# K-FACTOR VALUES WITH LARGE-SIZED MODELS FOR LIGHTNING IMPULSE TEST WAVEFORM OF UHV EQUIPMENT

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**Abstract**: The present study reports the experimental results of the insulation breakdown characteristics for the lightning impulse withstand voltage test waveform with the largest SF6 gas insulation and oil insulation models possible assuming actual UHV-class equipment such as gas insulated switchgear and oil-immersed transformer. Breakdown voltage and breakdown time were measured with the superimposed oscillation frequency, overshoot rate, and front time as parameters. Following evaluation of the k-factor values based on these experimental results, the k-factor values with the overshoot rate of 10% were almost identical to those of the existing k-factor function. Consequently, evaluation using the existing k-factor function is considered appropriate also for UHV-class equipment. In addition, it emerged that changes in the insulation breakdown characteristics due to the extension of the front time were small. It was considered that extending the front time, rather than allowing an excessive overshoot rate, would enable proper verification of the insulation performance as part of standard assuming UHV-class equipment.

## 1 INTRODUCTION

For electric power equipment such as gas insulated switchgear (GIS) and transformer, a withstand voltage test is specified to check the dielectric strength. For the lightning impulse withstand voltage (LIWV) test, the IEC 60060-1 "High-voltage test techniques" as revised in 2010 [1] specifies a test waveform with its value of test voltage Ut within ± 3%, front time Tf = 1.2 μs ± 30%, time to half-value Tt = 50 μs ± 20%, and overshoot rate (hereinafter referred to as "OS rate") β' of 10% or less.

Increasing equipment capacitance makes it more difficult to apply a standard voltage waveform, hence the reasonable relaxation of the standard value was required while also making the standard clearer. In addition, evaluation using the k-factor function, which converts an overshoot waveform to the test voltage waveform, was introduced with the digitization of the measurement system [2-4]. At present, the test standard for UHV-class equipment is in committee (IEC TC42 "High-voltage test techniques", WG 19 "Adaptation of TC 42 standards to UHV test requirements") [5,6].

For a study on the standard for the test waveform for the LIWV test, insulation characteristics related to waveform parameters, such as the front time and OS rate, must be understood [7]. The present study reports on the experimental results of the insulation breakdown characteristics under the LIWV test waveforms for large-scale $SF_6$ gas and oil gaps, the breakdown voltage of which is about 1000 kV, assuming actual GIS and transformer. In the experiment, the breakdown voltage and breakdown time were measured whereby the superimposed oscillation frequency (hereinafter referred to as "fs") and OS rate were changed as waveform parameters. Based on the experimental results, changes in the insulation breakdown characteristics were investigated to evaluate the influence of each waveform parameter. Furthermore, the k-factor value, calculated based on the experiment, was also indicated and compared with the existing k-factor function specified mainly supposing 800 kV or less. In addition, the insulation breakdown characteristics were obtained where the front time was extended. Based on the experimental results, the influence on the insulation breakdown characteristics is evaluated from the view point of relaxing the standard value for the front time.

## 2 EXPERIMENTAL OUTLINE

### 2.1 EXPERIMENTAL CIRCUIT

Figure 1 is a photo of the test equipment with the oil insulation case. The lightning impulse voltage generated by the impulse voltage generator is applied to the test equipment and the measured waveform is recorded via the voltage divider using a digital recorder.

The test bus is coaxially cylindrical, assuming actual GIS. Four electrodes, of diameter Φ240 mm and length 100 mm, were installed within the bus of diameter 340 mm and used to simulate the insulation spacer shield part where the electric field peaked. The effective area of the electrode (where the electric field strength was 90% or more of its maximum strength) was $4.5 \times 10^4$ $mm^2$ and the

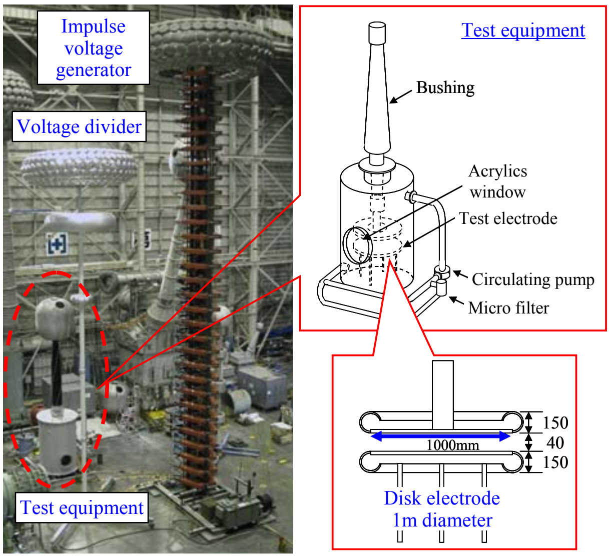


**Figure 1:** Outline of the test equipment

electric field utilization factor was about 0.6, both of which were within the standard range as GIS. The electrodes were made of stainless steel with a surface finish equivalent to machining 25S (maximum surface roughness height: 25 μm) as is the case for actual equipment. The $SF_6$ gas pressure during the test was set to an absolute pressure of 0.5 MPa, the same as the gas pressure when equipment is operated.

Used for the test electrodes constituting the oil gap were aluminum disk electrodes 1,000 mm in diameter and with smooth finished surfaces (maximum surface roughness height: 50 μm). They were also structured with parallel plain plates of gap length 40 mm. The volume of the space where the electric field intensity was 90% or more of the maximum was $3.1 \times 10^4$ $cm^3$, which represents about 1/3 of the volume of the main insulation part between windings of an actual 500 kV transformer with equivalent electric field intensity.

In the experiment, new oil to be used for power transformers was used. This contains 500 per 100 mℓ or fewer of particles of 5 μm to 20 μm and 16 per 100 mℓ or fewer of particles of 20 μm to 50 μm, and this condition was maintained during the experiment.

## 2.2 EXPERIMENTAL CONDITIONS

Breakdown voltage characteristics were measured for the standard waveform (front time Tf = 1.2 μs, OS rate = 0%) and the overshoot waveform (OS rate = 10%, 20% and 30%). When the front time was maintained at 1.2 μs, the fs of overshoot waveform was about 250 kHz. Furthermore, the experiment under the conditions of fs = 120 kHz and 450 kHz was conducted to investigate the frequency dependence of the k-factor function. The k-factor values were calculated based on the results for the waveforms with OS rates of 10%, 20%, and 30%, respectively.

In addition, insulation characteristics were obtained with the front time as a parameter. In adjusting the waveform in the LIWV test, the OS rate and front time are the relations of a trade-off to each other. For the overshoot waveform, the voltage is lower at the wavetail of the waveform compared with the standard waveform with same peak value. Conversely, a waveform with a longer front time is close to the standard waveform, despite being less steep, and is thus considered capable of verifying the insulation performance more appropriately than the overshoot waveform depending on the tested equipment. Consequently, a test was conducted with respective front times of 1.2, 2.4, (3.6) and 4.8 μs while maintaining a double exponential function waveform without overshoot. The influence of the front time on the insulation characteristics was subsequently evaluated based on these test results.

# 3 EXPERIMENTAL RESULTS

## 3.1 CASES WHERE THE OVERSHOOT RATE IS CHANGED

*3.1.1 Superimposed Oscillation Frequency fs = 250 kHz ($SF_6$ Gas Insulation For GIS)* Table 1 summarizes the test results where the OS rate was changed (fs: approx. 250 kHz) with the front time maintained at 1.2 μs. In Figure 2, the peak values of the applied voltage and the breakdown times are plotted. In addition, the voltage waveforms without breakdown are normalized and illustrated. Based on the results summarized in Table 1, changes in the 50%BDV and average breakdown time with respect to the OS rate are exhibited in Figure 3.

**Table 1:** Breakdown voltage characteristics with respect to the OS rate in case of fs = 250 kHz ($SF_6$ gas insulation for GIS)

| | | Target OS rate (%) (Experimental value of the OS rate) | | | |
|---|---|---|---|---|---|
| | | **0%** | **10% (9.9%)** | **20% (18.1%)** | **30% (24.4%)** |
| Wave form | Superimposed oscillation frequency (kHz) | Smooth waveform | 240 | 290 | 300 |
| Wave form | Front time (μs) | 1.3 | 1.4 | 1.1 | 1.1 |
| Experimental results | 50% BDV (kV) (Ratio to the S.W. %) | **1020.7** (100.0%) | **1041.2** (102.0%) | **1135.9** (111.3%) | **1156.9** (113.3%) |
| Experimental results | σ (kV), (Ratio to the 50% BDV) | 39.9 (3.9%) | 29.0 (2.8%) | 22.4 (2.0%) | 7.6 (0.7%) |
| Experimental results | Average breakdown time (μs) | **17.9** | **13.7** | **6.3** | **1.8** |

According to the plots of the breakdown time in Figure 2, it is confirmed that, where the OS rate is high, the ratio of breakdown occurring at the wavefront increases. According to Figure 3, the higher the OS rate, the shorter the average breakdown time becomes. Also, the higher the OS rate, the higher the 50% BDV becomes. Assuming that the 50%BDV was 100% when the OS rate was 0%, it was 102.0%, 111.3%, and 113.3% when the OS rate was 10%, 20%, and 30%, respectively. If the OS rate is high, the voltage significantly decreases after the wavefront and hence does not contribute to the wavetail insulation breakdown. Consequently, the breakdown voltage is considered to rise. As in this case, where the 50%BDV of the overshoot waveform becomes higher than that of the waveform with the OS rate of 0%, the conversion of the waveform using the k-factor function is effective. In the previous standard, an oscillatory component of 500 kHz or less was determined to be included in the crest value. The test result in the present study indicated that the previous method slightly overestimated the withstand voltage.

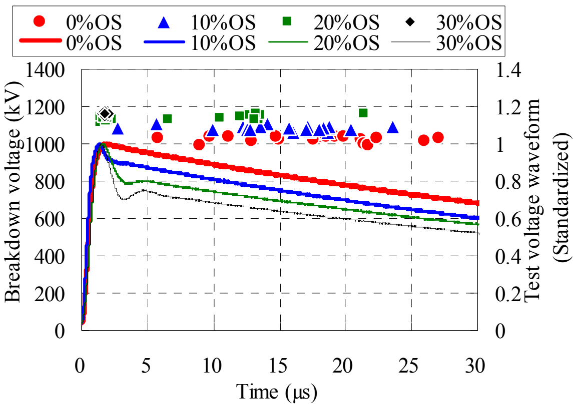


**Figure 2:** Characteristics of the breakdown voltage and time with respect to the OS rate in case of fs = 250 kHz ($SF_6$ gas insulation for GIS)

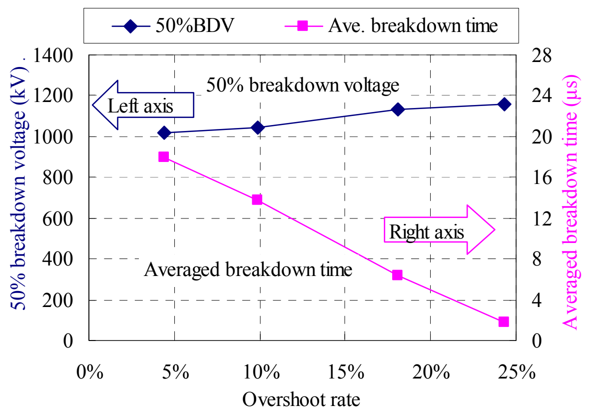


**Figure 3:** Changes in the breakdown voltage and time with respect to the OS rate in case of fs = 250 kHz ($SF_6$ gas insulation for GIS)

*3.1.2 Superimposed Oscillation Frequency fs = 150 kHz (Oil Insulation For Transformer)* Table 2 summarizes the experimental results where the OS rate was changed with fs = 150 kHz. The peak values of the applied voltage and the breakdown times are plotted in Figure 4. Changes in the 50%BDV and average breakdown time with respect to the OS rate are exhibited in Figure 5.

According to Table 2, the 50%BDV for the waveforms with an OS rate of 10%, 20%, or 30% is about 104% of that with the OS rate of 0%.

**Table 2:** Breakdown voltage characteristics with respect to the OS rate in case of fs = 150 kHz (oil insulation for transformer)

| | | Target OS rate (%) (Experimental value of the OS rate) | | | |
|---|---|---|---|---|---|
| | | **0%** | **10% (11.9%)** | **20% (18.0%)** | **30% (23.5%)** |
| Wave form | Superimposed oscillation frequency (kHz) | Smooth waveform | 150 | 150 | 150 |
| Wave form | Front time (μs) | 2.0 | 2.4 | 2.2 | 2.5 |
| Experimental results | 50% BDV (kV) (Ratio to the S.W. %) | **849.5** (100.0%) | **886.0** (104.3%) | **880.0** (103.6%) | **884.5** (104.1%) |
| Experimental results | σ (kV), (Ratio to the 50% BDV) | 23.9 (2.8%) | 27.8 (3.1%) | 25.6 (2.9%) | 20.7 (2.3%) |
| Experimental results | Average breakdown time (μs) | **4.7** | **3.6** | **3.2** | **3.5** |

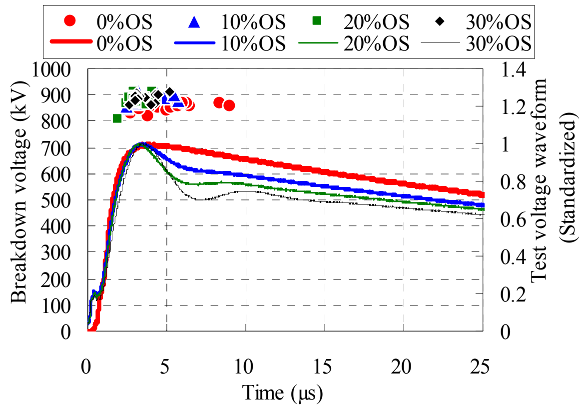


**Figure 4:** Characteristics of the breakdown voltage and time with respect to the OS rate in case of fs = 150 kHz (oil insulation for transformer)

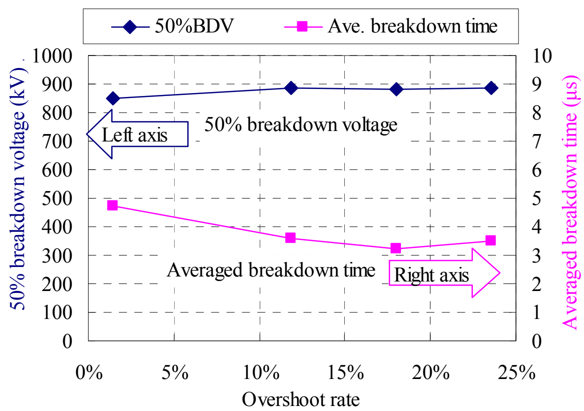


**Figure 5:** Changes in the breakdown voltage and time with respect to the OS rate in case of fs = 150 kHz (oil insulation for transformer)

Compared with the results for fs = 250 kHz, the increase rate of the 50%BDV with the increase in the OS rate is lower. This is considered attributable to the fact that, since the front time of the waveforms is relatively long in Figure 4, the overshoot waveforms in the range of the breakdown time (2 μs to 6 μs) are relatively close to the waveform with the OS rate of 0%. Consequently, the difference in the 50%BDV with respect to the OS rate is smaller than that for other fs and less than 1/4 of the value σ (the difference in the 50%BDV between the OS rates of 10 and 20% is only 6 kV as compared with the value σ of 25.6 kV for the OS rate of 20%). According to these results, it is also undeniable that the 50%BDV for the OS rate of 10% is potentially relatively high within the range of the value σ. According to the waveforms and the distribution of the breakdown times in Figure 4, the 50%BDV is estimated to essentially increase with the increase in the OS rate.

However, for fs = 150 kHz, the 50%BDV of the overshoot waveforms is also higher than that of the waveform with the OS rate of 0%, meaning that the conversion of the waveforms using the k-factor function is effective. The test result for fs = 150 kHz indicated that the previous method slightly overestimated the breakdown voltage.

### 3.2 CASES WHERE THE FRONT TIME IS CHANGED

*3.2.1 $SF_6$ Gas Insulation For GIS* Figure 6 displays the relationship between the breakdown voltage and time with respect to the front time. Changes in the 50% BDV and the average breakdown time with respect to the front time are indicated in Figure 7.

According to the plots of the breakdown time in Figure 6, for each front time, there are several cases of insulation breakdown at the rising part; however, insulation breakdown occurs in most cases after the wavefront in around 10 μs to 20 μs. Although this may be a relatively longer insulation breakdown time for the $SF_6$ gap, these phenomena are considered to have appeared because the step voltage was set sufficiently small. This is also implied by a small value of σ.

As for changes in the average breakdown time in Figure 7, the average breakdown time increases slightly as the front time is extended, but the change is small as compared with the characteristics related to the OS rate in Figure 3.

As for changes in the 50% BDV, the 50% BDV decreases by 0.8% where the front time is extended to 4.8 μs; however, the insulation characteristics hardly change compared to Figure 3. Consequently, for LIWV test waveforms, allowing the extension of the front time is more likely to facilitate testing to verify the insulation performance rather than increase the OS rate.

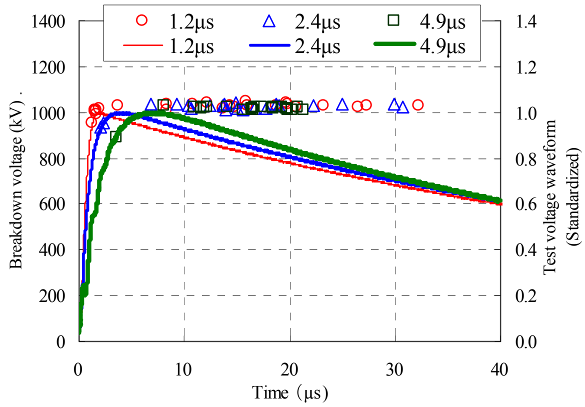


**Figure 6:** Characteristics of the breakdown voltage and time with respect to the front time (SF6 gas insulation for GIS)

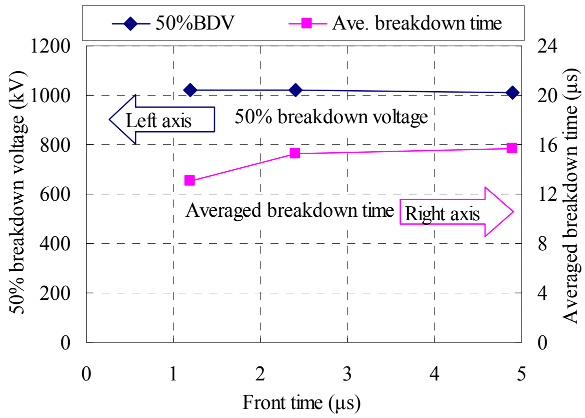


**Figure 7:** Changes in the breakdown voltage and time with respect to the front time (SF6 gas insulation for GIS)

*3.2.2 Oil Insulation For Transformer* The relationship of the breakdown voltage and breakdown time with respect to the front time is displayed in Figure 8 similarly to Figure 4. Changes in the 50%BDV and the average breakdown time with respect to the front time are summarized in Figure 9.

First, attention is focused on the cases where the front time is 1.2 μs to 3.5 μs. According to the plots of the breakdown time in Figure 8, breakdown occurs after the peak of the waveform and generally within 10 μs. According to Figure 9, the longer the front time, the longer the average breakdown time becomes. The 50%BDV varies less compared with that in Figure 5 where the OS rate is changed. Compared with the 50%BDV for the front time of 1.2 μs, it is 104.1% for the front time of 2.4 μs and 103.0% for the front time of 3.5 μs, or within a ± 3% range, which is the test voltage tolerance. Consequently, for LIWV test waveforms, allowing the extension of the front time is more likely to facilitate testing to verify the insulation performance rather than increasing the OS rate.

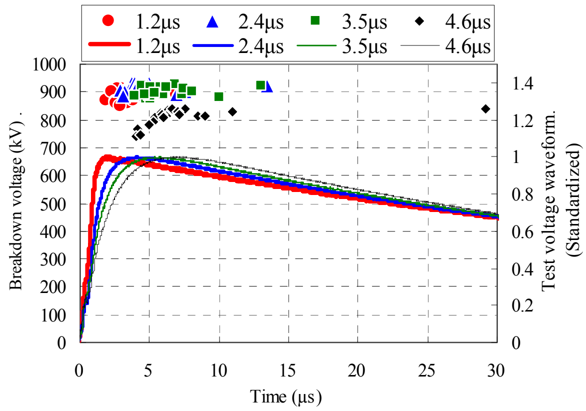


**Figure 8:** Characteristics of the breakdown voltage and time with respect to the front time (oil insulation for transformer)

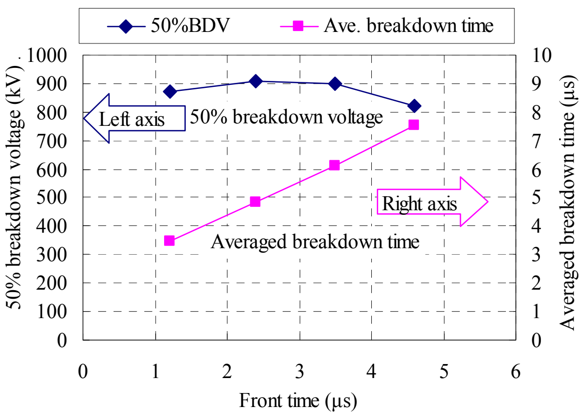


**Figure 9:** Changes in the breakdown voltage and time with respect to the front time (oil insulation for transformer)

Conversely, where the front time is 4.6 μs, some breakdowns are observed at the rising part of the waveform. The 50%BDV (822.5 kV) for the front time of 4.6 μs was about 6% lower than that (874.0 kV) for the front time of 1.2 μs. Accordingly, where the steepness decreases with the front time increased to about 4.6 μs, the aspect of breakdown is considered to differ from that under the standard waveform. Consequently, where the relaxation of the standard for the front time is assumed for the main insulation of an oil-immersed transformer, it will have to be about 3.6 μs or less.

## 4 DISCUSSION ON THE K-FACTOR VALUE

### 4.1 $SF_6$ GAS INSULATION FOR GIS

Figure 10 displays the evaluation result of k-factor value. Since the result, particularly for the OS rate of 10%, agrees quite familiar with the existing k-factor curve, the present evaluation using the k-factor function is considered applicable to UHV-class equipment. Meanwhile, in the previous standard, a frequency component of 500 kHz or less was determined to be included in the crest value (k = 1). In the present study, the k-factor

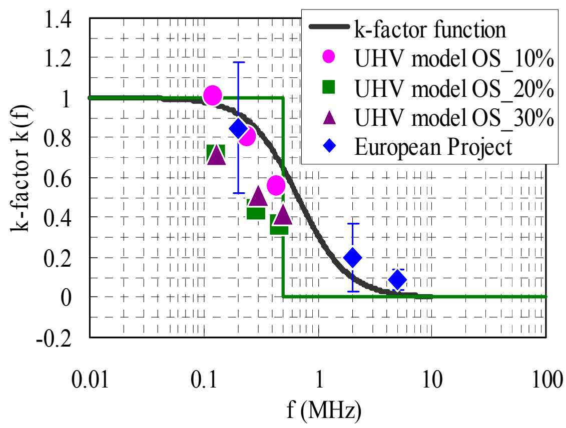


**Figure 10:** K-factor values based on the experimental values ($SF_6$ gas insulation for GIS)

value of the superimposed oscillation frequency of 240 kHz was evaluated at 0.81. Consequently, in the previous standard, the withstand voltage performance was estimated to be higher than the actual one. The introduction of k-factor evaluation makes it possible to evaluate the withstand voltage performance of equipment more rigorously. In the present experiment, a result was obtained assuming UHV-class GIS, hence the potential to apply the evaluation using the k-factor function to UHV-class GIS was indicated.

On the other hand, when the OS rate exceeds 20%, the k-factor value turned into a relatively small value in each fs as compared with the result of 10% OS rate. Based on the study of the overshoot waveform and the insulation breakdown aspect described in Section 3.1.1, the k-factor value is considered to deviate from the assumption of the evaluation method using the k-factor function for the waveform with a large OS rate. In the relationship between the overshoot waveform and the breakdown time shown in Figure 3 in Section 3.1.1, the insulation breakdown occurs after the overshoot part if the OS rate is 10% and the breakdown voltage characteristics include the influence of the overshoot part. However, for a waveform with the OS rate of 20% or more, the insulation breakdown occurs at the wavefront part in almost all cases. In other words, the overshoot part has no influence on the breakdown phenomenon. This indicates that, in an actual test for UHV-class GIS, the equivalence to the standard waveform in the k-factor evaluation may not be maintained for a test waveform with an excessive OS rate.

### 4.2 OIL INSULATION FOR TRANSFORMER

Figure 11 displays the evaluation results of the k-factor values. The results of all OS rates of 10%, 20%, and 30% were slightly lower than the existing k- factor values; however, the trend of change with respect to fs was similar. These results were also equivalent to the results of the European Project,

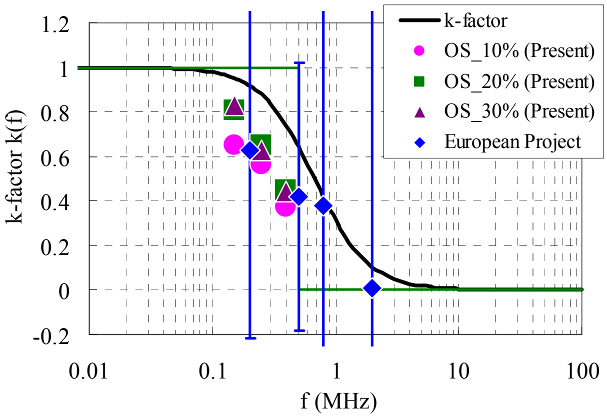


**Figure 11:** K-factor values based on the experimental values (oil insulation for transformer)

on which the existing k-factor function is based. Meanwhile, in the previous standard, a frequency component of 500 kHz or less was determined to be included in the crest value (k = 1). In the present study, the k-factor values actually measured were evaluated at about 0.7 to 0.8 for fs = 150 kHz, about 0.6 for fs = 250 kHz, and about 0.4 for fs = 400 kHz respectively.

Consequently, in the previous standard, the withstand voltage performance was estimated to be higher than the actual one. As referred to in Section 3.1.2, the introduction of the k-factor evaluation is considered to allow more rigorous evaluation of the withstand voltage performance of equipment. Furthermore, according to the result of the present experiment, the potential to apply the evaluation using the k-factor function to a UHV-class transformer was indicated. Consequently, the k-factor values, in terms of their change with respect to fs, were in accordance with the k-factor function and almost identical to those of the European Project, which represent the basic data to derive the existing k-factor function. Accordingly, for UHV-class oil-immersed transformers, the application of the existing k-factor function is assumed to be reasonable from an engineering perspective.

## 5 CONCLUSION

The present paper reported the experimental results of the insulation breakdown characteristics for the LIWV test waveform in large-scale models assuming actual UHV-class GIS and transformer. In the experiment, the breakdown voltage and time were measured where the superimposed oscillation frequency, overshoot rate, and front time were changed as waveform parameters. Based on the test results, changes in the insulation breakdown characteristics were analyzed. Furthermore, based on the experimental results, the k-factor values were calculated and compared with the existing k-factor function.

Consequently, the result was obtained, whereby the OS rate of 10% almost coincided with the existing k-factor function and the present evaluation using the k-factor function were considered appropriate and also expected to be effective for UHV-class equipment. However, where the OS rate was 20% or more, as opposed to the insulation breakdown phenomenon in the standard waveform, the k-factor evaluation for such waveforms may be unable to maintain equivalence to the standard waveform because the insulation breakdown often occurs at the rising part of the lightning impulse waveform. Conversely, it was indicated that the change in the insulation breakdown characteristics was minor where the front time had been extended. Consequently, in the standard assuming UHV-class equipment, it is considered more efficient to extend the front time rather than allow an excessive overshot rate.

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