Experimental Assessment on Air Clearance of Multiple Valve Unit Considering Switching Impulse and DC Superimposed Switching Impulse

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Abstract: Multiple valve unit (MVU), which converts AC to DC and DC to AC, is one of the key elements of high voltage DC (HVDC) transmission. Therefore, the insulation design of MVU against overvoltage should be considered for the stable and reliable operation of HVDC transmission system. Especially, the air clearance of MVU should be calculated based the switching impulse, since it is fatal to MVU in terms of electrical insulation. However, the previous studies were limited to wave front, and the air clearance of the switching impulse is specified only for an ultra-high voltage (UHV) above 750 kV. As a result, it is difficult to calculate the air clearance of MVU which must endure for a switching impulse under 750 kV. In addition, when the switching impulse introduced while the MVU is in normal operation, it is superimposed to DC and creates the most severe situation, but the studies on such subjects are also insufficient. Therefore, as a fundamental step to calculate the air clearance of MVU, the dielectric characteristics of switching impulse and DC superimposed switching impulse in air have been investigated. The experiments on switching impulse showed that the critical flashover voltage was varied according to the curvature of electrode in the gap distance, up to eight times of the electrode radius. However, beyond that gap distance, the critical flashover voltage became similar, regardless of the radius of electrodes. In case of the superimposed experiment, it was performed according to DC pre-stress level and the polarities of switching impulse. The results were most severe when the positive switching impulse was superimposed on the positive DC, and the peak voltage at which flashover occurs was independent of DC pre-stress.

Keywords: air clearance; critical flashover voltage; DC; DC pre-stress; dielectric characteristics; HVDC; multiple valve unit; superimposed; switching impulse

1. Introduction

The high voltage DC (HVDC) transmission system consists of three basic parts: (1) converter station to convert AC to DC, (2) transmission line, (3) second converter station to convert back to AC. HVDC transmission systems can be configured in many ways, based on cost, flexibility, and operational requirements. One of the most important factors that constitutes the HVDC transmission system is multiple valve unit (MVU), which converts AC into DC or DC into AC. The MVU is loaded high operating voltage, and many elements of MVU, such as thyristors or insulated gate bipolar transistors (IGBTs), are connected in series and these are operated in a valve hall in a HVDC converter station [1]. For the protection of these elements and the safe operation of MVU, reliable insulation design is
essential. As a fundamental step of insulation design, the air clearance of MVU that can endure overvoltage should be calculated. Therefore, research on the precise air clearance calculation that does not cause the flashover between MVU and the ground, the wall, and the ceiling of HVDC converter valve hall should be preceded.

Prior to the study of calculating the precise air clearance, it is necessary to examine the types and characteristics of overvoltage introducing into the MVU. Representative overvoltage can be divided into lightning impulse, switching impulse, and DC overvoltage. Lightning impulse should be considered in outdoor facilities such as HVDC yards, transmission tower, etc., and it can be protected by lightning arrester. Also, it is a minor design factor in the HVDC system, where the submarine or underground line is mainly composed, and facilities located indoors, such as MVU, can be protected by the grounding design of the converter station. In the case of DC overvoltage, it can be regarded as an important factor in HVDC power equipment protected by an insulant that causes space charge or surface charge accumulation. However, the situation is different when it comes to switching impulse. When a fault location is separated from the system, the switching impulse occurs and introduces into the MVU. The switching impulse has a relatively long duration so that it makes large load on the power device even with the same amplitude compared to a lightning impulse. Accordingly, in order to calculate the air clearance of the MVU, it is essential to analyze the dielectric characteristics of switching impulse in air.

In case of AC, the standard insulation levels of power apparatus under 245 kV are not specified for the switching impulse, and the insulation design for it is based on lightning impulse standard insulation levels. For the equipment over 245 kV, both lightning impulse and switching impulse are stated [2]. This is because the standard insulation level of lightning impulse can cover that of switching impulse for the power devices under 245 kV. On the contrary, there is no actual announcement about standard insulation levels for DC, and the study on it is also insufficient. In addition, the fact that the air clearance of the switching impulse withstands voltage only for the amplitude over 750 kV is stipulated, which implies that the studies on switching impulse for the voltage levels, from tens of kilovolt to 750 kV, are absent [3].

There are many impulse voltage flashover experiments for the estimate of the critical flashover voltage of air for short and long gap distances. The definition of critical flashover voltage, which is also called critical flashover voltage, is the amplitude of voltage of a given waveform that, under specified conditions, causes flashover through the surrounding medium on 50% of the voltage applications. The experiments on measuring the critical flashover voltage of air with lightning and switching impulse for diverse electrode configuration such as needle-plane and needle-needle electrode, i.e., extremely non-uniform field, are reported by R. Arora et al. The experiments were conducted for both positive and negative polarities and for gap distances up to 150 mm [4]. The report shows that the dielectric characteristics of air are the most vulnerable to positive switching impulse under extremely non-uniform field. Therefore, the dielectric characteristics of positive switching impulse should be investigated so as to calculate the air clearance of power apparatus.

In the case of conventional research before the 1990s, there are lots of experiments on analysis of the dielectric characteristics of impulses in air. L. Paris et al. had reported the dielectric characteristics of air for diverse electrode configuration, such as rod–plane, rod–rod, conductor–rod, etc. The experiments include both switching impulse and lightning impulse for both polarities, positive and negative. The gap distances were up to 6 m for switching impulse, and 10 m for lightning impulse [5,6]. However, the waveform of switching impulse was 120/4000 µs, which is quite different from that of the standard switching impulse defined as 250/2500 µs [7]. H. M. Schneider and F. J. Turner studied for the switching impulse behavior of UHV station electrodes, by investigating the performance of sphere–plane electrode configuration for gap distances 1 m to 11 m. In this case, a diameter for the high voltage applied electrodes between 0.5 to 1 m was used. The wave front of this study was between 75 to 1220 µs, but does not fit the standard switching impulse, either [8,9]. F. A. M. Rizk had also reported the dielectric characteristics of the switching impulse in air for double toroid electrodes and sphere–plane electrode...
configuration up to gap distance 4.55 m, but impulse wave front was 5 to 500 µs [10]. The reports of G. Gallet et al. had showed the most enormous gap distance range from 1 to at least 30 m for diverse impulse wave front, but it also does not meet standard switching impulse [11].

More recent research has been started to show the dielectric characteristics of the standard switching impulse in air. The study on gap distances up to 150 mm for diameter of 250 mm sphere electrode under standard switching impulse had been carried out by D. E. Gourgoulis et al. [12] For the long gap distance experiments, two different electrode configurations: rod-plane, sphere–plane for gap distances 3 m and 4 m was verified by S. Chen et al. and 2 m to 5 m by J. Cao et al. [13,14] Although these studies on the dielectric characteristics of air for impulses have been reported, there is no overall study on standard switching impulse in air for voltage level up to 750 kV.

The test results of conventional and recent studies showed that the dielectric characteristics of impulses in air vary not only with the impulse wave front, but also with the curvature of the electrode. Since the structure of MVU has various curvature, the dielectric characteristics of impulses in air must be analyzed according to the curvature of electrodes.

The switching impulse is usually introduced MVU into when HVDC converter station is on normal operation, i.e., DC pre-stress of a level corresponding to the operating voltage is applied. As a result, the introduced switching impulse is superimposed to DC operating voltage and causes the most severe situation. Moreover, DC and switching impulse have their own polarities, dielectric characteristics according to them should be analyzed. As mentioned above, DC overvoltage can be regarded as an important factor in HVDC power equipment protected by an insulant; tests for such cases are usually studied and specified. Many studies have been conducted on the DC cable based on space charge or surface charge, and through these research, the DC superimposed lightning and switching impulse tests for cables with extruded insulation and their accessories up to 320 kV was stipulated [15]. The research on DC spacer is also studied for metallic particle behavior, temperature, gases, etc. [16–18].

There is also research on DC superimposed switching impulse dielectric characteristics of air, but they are limited to experiment on overhead line from several meters to tens of meters [19–21]. For example, N.L. Allen et al. conducted experiments on DC superimposed switching impulse for tube–plane electrode configuration. The gap distances were 0.5 m and 0.8 m. However, the waveform of switching impulse was 240/1200 µs, 190/800 µs, and 180/1400 µs, which is different from the standard impulse [21]. In other words, the study on DC superimposed standard switching impulse is even more insufficient. Consequently, it is necessary to study the dielectric characteristics of the DC superimposed switching impulse in air.

For these reasons, in this work, the critical flashover voltage of air of standard switching impulse according to gap distances from tens of millimeters to thousands of millimeters and the curvature of electrodes have been measured as a fundamental study for the precise calculation of the air clearance of MVU. In addition, the dielectric characteristics of DC superimposed standard switching impulse in air had been investigated according to DC pre-stress level and polarities of standard switching impulse.

2. Experimental Set-Up and Methods

2.1. Electrode Configuration

The electric field analysis using COMSOL multiphysics to determine the electrode configuration of the experiment was conducted. The wall, floor, and ceiling of the HVDC converter valve hall can be assumed to be an infinite plane when it compared to the MVU. Accordingly, the electric field analysis for sphere–plane and electrode configuration was performed. The radii of high voltage applied electrodes (HV electrodes) were 12.5 mm, 25 mm, 50 mm, and 75 mm, which were supposed to be used in the experiment. The radii of the grounded plate electrode were 0.5 m, 1 m, 1.5 m, 2 m, and infinite. The gap distances were 0.5 m and 1 m. In electric field analysis, 2d axisymmetric geometry was used. The outer boundary was set to ground and infinite size, to create the same condition as the experiment.
For the infinite case, the grounded electrode was connected to the outer boundary to make it infinite ground. On the contrary, the grounded electrode was separated from the outer boundary finite case, and the electric field analysis was conducted.

The electric field analysis results are shown and summarized in Figure 1 and Table 1, respectively. The values in table represent the percentage of maximum electric field of finite grounded plate case compared to that of infinite grounded plate case, in percent. We assumed that configuration of HV electrode and grounded electrode can be considered as MVU and the HVDC converter valve hall when it exceeds 95%. As shown in Table 1, values are greater than 95% for all cases when the radius of the HV electrode is 12.5 mm. However, values under 95% are observed for the other cases. The radius of the 75 mm HV electrode shows the lowest percentage among them, and 95% transition occurs between the grounded electrode radius of 1 m and 1.5 m. Therefore, the detailed electric field analysis should be conducted for 1 m to 1.5 m grounded electrode, in order to find out the accurate 95% transition point.

![Electric field analysis results](image)

**Figure 1.** Electric field analysis results (a) Infinite grounded electrode, (b) Finite grounded electrode.

| High voltage (HV) Electrode | Gap Distance (m) | Grounded Electrode Radius (mm) | Gap Distance (m) |
|---------------------------|------------------|-------------------------------|-----------------|
| Radius 12.5 (mm)          | 0.5              | 98.0                          | 96.4            |
|                           | 1                | 99.6                          | 99.0            |
|                           | 1.5              | 99.9                          | 99.6            |
|                           | 2                | 99.9                          | 99.8            |
| Radius 25 (mm)            | 0.5              | 95.9                          | 92.9            |
|                           | 1                | 99.2                          | 97.9            |
|                           | 1.5              | 99.7                          | 99.2            |
|                           | 2                | 100                           | 100             |
| Radius 75 (mm)            | 0.5              | 99.6                          | 99.0            |
|                           | 1                | 100                           | 100             |

**Table 1.** Electric field analysis results for determining the electrode configuration.

The simulation results are shown in Table 2. Moreover, 95% transition occurred when grounded electrode radius was 1.2 m. Consequently, two 2.4 × 1.2 m plate aluminum were attached to form a grounded electrode with a size of 2.4 × 2.4 m. Figure 2a,b shows the HV electrodes and the test view used in the experiments, respectively. The HV electrodes material is aluminum, and a curvature of a 5 mm rod (R5), a radius of 10 mm sphere (R10), a 25 mm sphere (R25), and a 50 mm (R50) sphere were used for the experiment on switching impulse test. For DC and the DC superimposed switching impulse test, R5, R10, radius of 12.5 mm sphere (R12.5), and, R50 were confirmed, but the use of HV electrodes for each case differed.
As shown in Figure 3, the point where the straight line connecting the 30% and 90% of the peak value meets the time axis is called the virtual zero point. The wave front is the time between when virtual zero point and the line meets the peak value of switching impulse. Wave tail is defined between the waveform for it is described in Figure 3. Moreover, 2500 µs and 2500 µs, which corresponds to the IEC 60060-1 standard, and the waveform for it is described in Figure 3. Moreover, 2500 µs and 2500 µs mean front time and wave tail, respectively. As shown in Figure 3, the point where the straight line connecting the 30% and 90% of the peak value meets the time axis is called the virtual zero point. The wave front is the time between when virtual zero point and the line meets the peak value of switching impulse. Wave tail is defined between the time at which the voltage is 50% of the peak value and the virtual zero point.

Table 2. Detailed electric field analysis result.

| Gap Distance 1 (m) | HV Electrodes Radius (mm) |
|-------------------|--------------------------|
|                   | 12.5         | 25     | 50     | 75     |
| 1.1               | 99.2         | 98.3   | 96.5   | 94.7   |
| 1.2               | 99.3         | 98.6   | 97.1   | 95.6   |
| 1.3               | 99.4         | 98.8   | 97.6   | 96.3   |
| 1.4               | 99.5         | 99.0   | 98.0   | 96.9   |

Figure 2. Experimental set-up ((a) HV electrodes, (b) test view (c) contact of grounded electrode).

A preliminary experiment was conducted to verify whether the contact of grounded electrodes, as shown in Figure 2c, affects the flashover of voltage or not. The HV electrode was placed on the contact of grounded electrode and flashover voltage was measured. Same process has been carried out in the case when HV electrode placed apart from contact of grounded electrodes. Test results showed that the flashover voltage between them did not differ. Accordingly, it was concluded that the influence of the contact part of the grounded electrode is negligible.

2.2. Switching Impulse

The switching impulse was generated by a 16-stage impulse generator rated 1600 kV. The waveform of switching impulse is 250/2500 µs, which corresponds to the IEC 60060-1 standard, and the waveform for it is described in Figure 3. Moreover, 250 µs and 2500 µs mean front time and wave tail, respectively. As shown in Figure 3, the point where the straight line connecting the 30% and 90% of the peak value meets the time axis is called the virtual zero point. The wave front is the time between when virtual zero point and the line meets the peak value of switching impulse. Wave tail is defined between the time at which the voltage is 50% of the peak value and the virtual zero point.

![Figure 3. The waveform of standard switching impulse.](image-url)
As shown in Figure 2b, the insulator string and 154 kV level polymer insulator were used to separate the crane from the suspended HV electrodes. At the point where a high voltage was applied to a connector and a HV electrode, a pair of stainless-steel spheres were used to prevent corona inception.

For each case, the switching impulse was applied for a gap distances of at least 10 mm to a maximum of 1200 mm. Critical flashover voltage was derived after 20 times of flashover by the up and down method, adopting 3% interval of the initial flashover voltage. The solid sphere had smooth, polished surfaces, free of protrusions or abrasions. Before tests, the surfaces were cleaned with ethanol to remove excess foreign matters. The critical flashover voltage was corrected, corresponding to IEC 60060-1, by measuring the temperature, humidity, and air pressure that could affect the experimental results [7].

2.3. DC Superimposed Switching Impulse

As mentioned above, switching impulse is normally introduced into MVU while DC voltage is applied, and causes switching impulse superimposed overvoltage stresses. Therefore, it is necessary to study the dielectric characteristics of the DC superimposed switching impulse, but there are no clear studies on them, as well as the experimental procedures specified in the standard. Accordingly, the study was conducted to verify the dielectric characteristics of air under DC superimposed switching impulse by varying DC pre-stress level [19].

Prior to examining the critical flashover voltage of DC superimposed switching impulse, the DC flashover experiment was preceded in order to calculate the DC pre-stress level. Figure 4 shows the circuit diagram of DC experiment. As shown in Figure 4, the AC voltage was generated from 400 kVA AC voltage generator and converted to DC through the two-stage Cockcroft–Walton rectifier. The DC voltage was applied at a rate of 3 kV/s. The tests were conducted five times and the flashover voltage was determined from the median of the test results. When any test result deviated by more than 15% from the median, five additional tests were conducted. The flashover voltage was then determined from the median of the 10 test results [22,23]. The applied voltage was measured through a 10,000:1 R-C divider connected in parallel to the specimen. The connected multi-meter was Fluke 83V measuring range up to 1000 kVDC with accuracy of ±0.1%. For each case, as in the switching impulse tests, the temperature, humidity, and air pressure were measured, then critical flashover voltage was corrected [7].

Figure 4. The circuit diagram used for the superimposed switching impulse, with the addition of a blocking capacitor and protection resistor to prevent the switching impulse introducing into the DC rectifier circuit and the converted DC voltage into the impulse generator. The blocking capacitor and protection resistor were connected in series to the impulse generator and DC rectifier circuit, respectively. The configuration of high voltage applying part and measurement method was exactly same as switching impulse tests. In order to verify the air dielectric characteristics of DC superimposed
switching impulse according to DC pre-stress level, 30%, 40%, 50%, and 60% DC voltage was applied for both polarities of switching impulse. The tested gap distances were 160 mm, 200 mm, 240 mm, and 280 mm in the case of the DC superimpose positive switching impulse. In the case of the DC superimposed negative switching impulse test, gap distances of 50 mm, 60 mm, 70 mm, and 80 mm were carried out. The identical experiment procedure as an impulse test was adopted.

The experiment of analysis on the dielectric characteristics of switching impulse in air was carried out in air for a gap distances of at least 10 mm to a maximum of 1200 mm, and the results are depicted in Figure 6a. As shown in Figure 6a, it was found that the critical flashover voltage differs according to the radius of the HV electrodes in the short gap distances. However, the critical flashover voltage became similar regardless of the HV electrodes radius when the gap distance reached a certain value. A detailed experiment was performed for all cases to clarify the transition point, in which the dielectric characteristics was expected to change; the results are depicted in Figure 6b. As shown in Figure 6b, the transition point of R5, R10, R25, and R50 was 40 mm, 80 mm, 200 mm, and 400 mm, respectively. Consequently, the trend of critical flashover voltage was varied according to the curvature of electrode in the gap distance being up to eight times as much as the electrode radius.

3. Experimental Results and Discussions

3.1. Switching Impulse

The experiment of analysis on the dielectric characteristics of switching impulse in air was carried out in air for a gap distances of at least 10 mm to a maximum of 1200 mm, and the results are depicted in Figure 6a. As shown in Figure 6a, it was found that the critical flashover voltage differs according to the radius of the HV electrodes in the short gap distances. However, the critical flashover voltage became similar regardless of the HV electrodes radius when the gap distance reached a certain value. A detailed experiment was performed for all cases to clarify the transition point, in which the dielectric characteristics was expected to change; the results are depicted in Figure 6b. As shown in Figure 6b, the transition point of R5, R10, R25, and R50 was 40 mm, 80 mm, 200 mm, and 400 mm, respectively. Consequently, the trend of critical flashover voltage was varied according to the curvature of electrode in the gap distance being up to eight times as much as the electrode radius.
The phenomena of critical flashover voltage become similar, regardless of the radius of the HV electrodes, due to changes in the flashover mechanism. At a short gap distance, in which the electric field is relatively uniform compared to a long gap distance, flashover occurs simultaneously with the start of the streamer corona. On the other hand, the flashover mechanism of the long gap distance is quite a bit more complicated than that of the short gap distance. In long gap distance, which is enough to grow corona, it forms stable streamers before flashover. On raising the applied voltage, these streamers propagate in the main field direction toward the opposite electrode, besides spreading in radial direction. If the condition required for the growth of streamer is met throughout the gap distance, the streamers can extend up to the opposite electrode. At this stage, a stable streamer is rendered unstable.

As soon as the streamer can extend itself up to the opposite, i.e., the grounded electrode, the conduction path forms, and flashover occurs [4]. We defined the region before the flashover mechanism changes as Region A, and after the flashover mechanism changes as Region B, for the ease of explanation.

To calculate the air clearance between MVU and the HVDC converter valve hall, an analysis of the two regions is essential. Consequently, the trend lines of the critical flashover voltage against the gap distance are derived in this study. Since the critical flashover voltage varies with the radius of the HV electrodes at Region A, the equation of trend lines is represented by the radius of HV electrodes ($R$) and gap distances ($d$) as variables. On the other hand, the trend line of Region B was derived only for the variable of $d$, because the dimension of HV electrodes has nothing to do with critical flashover voltage. The Equation (1) represents the critical flashover voltage trend lines of switching impulse in Region A, and Equation (2) represents the critical flashover voltage trend lines of switching impulse in Region B.

\[
U_{SICFO, A} = 5.56R^{0.37}d^{0.38} \quad (1) \\
U_{SICFO, B} = 1.50d^{0.93} \quad (2)
\]

where $U_{SICFO}$ is critical flashover voltage of switching impulse in kV, $R$ is radius of HV electrode in mm, $d$ is gap distance in mm, $A$ represents Region A, $B$ represents Region B.

Figure 7a shows the trend lines of Region A, the region where flashover mechanism transition does not occur. In this region, the trend line of Region A is the actual flashover voltage. As shown in Figure 7a, the actual flashover voltage in Region A is higher than that of the trend line of Region B. The critical flashover voltage difference between trend line of Region A and Region B can be considered as margin if air clearance is calculated based on the trend line of Region B. In other words, if the air clearance calculation is done based on the trend line of Region B, the air clearance margin, the difference between the trend line of Region A and the trend line of Region B, can be obtained in this area.

Figure 7b shows the trend lines at Region B, the region where the flashover mechanism is changed. In this region, opposed to the Figure 7a, the trend line of Region B is the actual flashover voltage. In this case, the actual flashover voltage is higher than that along the trend line of Region A. In other word, the voltage margin of difference between the trend line of Region A and Region B can be obtained if air clearance is calculated based on the trend line of Region A. However, the flashover voltage along the trend line of Region A is not an actual flashover voltage, which implies that the enough air clearance can be obtained even though it is calculated based on the trend line of Region B.

In conclusion, it is possible to secure the air clearance between MVU and HVDC converter valve hall, satisfying both Region A and Region B if the air clearance calculation is based on the trend line of Region B. Meanwhile, the elements in the MVU are composed of a relatively small size with short gap distances. These components produce switching impulse whenever they are switched. Therefore, it is considered that, if the insulation design is conducted based on Region A for such cases, a more precise air clearance could be calculated.
which implies that the air clearance calculation based on the trend line of Region B satisfies overall where $U_{CFO,DC}$ is critical flashover voltage of positive DC in kV, $d$ is gap distance in mm.

Based on the equations, DC pre-stress level was calculated that went through the DC superimposed switching impulse experiment. For the positive DC superimposed positive switching impulse experiment, R10 and R12.5 electrodes were used and only R10 electrode was used for positive DC superimposed negative switching impulse.

The dielectric characteristics of DC superimposed switching impulse according to the DC pre-stress level and polarities of switching impulse is shown in Figures 9–11. Figures 9 and 10 show the experimental results of positive DC superimposed positive switching impulse, and Figure 11 shows the positive DC superimposed negative switching impulse. Each plot contains the critical flashover voltage of switching impulse to compare the dielectric characteristics of the switching impulse and DC superimposed switching impulse.

Figure 7. The trend line analysis of critical flashover voltage of switching impulse.

3.2. DC and DC Superimposed Switching Impulse

DC flashover experiment was preceded to calculate the DC pre-stress for DC superimposed switching impulse test. Figure 8a,b shows the experimental results of positive and negative DC flashover experiment, respectively. As shown in Figure 8, the transition point, that the dielectric characteristics changed, was present for R10, and R12.5. The transition point of negative DC appeared only in case of R5. From the results of the switching impulse experiment, it can be seen that the critical flashover voltage increases when the transition to Region B occurs. It is deduced that the increment rate of critical flashover voltage is too high; that the transition of trend did not observe in case of negative DC. In other word, the critical flashover voltage of positive DC is much lower than that of negative DC. Besides, the dielectric characteristics of DC are similar to that of the switching impulse, which implies that the air clearance calculation based on the trend line of Region B satisfies over all regions. Therefore, DC superimposed switching impulse experiments were conducted only for Region B for positive DC pre-stress. The trend line equation of Region B positive DC for R10 and R12.5 was deduced in Equations (3) and (4), respectively.

$$U_{CFO,DC} = 0.43d^{1.06}$$  \hspace{1cm} (3)\

$$U_{CFO, DC} = 0.80d^{0.93}$$  \hspace{1cm} (4)

where $U_{CFO,DC}$ is critical flashover voltage of positive DC in kV, $d$ is gap distance in mm.

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\[
U_{\text{UCFO,DC}} = 0.43 \times d^{0.05} \tag{3}
\]

\[
U_{\text{UCFO,DC}} = 0.80 \times d^{0.07} \tag{4}
\]

where \(U_{\text{UCFO,DC}}\) is critical flashover voltage of positive DC in kV, \(d\) is gap distance in mm.

Based on the equations, DC pre-stress level was calculated that went through the DC superimposed switching impulse experiment. For the positive DC superimposed positive switching impulse experiment, R10 and R12.5 electrodes were used and only R10 electrode was used for positive DC superimposed negative switching impulse.

![Figure 8. The flashover experiment results of DC.](image1)

**Figure 8.** The flashover experiment results of DC.

![Figure 9. The experiment results of positive DC superimposed positive switching impulse for R10.](image2)

**Figure 9.** The experiment results of positive DC superimposed positive switching impulse for R10.

![Figure 10. The experiment results of positive DC superimposed positive switching impulse for R12.5.](image3)

**Figure 10.** The experiment results of positive DC superimposed positive switching impulse for R12.5.
As shown in Figures 9–11, the introduced switching impulse to cause flashover decreased as the DC pre-stress increased, in case of DC and switching impulse had same polarities. However, when the different polarity of switching impulse was superimposed into DC, the amplitude of the switching impulse to make the flashover increased as the DC pre-stress increased. This is due to the change of voltage offset caused by DC pre-stress. The analysis in Figures 9 and 10 shows that the critical flashover voltages of switching impulse and DC superimposed switching impulse are not significantly different. As a result, the magnitude of the switching impulse to cause flashover is reduced by the that of the offset due to DC pre-stress, in case the same polarity of the switching impulse is introduced. On the other hand, when a different polarity switching impulse is introduced, the amplitude of the switching impulse, which caused flashover, increased, because the additional amplitude of the switching impulse was needed to offset the DC pre-stress of the opposite polarity.

The critical flashover voltages of switching impulse and DC superimposed switching impulse was compared to median value in percentage, and experimental errors of at most 11% were observed. Since this is an experimental error of less than 15% of the median value, which is specified in IEC 60243-1, it could be assumed that the critical flashover voltage of DC superimposed switching impulse and switching impulse is independent of DC pre-stress level.

Since the dielectric characteristics of DC superimposed switching impulse is independent of DC pre-stress level, it can be concluded that MVU is under the most severe condition when the same polarity switching impulse are introduced. Therefore, the operation DC voltage level of MVU must be taken in considered in calculating the air clearance. Accordingly, the formula for calculation air clearance considering the operating DC voltage level was deduced.

\[
d = k_1 \left( \frac{U_{DC} + U_{SICFO}}{1.50} \right)^{1/0.83}
\]  

(5)

where \(d\) is air clearance in mm, \(k_1\) is correction factor such as margin, \(U_{DC}\) is operating DC voltage in kV, and \(U_{SICFO}\) is critical flashover voltage of switching impulse in kV.

4. Conclusions

In this paper, as a fundamental study on the calculation of air clearance between MVU and HVDC converter valve hall, the dielectric characteristics of DC superimposed switching impulse as well as switching impulse in air has been investigated.
In the case of the switching impulse, the critical flashover voltage varied according to the curvature of electrode in the gap distance up to 8 times of the electrode radius. However, beyond that gap distance, the critical flashover voltage became similar, regardless of the radius of electrodes. It is considered that this is due to the difference between the flashover mechanism of short gap distance and long gap distance. In the case of a short gap distance, flashover occurs immediately when a streamer corona occurs, as the electric field is relatively more uniform than that of long gap distance. On the other hand, in the case of a long gap distance, the flashover is delayed due to stable streamer corona. As a result, the dielectric characteristics of air have been changed.

The result of analyzing the tendency of the critical flashover voltage showed that it is reasonable to calculate the air clearance between relatively long gap distances such as MVU and HVDC converter valve hall, based on Region B. Meanwhile, for a relatively small and short gap distance, such as elements in the MVU, more precise air clearance could be calculated if it is calculated by equation of Region A. Therefore, the formula of the air clearance calculation was deduced for both Region A and Region B.

The dielectric characteristics of the DC superimposed switching impulse have also been verified according to DC pre-stress levels and polarities of switching impulse. The experimental results showed that the most severe situation occurs when switching impulse with same polarity as DC pre-stress is introduced into MVU. However, the critical flashover voltage was independent of the DC pre-stress level, i.e., the critical flashover voltage of switching impulse and DC superimposed switching impulse did not have many differences. Consequently, the operating voltage level of MVU should be considered when calculating air clearance between MVU and HVDC converter valve hall, and the formula of air clearance calculation, considering the operating DC voltage level, was derived.

Finally, the fundamental data to calculate the air clearance between MVU and HVDC converter valve fall have been found through this study.

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References
1. Xiao, S.; Cao, J.; Donoghue, M. Stray capacitance and compensation for the converter valves for ultra-high voltage HVDC application. In Proceedings of the 2010 International Conference on Power System Technology; Institute of Electrical and Electronics Engineers (IEEE), Hangzhou, China, 14–18 October 2010; pp. 1–7.
2. International Electrotechnical Commission (IEC). 60071-1: Insulation Co-Ordination—Part 1: Definitions, Principles and Rules; IEC: Geneva, Switzerland, 2011.
3. International Electrotechnical Commission (IEC). IEC 60071-2: Insulation Co-Ordination—Part 2: Application Guide; IEC: Geneva, Switzerland, 2018.
4. Arora, R.; Mosch, W. High Voltage and Electrical Insulation Engineering; Wiley: Hoboken, NJ, USA, 2011; p. 69.
5. Paris, L.; Cortina, R. Switching and Lightning Impulse Discharge Characteristics of Large Air Gaps and Long Insulator Strings. IEEE Trans. Power Appar. Syst. 1968, 4, 947–957. [CrossRef]
6. Paris, L. Influence of air gap characteristics on line-to-ground switching surge strength. IEEE Trans. Power Appar. Syst. 1967, 8, 936–947. [CrossRef]
7. International Electrotechnical Commission (IEC). IEC 60060-1: High-Voltage Test Techniques—Part 1: General Definitions and Test Requirements; IEC: Geneva, Switzerland, 2010.
8. Schneider, H.; Turner, F. Switching-surge flashover characteristics of long sphere-plane gaps for UHV station design. IEEE Trans. Power Appar. Syst. 1975, 94, 551–560. [CrossRef]
9. Los, E.; Schneider, H. Switching Surge Breakdown Development in Large Conductor-Tower Air Gaps. *Trans. Power Appar. Syst.* 1978, 3, 866–874. [CrossRef]

10. Rohlfs, A.; Schneider, H.J. Switching impulse strength of compacted transmission line flat and delta configurations. *IEEE Trans. Power Appar. Syst.* 1983, 4, 822–831. [CrossRef]

11. Rizk, F.A.M. Effect of large electrodes on sparkover characteristics of air gaps and station insulators. *IEEE Trans. Power Appar. Syst.* 1978, 4, 1224–1231. [CrossRef]

12. Gallet, G.; Leroy, G.; Lacey, R.; Kromer, I. General expression for positive switching impulse strength valid up to extra long air gaps. *IEEE Trans. Power Appar. Syst.* 1975, 94, 1989–1993. [CrossRef]

13. Chen, S.; Zeng, R.; Zhuang, C.; Yu, Z.; He, J. Switching impulse breakdown characteristics of large sphere-plane air gaps compared with rod-plane air gap. *IEEE Trans. Dielectr. Electr. Insul.* 2013, 20, 839–844. [CrossRef]

14. Gourgoulis, D.E.; Mikropoulos, P.N.; Stassinopoulos, C.A. Sparkover voltage of sphere gaps under standard lightning and switching impulse voltages. *IEEE Proc. Sci. Meas. Technol.* 1996, 143, 187–194. [CrossRef]

15. International Electrotechnical Commission (IEC). IEC 62895: High Voltage Direct Current (HVDC) Power Transmission-Cables with Extruded Insulation and Their Accessories for Rated Voltages up to 320 kV for Land Applications-Test Methods and Requirements; IEC: Geneva, Switzerland, 2017.

16. Khan, Y.; Okabe, S.; Suehiro, J.; Hara, M. Particle-initiated Breakdown Characteristics around Spacer under Lightning Impulse Voltage Superimposed on Pre-stressed DC. *IEEE Trans. Fundam. Mater.* 2004, 124, 547–552. [CrossRef]

17. Ma, G.-M.; Zhou, H.-Y.; Wang, Y.; Zhang, H.-C.; Lu, S.-J.; Tu, Y.-P.; Wang, J.; Li, C.-R. Flashover behavior of cone-type spacers with inhomogeneous temperature distribution in SF 6/N 2-filled DC-GIL under lightning impulse with DC voltage superimposed. *CSEE J. Power Energy Syst.* 2019, 6, 427–433.

18. Okabe, S.; Ueta, G.; Utsumi, T.; Nukaga, J. Insulation characteristics of GIS insulators under lightning impulse with DC voltage superimposed. *IEEE Trans. Dielectr. Electr. Insul.* 2015, 22, 1–9. [CrossRef]

19. Knudsen, N.; Iliceto, F. Flashover tests on large air gaps with DC voltage and with switching surges superimposed on DC voltage. *IEEE Trans. Power Appar. Syst.* 1970, 5, 781–788. [CrossRef]

20. Liao, Y.; Li, R.; Gao, C.; Wang, G.; Liu, Z. Flashover tests on air gap of ±800 kV DC transmission line under composite DC and switching impulse voltage. *IEEE Trans. Power Appar. Syst.* 2014, 21, 2095–2101. [CrossRef]

21. Allen, N.L.; Huang, C.F.; Cornick, K.J.; Greaves, D.A. Sparkover in the conductor-rod and conductor-plane test gaps under composite slow from impulse/direct voltages. *IEEE Proc. Sci. Meas. Technol.* 1999, 146, 135–141. [CrossRef]

22. International Electrotechnical Commission (IEC). IEC60243-1: Electric Strength of Insulating Materials-Test Methods-Part 1: Tests at Power Frequencies; IEC: Geneva, Switzerland, 2013.

23. International Electrotechnical Commission (IEC). IEC60243-2: Electric Strength of Insulating Materials-Test Methods-Part 2: Additional Requirements for Tests Using Direct Voltage; IEC: Geneva, Switzerland, 2013.

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