. Electrode configuration of coaxial cylinder structure with conductive protrusion.

Table 1. Parameters of the test gap.

Voltage class	Φ_1/Φ_2	L=3 mm	L=5 mm	L=10 mm
		d/mm	d/mm	d/mm
252 kV	72/320 mm	121	119	114
550 kV	170/550 mm	187	185	180

2.2 EXPERIMENTAL METHOD

In a highly inhomogeneous electric field in SF_6, the breakdown voltage under positive polarity is lower than that under negative polarity. Therefore, a positive polarity voltage was used in this study. The waveforms were recorded using an oscilloscope (Tektronix DPO4104, Tektronix, USA) with a bandwidth of 1 GHz and a sample rate of 5 Gs/s. Calibration results were that the response time of the measuring system was less than 5 ns, and the uncertainty of the divider ratio was less than 3%.

The voltage–time characteristic of the electrode system was obtained by applying impulse voltages of various amplitudes and a 50% breakdown voltage by using the up-and-down method described in IEC 60060-1 [6]. The prospective voltage value used in the calculation of the 50% breakdown voltage, and the breakdown voltage value used in the voltage–time characteristic, were clarified in our previous paper [15], which may cause some misunderstanding in the following discussions of insulation defect-detection effectiveness. The 50% breakdown voltage is the prospective voltage value which has a 50% probability of producing a disruptive discharge. The prospective voltage value, not affected by the measured waveform, is the peak value of the impulse voltage stressed on the test object assumed that there is no disruptive discharge. The breakdown voltage value in the voltage–time characteristic is the value of the breakdown point value when breakdown occures in the wavefront, or the peak value of the impulse when breakdown occurs in the wave tail or peak.

The breakdown voltage of SF_6 under an impulse voltage has a statistical characteristic that can be obtained by the rising-voltage test method. The method is shown in Figure 4. In the experiment, a nominal voltage to earth (U_0), which is lower than the static discharge voltage (the lowest breakdown voltage), was selected as the starting point. A 2% voltage interval ΔU of the U_0 was then selected. A voltage was applied once at the U_0. If no breakdown occurred, the voltage $U_0 + \Delta U$ was applied next time until the gap broke down. The discharge voltage at that time was recorded as $U_k = U_0 + k\Delta U$. The next experiment continued with the U_0 as the starting point, and the program repeated n times. The breakdown times at U_k were recorded as m_k. The discharge probability of the test object under U_k can be obtained by Equation (1) [16].

$$P(U_k) = \frac{m_k}{n+1} \tag{1}$$

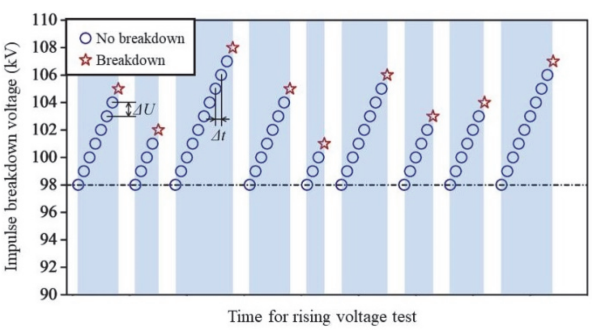


Figure 4. Rising-voltage test method.

3 ANALYSIS OF THE INFLUENCE OF EXTENDING WAVEFRONT TIME ON THE DEFECT DETECTION EFFECTIVENESS

Figure 5 shows the breakdown voltage (U_b) as a function of time-to-breakdown (t_b) under five different wavefront times at an SF_6 pressure of 0.6 MPa for a 252-kV GIS with L = 10 mm. It is found that the voltage–time curve for an SF_6 gas gap with a highly inhomogeneous electric field shows a bathtub trend similar to the result in [8], as shown in Figure 5. As the t_b increases, the breakdown voltage first decreases, then levels out, then increases. The level portion is in the range of 1 μs to 5 μs. From this point of view, it seems that extending T_f to 3.6 μs would not influence the insulation performance.

To some extent, the V-t curve could reflect the relation between the T_f and the breakdown voltage. However, the flat part of the V-t characteristic curve corresponding to the range of the discharge delay time is not equivalent to the T_f. Also, the research in [8] does not distinguish the data under impulse voltages with different T_f and can not accurately obtain the influence of the impulse voltage T_f on the discharge characteristics. The impulse voltage discharge delay time has randomness. Generally, when the wavefront time is short, the discharge occurs mostly at the peak and the tail. When the wavefront time is long, the discharge occurs mostly at the wavefront and the peak and rarely occurs at the wave tail. Only when the discharge occurs at the peak can the discharge delay time establish an approximate relation with the T_f. Therefore, the discharge delay time corresponding to the V-t curve cannot directly reflect the T_f of the impulse voltage. Consequently, the flat part of the V-t curve does not indicate that the discharge voltage does not change significantly when the T_f is within the range of 1 μs to 5 μs shown in Figure 5.

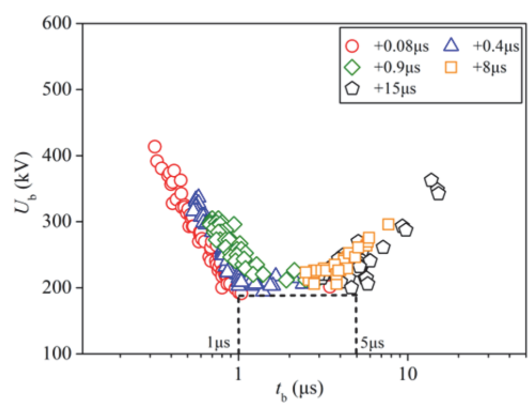


Figure 5. Breakdown voltage as a function of time-to-breakdown (t_b) under five different wavefront times at an SF_6 pressure of 0.6 MPa for a 252-kV GIS with L = 10 mm.

The minimum value (U_{min}) of the U_b obtained from the V-t curve is usually used to evaluate the insulation strength. From Figure 5, it can be seen that the U_{min} increased with the increase of T_f in the range of 0.08 μs to 1.2 μs. When T_f = 8 μs or 15 μs, the U_{min} has a decreasing trend. However, the U_b in the V-t curve is not the prospective voltage (U_p) stress on the test objective when the breakdown occurred in the front of the impulse, usually for an impulse with a long T_f such as $T_f = 8$ µs or 15 µs. So the decreasing trend from the V-t curve maynot the real trend of the prospective voltage. When the breakdown occurred in the peak or the tail of the impulse, the U_b is equal to the prospective voltage. For example, the t_b of the point of U_{min} ($T_f = 0.08$ µs) is greater than 0.08 µs, but that of U_{min} ($T_f = 15$ µs) is smaller than 15 µs.

When a impulse is stressed on the tested objective, we cannot confirm whether the breakdown will ocuur, not to speak of the breakdown time. Just the applied impulse voltage value (prospective voltage) can be obtained by calculation or the record waveform. Hence, for evaluating the insulation strength or detection effectiveness, the prospective voltage is more suitable. Usually, a 50% breakdown voltage is used to evaluate the insulation strength. Figure 6 shows the 50% breakdown voltage in relation to the T_f. Clearly, when T_f exceeds 2.0 µs, the 50% breakdown voltage is higher than that of a standard LI. From this point of view, the impulse T_f has a great influence on the insulation strength for SF_6 with a highly inhomogeneous electric field. That is to say, extending T_f will decrease the insulation defect detection effectiveness.

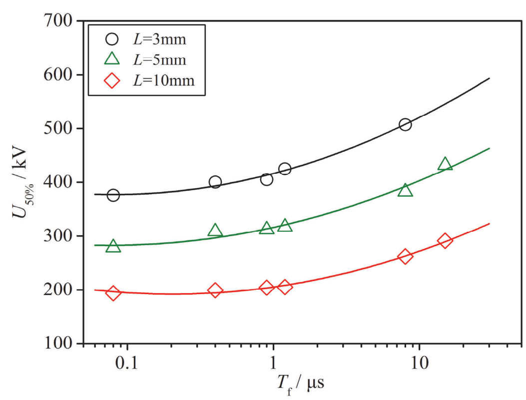


Figure 6. A 50% breakdown voltage in relationship with impulse wavefront times T_f in the range of 0.08 µs to 23.5 µs at 0.6 MPa for a 252-kV GIS with a defect in the bus.

4 A NEW METHOD TO EVALUATE INSULATION DEFECT DETECTION EFFECTIVENESS

4.1 IMPULSE DISCHARGE STATISTIC CHARACTERISTICS FOR A GIS WITH AN INSULATION DEFECT

An SF_6 discharge under impulse has significant statistical characteristics. The standard deviation of the effective data measured after enough insulation recovery is characterized by Equation (2):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \, , \tag{2}$$

where n is the number of effective data in the present group, x_i is the ith effective data, and $\bar{x}$ is the average of the effective data. Based on this, the dispersion coefficient in Equation (3) can reflect the degree of dispersion:

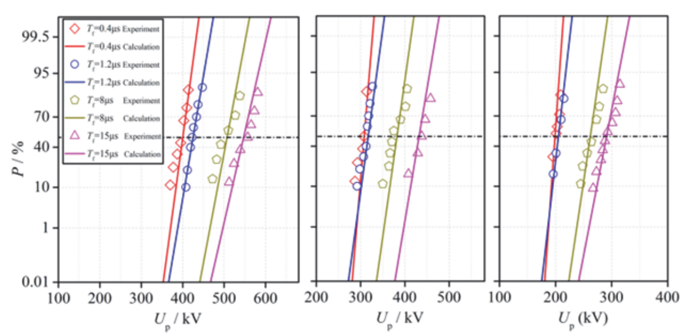
$$\varepsilon = \sigma / U_{50\%} \, . \tag{3}$$

The breakdown voltage distribution of the gas gap under the impulse is close to a normal distribution [16], characterized by Equation (4):

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{(t-u)^2}{2\sigma^2}} \mathrm{d}t, \quad -\infty < x < \infty \, , \tag{4}$$

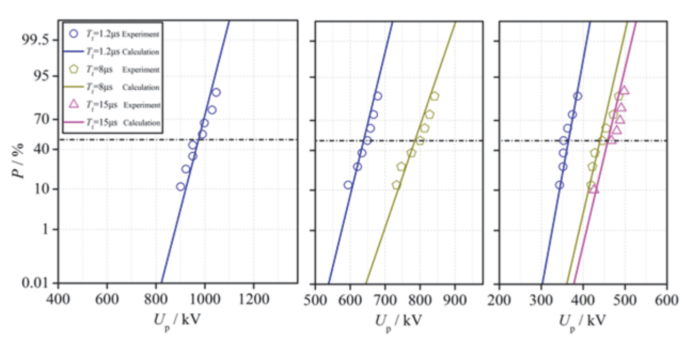
where u is the average value of the effective data, $U_{50\%}$.

Therefore, using the $U_{50\%}$ and the standard deviation σ obtained from the up-and-down test, the normal distribution of the gas discharge can be calculated. The discharge probability in relation to the prospective breakdown for a 252-kV and a 550-kV GIS with defects are shown in Figures 7 and 8. In the figures, the points are the experimental results, which are obtained by the rising voltage test method. The solid line is the calculation result, which is obtained by the up-and-down method data. It can be seen from Figures 7 and 8 that the discharge voltage distribution is in good agreement with the normal distribution. As the T_f increases, the curve shifts to the right. Among them, the $U_{50\%}$ obtained by the rising voltage test method is the cumulative probability, which is different from that obtained by the up-and-down method theoretically. However, the difference between the two values is small. Therefore, it can be approximated that the $U_{50\%}$ obtained by the up-and-down method is a voltage value having a 50% discharge cumulative probability.



(a) L = 3 mm (b) L = 5 mm (c) L = 10 mm

Figure 7. Breakdown probability in relation to prospective breakdown voltage for a 252-kV GIS with a defect in the bus under an impulse with different T_f at $p = 0.6$ MPa.



(a) L = 3 mm (b) L = 5 mm (c) L = 10 mm

Figure 8. Breakdown probability in relation to prospective breakdown voltage for a 550-kV GIS with a defect in the bus under an impulse with different T_f at $p = 0.6$ MPa.

4.2 QUANTITATIVE ANALYSIS METHOD TO DETERMINE THE EFFECTIVENESS OF INSULATION DEFECT DETECTION

The effectiveness of impulse voltage insulation defect detection can be reflected by the pre-impulse voltage amplitude (prospective voltage). In other words, the lower the prospective voltage amplitude when breakdowns, the higher the detection efficiency for the same insulation defect under impulses with different T_f. However, the difference in prospective voltage can only qualitatively indicate which impulse waveform is better; it cannot quantitatively reflect the detection effectiveness. The essence of detection effectiveness under impulse voltages with different wavefront parameters is a comparison of the probability of detecting the same insulation defect.

The on-site impulse withstand voltage test, for example, is carried out with three impulses of each polarity at the test voltage specified for the equipment under test, which is specified in the IEC [4]. As mentioned above, an impulse with positive polarity has a greater probability of finding defects. Therefore, the positive three times test is very crucial. Assuming that each test is independent, the breakdown probability is P_0. The probability P of breakdown if n times impulse are applied in testing is

$$P=1-(1-P_0)^n \ . \tag{5}$$

When $P_0 = 0.9$ and $n = 3$, $P = 0.999 = 99.9\% \approx 1$. Therefore, based on the 90% discharge voltage value of an insulation defect under standard LI, the discharge probability under different waveform parameters is normalized and quantitative analysis is done. The detect effectiveness in this paper is defined as the discharge probability under impulse with T_f at the voltage value of 90% discharge voltage under standard LI for the same defect.

When there is a defect in the GIS, the 90% breakdown voltage under a standard LI of it is recorded as $U_{90\%\text{-SLI}}$. Then $F_{T_f}(U_{90\%-SLI})$ can be used to represent the defect detection effectiveness under impulse with T_f, where F_{T_f} is the discharge probability distribution function of the defect under impulse with T_f. Hence, the probability of a GIS insulation defect being detected under three impulse tests can be expressed as:

$$P_{n=3} = 1-[1-F_{T_f}(U_{90\%-SLI})]^3 \ . \tag{6}$$

When the discharge distribution satisfies the normal distribution, $F_{T_f}(U_{90\%-SLI})$ can be calculated by:

$$F_{T_f}(U_{90\%-SLI}) = \Phi\left[\frac{U_{90\%-SLI} - U_{50\%-T_f}}{U_{50\%-T_f} \cdot \varepsilon_{T_f}}\right] , \tag{7}$$

where Φ is the standard normal distribution function; $U_{50\%-T_f}$ is the 50% breakdown voltage of the defect under impulse with T_f, in kV; and ε_{T_f} is the relative standard deviation of the defect under impulse with T_f. Hence, when $U_{50\%}$ and ε_{T_f} are known, the detection effectiveness can be calculated.

Taking a 550-kV GIS with a needle defect $L = 10$ mm as an example, from Figure 8, when $P_{n=1}(T_f, U_t) = P_{n=1}(1.2\ \mu s, U_t) = 90\%$, and then $U_t = 387$ kV, $P_{n=1}(8\ \mu s, 387\ kV) = 0.6\%$, $P_{n=1}(15\ \mu s, 387\ kV) = 0.04\%$, $P_{n=3}(8\ \mu s, 387\ kV) = 1.79\%$, $P_{n=3}(15\ \mu s, 387\ kV) = 0.12\%$. With the impulse T_f. increase, the detection effectiveness decreases markedly, as shown in Figure 9.

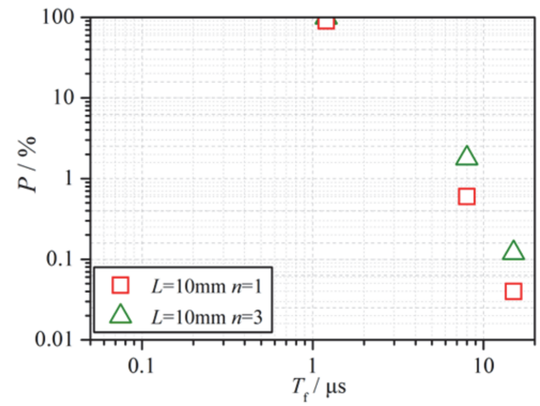


Figure 9. Breakdown probability of a 550-kV GIS with a bus defect under impulse with different T_f at $p = 0.6$ MPa.

Figure 10 shows the 50% discharge voltage under impulses with different T_f. and its conversion relation with a standard LI at a defect length of $L = 10$ mm. It is clear in Figure 10 that when the T_f. increases from 1.2 μs to 8 μs and then 15 μs, the discharge voltage increases by approximately 21% and 26%. However, as Figure 9 shows, the 21% to 26% voltage increase causes the probability of defect detection to drop significantly. The probability of one time discharge decreases from 90% to 0.6% and 0.04% respectively. Hence the detection effectiveness of three time test decreases from 100% to 1.79% and 0.12% respectively.

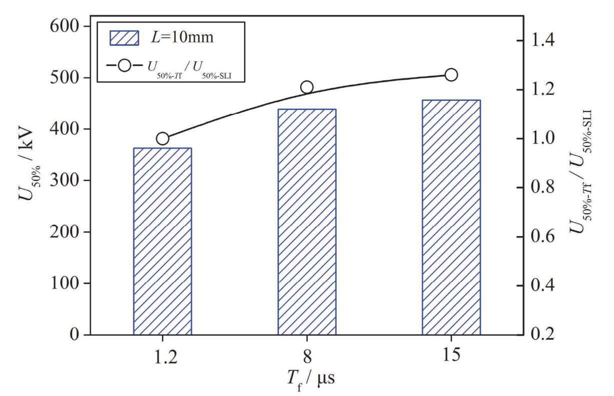


Figure 10. 50% breakdown voltage and a voltage conversion factor of a 550-kV GIS with a bus defect under impulse with different T_f at $p = 0.6$ MPa.

The effectiveness of detecting insulation defects in an impulse test can be improved by shortening the impulse wave wavefront time, increasing the test voltage, and increasing the number of tests. Among these factors, the wavefront time parameter is subject to the impulse voltage generator body inductance and load capacitance, and the test voltage value and the number of tests can be determined according to the test waveform parameters to obtain a satisfied detect effectiveness.

5 CONCLUSION

The purpose of this study was to evaluate the detection effectiveness of an on-site LI test for GIS equipment with insulation defects, based on the established multiple-parameter impulse generating system. The insulation characteristics of a coaxial cylinder structure SF_6 gas gap with a conductive protrusion in a bus under the impulses of different wavefront parameters were investigated. The following conclusions can be derived based on the experimental results:

(1) The voltage–time curve of the gap shows a bathtub trend that had a flat part in the range of 1 μs to 5 μs, which is similar to the results of other researchers. But the detect effectiveness is not suitable obtained from the flat part of V-t curve by the different meaning of the breakdown voltage in voltage-time curve and 50% breakdown voltage.

(2) With a T_f increase, the 50% breakdown voltage increases. The impulse wavefront time greatly influences the insulation strength of SF_6 with a highly inhomogeneous electric field. Extending the T_f would decrease the effectiveness of the insulation defect detection.

(3) The essence of detection effectiveness under impulse voltages with different wavefront parameters is a comparison of the probability of detecting the same insulation defect. Based on the discharge probability distribution, a new quantitative method to evaluate the insulation defect detection effectiveness of impulse voltages for GIS equipment is proposed, which is defined as the discharge probability under impulse with T_f at the voltage value of 90% discharge voltage under standard LI for the same defect.

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