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PROPOSAL OF NEW K-FACTOR FUNCTION IN LIGHTNING IMPULSE TEST FOR ELECTRIC POWER EQUIPMENT

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Abstract: Ultra high voltage (UHV) systems are increasingly being planned and constructed, hence studies are promoted on the standard for high-voltage test techniques for UHV-class equipment. For the lightning impulse voltage test, a study is being conducted on the application of a method of evaluating the test waveform through conversion using the test voltage function (k-factor function) that was adopted in IEC 60060-1. The existing k-factor function was established based on the experimental results for more compact models, as compared with the insulating structure of UHV-class equipment, mainly with a breakdown voltage of about 100 kV. To determine whether this k-factor function can also be used for the test of UHV-class equipment, the experimental results for large-sized models were needed. In the present paper, to address this issue, the authors initially obtained k-factor values experimentally using the largest possible model (UHV model) assuming UHV-class equipment. Substantially, a study was conducted on a new k-factor function based on these experimental results. First, in the study, several ideas for the k-factor function were shown and applied to various waveforms to clarify their advantages and disadvantages. Next, in addition to these results, a study was conducted on a k-factor function suitable for UHV-class equipment with considering the actual UHV facilities. Consequently, it was concluded that the form of the function should be the same as that of the existing one but that it would be reasonable to adopt a relatively lower k-factor function for UHV-class equipment by revising the constant. Further, this new function could replace the existing one in 60060-1 for all voltage classes to consider the breakdown voltage ranges as a basis and LIWV (Lightning Impulse Withstand Voltage) values.

1 INTRODUCTION

For high voltage test techniques, the International Electrotechnical Commission (IEC) TC42 established a new IEC 60060-1 in 2010 for equipment of 800 kV or less [1]. In the lightning impulse voltage test, a method of evaluating an overshoot waveform by converting it into the equivalent waveform in terms of insulation (called test voltage waveform) using the k-factor function (test voltage function) [2] was introduced. At present, WG19 “Adaptation of TC42 standards to UHV test requirements” is actively promoting a study on the relevant IEC standard for UHV-class equipment [3, 4]. In the WG activities, discussions are made on the use of the k-factor function, which has been mainly studied for equipment of 800 kV or less, for UHV-class equipment.

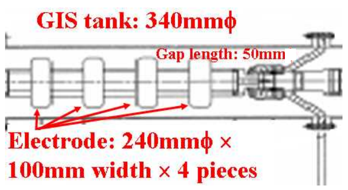
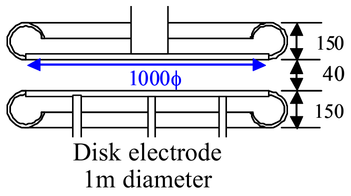
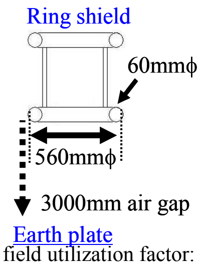
The existing k-factor function was established based on the experimental results of the European Project (E.P.) [5]. This experiment was conducted using more compact models, as compared with the insulating structure of UHV-class equipment, mainly with a breakdown voltage of about 100 kV or less. To determine whether this k-factor function can also be used to the test of UHV-class equipment, a study based on the experimental results for large-sized model is needed.

In the present paper, in response, the authors initially experimentally obtained the k-factor values for three types of insulating media, namely an SF_6 gas gap, oil gap, and air gap, using the largest possible models (hereinafter referred to as the “UHV models”) assuming UHV-class equipment. Subsequently, the experimental results were compared with the results of the E.P. and so forth to clarify the characteristics required for a longer insulation length for UHV-class equipment. Finally, based on these results, a study was conducted on a k-factor function suitable for UHV-class equipment with considering the actual UHV facilities.

2 EXPERIMENTAL RESULTS USING UHV MODELS

This section initially describes the experimental conditions of UHV models and the k-factor values obtained using these models. Subsequently, these k-factor values are compared with the results of the existing k-factor function and the E.P., on which the existing k-factor function is based, to

Table 1. Experimental conditions to obtain the insulation characteristics of SF_6 gas, oil, and air gaps of large-sized models (UHV models) with respect to overshoot waveforms.

	Test object	SF_6 gas gap (Gas insulated switchgear)	Oil gap (Oil-immersed transformer)	Air gap (Air insulation such as bushing)
Experimental conditions	Test electrode configuration	• Actual GIS (Coaxial cylinder)  *Electric field utilization factor: 0.59 *Electrode effective area: 4.5×10^4 mm^2	• Disk electrodes  *Electrode effective volume: 3.1×10^4 cm^3	• Bushing model  *Electric field utilization factor: 0.04
	Other conditions	Gas pressure: 0.50 MPa-abs	New oil for transformer	Atmospherically-corrected
Waveform	Polarity and magnitude	−1000 kV	−800 kV to −1000 kV	+1800 kV / −2400 kV
	Oscillation frequency	About 150 kHz, 250 kHz, and 400 kHz	About 150 kHz, 250 kHz, and 400 kHz	About 150 kHz, 250 kHz, and 400 kHz Only 250 kHz for negative polarity
	Target overshoot rate, β’	0%, 10%, 20%, and 30%	0%, 10%, 20%, and 30%	0%, 10%, and 20%

summarize the characteristics for a longer insulation length of UHV models.

2.1 Experimental conditions of UHV models

Table 1 summarizes the experimental conditions of UHV models used to measure the k-factor values. The experiment is conducted on three types of typical insulating elements, namely an SF_6 gas gap assuming gas insulated switchgear (GIS), an oil gap assuming an oil-immersed transformer, and an air gap assuming an air insulating part such as a bushing.

The voltage waveforms applied are the half-cycle overshoot waveforms represented in Figure 1, considering the overshoot waveform generation principle in an actual lightning impulse voltage test. The frequency of the overshoot part is set to several hundred kHz, which is actually at issue, and the overshoot rate β’ is varied. To calculate the k-factor value, a smooth impulse waveform (β’≈0%) with no overshoot part is also used for the experiment.

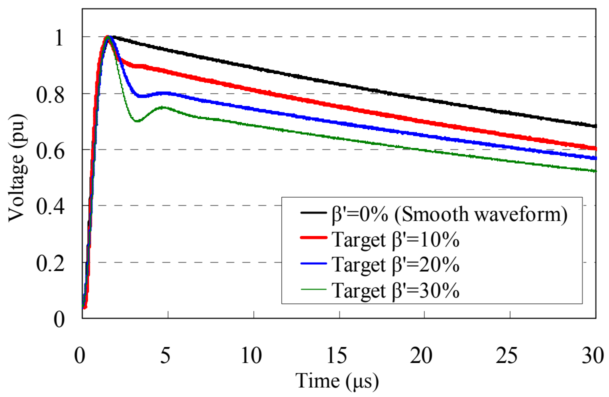


Figure 1. Example of overshoot waveforms applied (Oscillation frequency: 250 kHz, target overshoot rate β’: 0%, 10%, 20%, and 30%).

The lightning impulse breakdown voltage level for these test gaps is about 1,000 kV for SF_6 gas and oil gaps, and about 1,800 kV/2,400 kV for the positive/negative polarities, respectively, for air gap.

2.2 Experimental results for UHV models and comparison with existing k-factor function and European project

In Figure 2, all the k-factor values obtained in the experiment using UHV models are plotted. For comparison, the existing k-factor function is shown using a solid line, which was established based on the representative experimental results of the E.P.

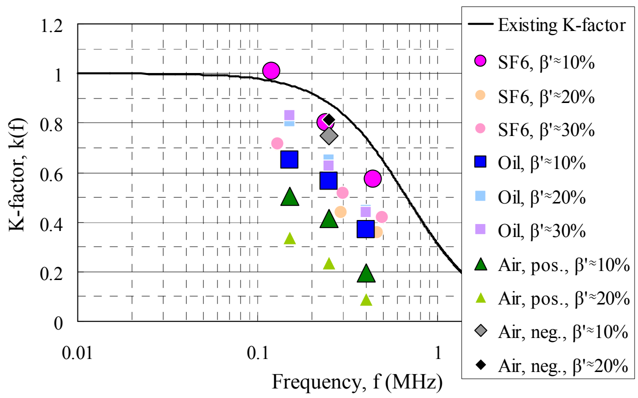


Figure 2. Comparison between the k-factor values obtained using UHV models and the existing K-factor function established based on the E.P. (The results for β’≈10% are highlighted using relatively large plots).

In the experiments of the E.P., k-factor values were obtained using SF_6 gas, oil, air and XLPE (cross-linked polyethylene) insulations, and the lightning impulse breakdown voltage level was about 100 kV or less. Based on the regression curve of these results, the k-factor function expressed in equation (1) was derived as f: frequency (MHz) [1].

$$k(f) = \frac{1}{1 + 2.2 \times f^2} \quad (1)$$

As compared in Figure 2, the k-factor values for UHV models are distributed relatively lower overall than the existing k-factor function, regardless of the insulating medium, overshoot rate β', or frequency. Conversely, the frequency dependency, whereby the higher the frequency, the lower the k-factor value, is similar for both. The comparison by insulating medium is as follows:

[SF_6 gas gap] Even though the k-factor values for β'≈10% for the UHV model are slightly lower than those of the E.P., there is no significant difference between them. They are also close to the existing k-factor function.

[Oil gap] The k-factor values for the UHV model are relatively lower than the existing k-factor function, but are almost the same as the results of the E.P.

[Air gap (Positive polarity)] The k-factor values for the UHV model are considerably lower as compared with the existing k-factor function. Even though the k-factor values of the E.P. vary, they remain relatively in line with the existing k-factor function. Consequently, the k-factor values for the UHV model are relatively lower than the results of the E.P.

3 STUDY OF NEW K-FACTOR FUNCTION FOR UHV CLASS EQUIPMENT

3.1 Ideas for k-factor function for UHV-class equipment

In addition to the experimental results for UHV models and their difference from the existing k-factor function, this section shows ideas for the k-factor function that are considered suitable for UHV-class equipment with the composition of facilities and the actual operation in UHV substations taken into consideration.

Firstly, there are two major ideas. One is to use the existing k-factor function as is, which is referred to as "Idea 1". The other is to establish a new k-factor function based on the results for UHV models, which is referred to as "Idea 2". The following are the concept and advantages and disadvantages for each:

3.1.1 Use of existing k-factor function (idea 1)

The following is an explanation of the concept of Idea 1, which follows the existing method. In UHV substations, GIS may be adopted from the perspective of the reliability and downsizing and air-insulated equipment can be limited to the bushings at the entrance of a substation [15], which makes the internal insulation of GIS and a transformer a major factor. To verify the insulation performance of air insulation, such as bushings, the switching impulse voltage test and ac voltage test in the case of pollution are dominant. In other words, air insulation is not essentially an issue for equipment in the lightning impulse voltage test. Consequently, with a focus on the characteristics for internal insulation, such as SF_6 gas and oil insulation, the results are almost the same as those in the E.P., meaning the existing k-factor function is used as-is under this concept. No change in the k-factor function facilitates handling. For example, IEC 60060-1 [1] can be applied as-is for the UHV standard, and the existing waveform processing procedures can be used unchanged for practical operations.

Subsequently, Idea 1 is evaluated from the perspective of verifying the degree of equipment reliability. For oil and air insulations, k-factor values exceeding the results for UHV models are used. As a result, the overshoot part of the recorded curve is over-evaluated and converted into a test voltage curve not equivalent but relatively higher. Consequently, the test is relatively less strict for transformers and air insulated equipment, raising concern that the insulation performance may not be adequately verified. Those for SF_6 gas insulation are considered to be properly verified because the characteristics are almost identical.

3.1.2 Establishment of a new k-factor function based on results for UHV models (idea 2)

Idea 2 is a concept to establish an original k-factor function for UHV-class equipment by considering the decrease in the k-factor values in oil and air gaps for UHV models compared with the existing k-factor function. For this new k-factor function, there could be several patterns as follows:

Idea 2-A: To establish a k-factor function using the experimental results for SF_6 gas and oil gaps, with excluding air gap. The results for air gap are excluded because air insulation is not essentially an issue for UHV equipment as mentioned in Section 3.1.1.

Idea 2-B: To establish a k-factor function using the experimental results for three insulating media, namely SF_6 gas, oil, and air gaps. This is the same as the concept of having established the existing k-factor function.

Idea 2-C: To establish a k-factor function on an individual basis because the k-factor values vary depending on the insulating medium. Here, Idea 2-C-1 is for SF6 gas gap, Idea 2-C-2 for oil gap, and Idea 2-C-3 for air gap.

Compared with Idea 1, the k-factor functions in Ideas 2-A and 2-B indicate insulation characteristics closer to the correct characteristics for a transformer and air insulated equipment. Conversely, they are relatively strict for the test of GIS, possibly leading to excessive insulation specifications. In Idea 2, the k-factor function must be changed, and a complicated handling method is required, particularly in Idea 2-C, whereby the function established differs by equipment.

As mentioned above, each idea has its own set of advantages and disadvantages. In the following sections, k-factor functions are derived based on Idea 2 to study their influence on the evaluation results of the actual test waveform through conversion.

3.2 Derivation of new k-factor function based on each idea

This section derives a k-factor function based on Idea 2 using the k-factor values for β'≈10%. The dependency of the k-factor values on frequency is similar to that of the existing k-factor function as indicated in Figure 2. Consequently, the form of the function is based on the existing equation (1) and the constants "a" and "b" ($2.2 \times f^2$ in (1) → $a \times f^b$) are reviewed.

Table 2 summarizes the constants "a" and "b" calculated and Figure 3 displays the k-factor curve in each idea. In Idea 2-A, the results for SF_6 gas and oil gaps are used and the k-factor curve is

Table 2. Calculation results of the constants "a" and "b" of the K-factor function in each idea.

Idea	Type of insulating medium used	Condition of the constant "b"	Calculation results	
			"a"	"b"
1	-	-	2.2	2
2-A	SF_6 and oil	b=2 fixed	7.5	2
		b parameter	4.19	1.52
2-B	SF_6, oil, and air	b=2 fixed	12.29	2
		b parameter	5.52	1.40
2-C-1	SF_6	b=2 fixed	3.82	2
		b parameter	4.79	2.22
2-C-2	Oil	b=2 fixed	13.82	2
		b parameter	4.64	1.19
2-C-3	Air	b=2 fixed	30.97	2
		b parameter	11.33	1.34

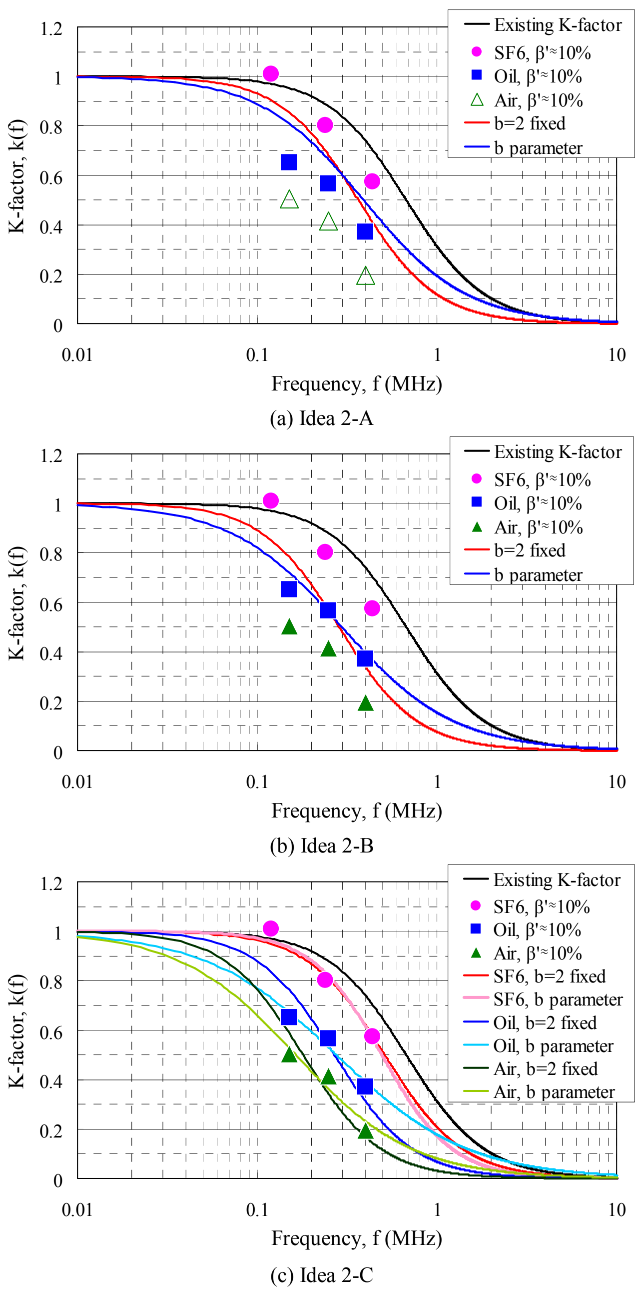


Figure 3. Results of deriving the K-factor function in each idea.

drawn between them and relatively lower than the existing k-factor curve. In Idea 2-B, the data for air and oil gaps are used and the k-factor curve is drawn between them and relatively lower than the existing k-factor curve. In Idea 2-B, the data for air gap are added, hence the k-factor curve is lowered further. In Ideas 2-A and 2-B, where "b" is a parameter, "b" is about 1.5 and the gradient of the k-factor curve is slightly smaller compared with the case where "b" is fixed to 2. In Idea 2-C, the k-factor curve descends in sequence of SF_6 gas, oil, and air insulations based on the magnitude of the k-factor values. Where "b" is a parameter, b=1.19 for oil and b=1.34 for air, indicating that the gradient is smaller.

Here, attention is focused on a frequency range of several hundred kHz, which is key for the lightning impulse voltage test of actual UHV-class equipment. In each idea, where "b" is a parameter, even though the gradient of the k-factor curve varies, the k-factor values themselves do not vary significantly within this frequency range.

4 STUDY ON REFLECTION IN STANDARD

In the previous sections, several ideas of the k-factor function were taken up based on the experimental results using UHV models to clarify their advantages and disadvantages through their use for actual waveforms. This section studies the k-factor function suitable for UHV-class equipment; taking various conditions into consideration and assuming its reflection in the standard for UHV.

In the evaluation of the test waveform, it emerged that the value of the test voltage Ut varied slightly depending on the k-factor function used, which potentially led to a change in the LIWV requirements satisfied by the waveform. Therefore, strictly speaking, Idea 2-C is considered positive because the k-factor function is established for each insulating medium (equipment). On the other hand, with practical handling in mind, Idea 2-C is too complicated as described in Section 3.1.2.

Ideas 1, 2-A, and 2-B provide relatively easy handling because the k-factor function common to each piece of equipment is used. Of these, the function of Idea 2-B includes the results for air gap and the k-factor values are relatively low. However, since air insulated equipment is limited in UHV substations and the lightning impulse voltage test is not dominant to verify the insulation performance, the results for air gap will not be significant. Furthermore, though the data for air gap used in the present study are experimental results under the non-uniform electric field assuming a bushing, some reports suggest that the k-factor values are larger under quasi-uniform conditions, even for the longer gap length. Consequently, it remains questionable to use Ideas 2-B or 2-C-3, which use the data for air gap.

Idea 2-A is the k-factor function established using the results for SF_6 gas and oil gaps. This is a function assuming GIS and transformers are key for UHV substations and considered to be more realistic. However, where this function is used, the test may be relatively slightly stricter for GIS and less strict for transformers and air insulated equipment. In this context, assuming the evaluation results of each equipment using Idea 2-C to be correct, the deviation from them are shown in Figure 4 in relative values. In the figure, the positive side means that the k-factor values are larger than those of Idea 2-C and the evaluation results in the test are relatively less strict. A relatively less strict evaluation may lead to inadequate verification of the insulation performance of equipment. On the other hand, the negative side means that the k-factor values are smaller and the evaluation results in the test are relatively stricter, potentially giving rise to an excessive insulation specification.

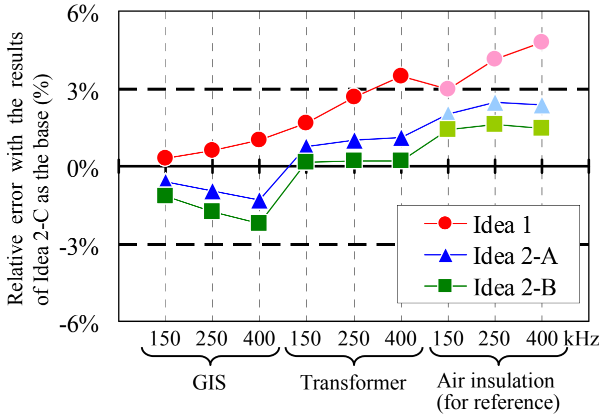


Figure 4. Deviation rate of the calculation results in other than Idea 2-C assuming the evaluation results of each piece of equipment using Idea 2-C to be correct.

It is found that Ideas 2-A and 2-B evaluate the value of the test voltage Ut relatively lower (stricter) for GIS and relatively higher (less strict) for transformers and air insulated equipment. However, the deviation is not so large. On the other hand, where the existing k-factor function of Idea 1 is adopted, the evaluation results are on the positive, i.e. less strict side, under all conditions. Accordingly, Idea 1 may not be able to appropriately verify the insulation performance of UHV equipment. When assuming the actual test for UHV equipment, the facilities which should be particularly considered are GIS and transformers. It emerges in Figure 4 that the deviation in Idea 2-A is the smallest among the ideas and is sufficiently small compared with the tolerance of 3% specified in the IEC standard [1].

Based on the above, the authors consider that, of these ideas, the function expressed by equation (2) with "b" fixed to 2 (as f: frequency (MHz)) in Idea 2-A is the most realistic and reasonable. Figure 5 exhibits the test voltage curves obtained using the k-factor function for waveforms of f = 150 kHz, and 400 kHz. For comparison, the results using the existing k-factor function in Idea 1 are given together. According to the comparison of the results in both ideas, where the frequency is low at a level of about 150 kHz, the difference in the k-factor value is small, as is the difference in the value of the test voltage Ut. Conversely, where the frequency is higher at a level of about 400 kHz, the difference in the k-factor value is relatively larger, and likewise the difference in the value of the test voltage Ut.

$$k(f) = \frac{1}{1 + 7.5 \times f^2} \tag{2}$$

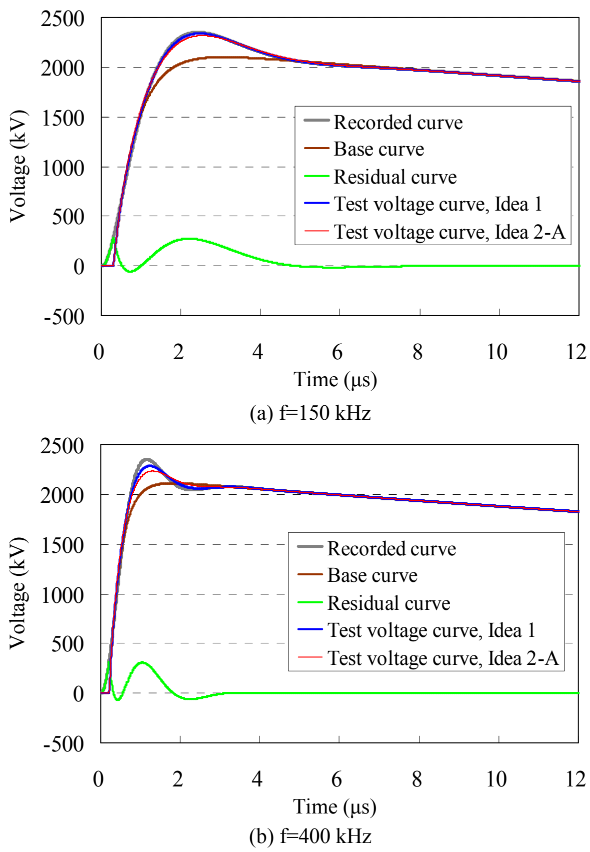


Figure 5. Test voltage curves converted and evaluated where the k-factor functions in Ideas 1 and 2-A are used for the actual overshoot waveforms.

Although the breakdown voltages for the proposed new k-factor function lie in a range of 1000 kV, which is more than ten times larger than that of E.P., they still remain at the LIWV level of 300 kV class equipment. As the k-factor evaluation is especially needed in higher than 300 kV class, where equipment have large size and static capacitance to ground, the proposed equation (2) should be applied to all voltage classes and may replace the existing equation (1) in IEC 60060-1 [1].

5 SUMMARY

In this paper, the k-factor function suitable for UHV-class equipment was studied. In the study, ideas of a new k-factor function were initially shown with the form of actual UHV equipment taken into consideration in addition to experimental results using a large-sized model (UHV-model) assuming UHV-class equipment. Subsequently, each idea was applied to actual overshoot waveforms, and the various parameters of the test voltage curve evaluated through conversion were calculated and compared to clarify respective advantages and disadvantages.

The examination results are summarized as follows:

(1) The dependency of the k-factor values on frequency in UHV models was similar to that of the existing k-factor function. Consequently, it is considered reasonable that the form of a new k-factor function for UHV-class equipment be the same as that of the existing one.

(2) Considering, for example, the form of actual UHV substation facilities, the k-factor function established based on the experimental results for SF_6 gas and oil gaps in UHV models is considered the most realistic and reasonable.

(3) The proposed equation (2), the basic breakdown voltage range for which corresponds to 300 kV class LIWV, should be applied to all voltage classes and may replace the existing equation (1) in IEC 60060-1.

The examination results in the present paper are expected to be useful as one of the materials used for decision-making in establishing the lightning impulse voltage test standard in the IEC and CIGRE WG.

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