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B2 OVERHEAD LINES
PS1 - Challenges & New Solutions in Design and Construction of New OHL

Electrical environment evaluation of HVAC/HVDC hybrid overhead transmission line using a reduced-scale model

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SUMMARY

To evaluate the electrical environmental effects according to the operation conditions of the HVAC/HVDC hybrid overhead transmission line, a corona discharge characteristic test of the HVAC/HVDC hybrid transmission line was performed using a reduced-scale model. A variable arm of reduced-scale model was designed to test by changing the coordinates for each pole height and pole spacing. The reduced-scale model was designed to reduce AC 765kV / DC ±500kV by 1/40 ratio. The evaluation system can measure DC electric field, AC electric field, and ion current density. 765kV HVAC one-circuit and 500kV HVDC one-bipole are installed on the left and right side, respectively, in a vertical configuration. Before performing the HVAC/HVDC hybrid reduced-scale model test, the evaluation of the HVDC transmission line was first performed in the reduced-scale model test to verify the reliability of the measured value. The values converted from measured values of HVDC double bipole power lines in the reduced-scale model to the full-scale lines were compared to the measured values of the 500kV DC double bipole in the full-scale lines that were carried out for a long-term evaluation test on the Gochang Electric Power Testing Centre in South Korea. Also, the value measured by the reduced-scale model were compared to calculated values by the simulation software based on the electric flux line method. As a result of the evaluation, the DC electric field on the ground surface in the reduced-scale model was smaller than the value measured for a long period on a full-scale line. It is determined that the reduced-scale model test was conducted in controlled conditions for a short period, however the full-scale lines tests were carried out for a long-term with various weather conditions. Therefore, a correction factor that can predict the DC electric field on a full-scale line in consideration of various weather conditions such as seasons was determined from the converted values in the reduced-scale model. And the two configurations of DC polarity arrangement were compared having a positive pole and negative pole at the downside, respectively. The applied voltage conditions of each AC line and DC line in hybrid lines were also compared and verified with a developed simulation software based on the electric flux line method. The results show that the AC electric field was not varied by the DC electric field. However, the DC electric field was changed by AC voltage variation. In the hybrid line, the conductor surface gradient of the DC line was changed according to the applied voltage conditions of the AC line, so the corona discharge of DC line was activated and the DC electric field increased compared to the case where there was only a DC line. These results will be used as basic design data to determine the height of HVAC/HVDC hybrid transmission line.

KEYWORDS

Hybrid Overhead Transmission Line, HVDC Electric Field, Ion Flow

I. INTRODUCTION

High-voltage direct-current (HVDC) overhead transmission technology, which is difficult in power systems due to its uneconomical initial installation cost, has several advantages over high-voltage alternating-current (HVAC) overhead transmission, particularly owing to the advancement of power electronics technology in recent years. In particular, it is advantageous to use HVDC lines when connecting systems with different frequencies or for the operation of long-distance lines. However, securing a path for the construction of a new HV overhead transmission line has been difficult worldwide due to civil complaints related to environmental issues. To alleviate these problems, a method that involves installing AC and DC lines in the same transmission tower and operating these AC and DC lines in parallel within the same site area is being considered. These lines are called hybrid lines.

Hybrid line operation induces interactions between AC and DC conductors in terms of electric field strength, corona onset voltage, and corona current, which affects the DC and AC electric field strength and ion current density [1-2]. This interaction can cause electrical shocks to the human body and other biological effects. Therefore, its evaluation is crucial considering human safety and health [3]. In addition, the commercial frequency of the AC line affects the DC line. Conversely, malfunctions may occur in the AC line due to the effect of ions in the DC line [4]. Therefore, it is important to study the electric environment and phenomena caused by various factors, such as the shape of the hybrid line, and the appropriate operating voltage prior to its construction. In this study, the electrical environmental characteristics of a hybrid line were evaluated in a short period using a reduced-scale model that simulates the scale down of the hybrid line.

A reduced-scale model evaluates the characteristics of the ions generated around the line by geometrically reducing the shape of the actual DC overhead power transmission line, operating voltage, sub-conductor diameter, sub-conductor spacing, pole height, and pole spacing. It is a tool used for evaluating the electrical environmental disturbances around other DC transmission lines in addition to the corona cage and DC test line. Additionally, it can easily simulate and analyze AC and DC high voltage corona discharge phenomena at a low cost and in a short period of time with various line shapes. The advantages and disadvantages of using this reduced-scale model can be summarized as follows. In terms of advantages, it enables the electrical environmental characteristics, such as line separation distance, bundle shape, and voltage condition, during the parallel operation of various AC/DC overhead power transmission lines to be evaluated within a short period of time and at a low cost. In terms of disadvantages, measurements and evaluation items are limited owing to its constraints. Therefore, it is difficult to measure the long-term characteristics of corona discharge in a reduced-scale model with changing weather conditions. Because the reduced-scale model test ignores the effects of wind direction and wind speed, which have a significant effect on the number of ions generated in the actual DC line, characteristic tests for each line shape can only be performed under limited weather conditions.

As described above, although the reduced-scale model has a few disadvantages, it can be used for preliminary evaluations before investigating the electrical environmental characteristics in a full-scale line. In this study, the scale factor calculation for simulating the electric environment of an actual hybrid overhead line is performed. Additionally, the design and development of the scale factor model are described.

II. THEORY

In order to theoretically analyze the corona discharge mechanism of the DC line, it is necessary to first set an assumption and use the test results to correct the analysis equation. To this end, it is crucial to acquire a large amount of data over a long period of time from a test site or a commercial line. However, because there are not many data in South Korea, an analysis algorithm was used; this algorithm extracts empirical parameters and retunes them with the limited data obtained from the Gochang test site. In this study, a basic DC analysis algorithm using the electric flux line method was employed, and the empirical parameters were applied as tuning values. The program development process is as follows. First, the ion and DC electric fields were calculated using the electric flux line method. The difference between the two analysis results was first corrected with the corona onset-related values by comparing the results of the basic DC analysis with those obtained at the Gochang Electric Power Testing Centre. Then, secondary correction coefficients for each major parameter such as line shape (single pole, bipole, double bipole, horizontal type, and vertical type), bundle shape (number of sub-conductors), line voltage, and L50 and L5 were determined. A correction function using cubic spline interpolation was developed for interpretation under conditions with the primary and secondary correction parameters.

The primary correction of the difference in analysis results with values related to corona onset voltage was performed because the amount of corona generated from the line is dependent on the corona onset voltage. The main factors that affect corona discharge generation are environmental conditions such as climate. This is because the corona onset voltage is determined according to the measurement conditions. It is difficult to explain the determination of the second correction factor for each major parameter. However, the shape of the transmission line and the shape of the bundle have the largest influence. Each correction equation was obtained according to the shape of the transmission line. Interpretation values vary depending on the stochastic variables L50 and L5, which implies that the measured values are different even under the same conditions. Although various correction parameters are obtained, it is impossible to simulate all cases. Therefore, correction or interpolation is crucial to perform analyses under arbitrary conditions. In this study, cubic spline interpolation was used. Cubic spline interpolation is a time-intensive method because each section is treated as a cubic function. In contrast, correction function treats all sections as a single function. However, cubic spline obtains a relatively accurate solution.

The numerical calculation method was developed to evaluate the design criteria of the ground electric field strength and the ground surface ion current density, which are the major electrical environment design parameters of the HVDC overhead transmission line. It is necessary to derive a governing equation for the analysis of the ion flow field considering the spatial distribution of ions generated by the corona generated from the HVDC overhead transmission line. Assuming positive and negative ion charges are generated, the general governing equation considering the effect of wind and recombination of electrons and ions is described using the following equations:

$$\nabla \cdot \vec{E}_s = (\rho^- - \rho^+)/\varepsilon_0 \tag{1}$$

$$\begin{cases} \vec{J}^+ = \rho^+(k^+\vec{E}_s + \vec{W}) \\ \vec{J}^- = \rho^-(k^-\vec{E}_s - \vec{W}) \end{cases} \tag{2}$$

$$\vec{J} = \vec{J}^+ + \vec{J}^- \tag{3}$$

$$\begin{cases} \nabla \cdot \vec{J}^+ = -R\rho^+\rho^-/e \\ \nabla \cdot \vec{J}^- = R\rho^+\rho^-/e \end{cases} \tag{4}$$

The definitions of the symbols are as follows:

$\vec{E}_s$: Intensity of the electric field in space considering ionic charge

ρ^+: Positive ion charge density

ρ^- : Negative ion charge density

k^+: Mobility of the positive ion charge

k^-: Mobility of the negative ion charge

$\vec{J}^+$: Positive ion current density vector

$\vec{J}^-$: Negative ion current density vector

$\vec{J}$: Total ion current density vector

$\overrightarrow{W}$: Vector representing the wind strength

R : Recombination coefficient of electrons and ions

ε_0: Permittivity of free space

e : Electron charge

The strength of the electric field and the ion current density can be obtained at an arbitrary point in space considering the ion charge using numerical methods by applying the boundary conditions according to the characteristics of the problem provided in this governing equation. However, in reality, only a few cases, except for extremely simple ones, can be solved using analytical approaches. Therefore, various numerical calculation methods have been studied, each with their own advantages and disadvantages. These methods include the finite element method, finite difference method, integral equation method, electric flux line method, and the recently published Gaussian tube method. In this study, the surface electric field strength and the ion current density were calculated based on the electric flux line method. The following assumptions are considered for the electric flux line method:

- The mobility of ions is constant regardless of field strength
- Thermal diffusion of ions is neglected.
- The space charge affects the magnitude of the electric field. It does not affect the direction of the electric field (Deutsch assumption).
- The electric field on the surface of the conductor where the corona discharge is occurring is constant at the value at the beginning of the corona discharge.

The electric flux line method is shown in Figure 1. It is assumed that the ions generated by the corona move along the electric flux lines in the absence of ions. Therefore, the generated ions do not change the direction of the electric field and only affect the magnitude of the electric field. The electric flux lines in the absence of ions are obtained based on the above assumptions using the electric flux line method. Subsequently, the potential distribution and the space-charge-free field that satisfy the boundary condition on the surface of the conductor are calculated along each electric flux line, and the average value of the space charge density is obtained using these values. The average value of the obtained space charge density is used as an initial value to calculate the space charge density on the surface of the conductor during the generation of ions in the presence of the corona discharge. The space charge density on the surface of the conductor is calculated using the Secant method using the initial value, and the correlation function between the electric field in the absence and presence of ions is determined using this value. The ultimate goal is to be able to obtain an electric field when ions are present. In addition, the ion current density can be determined using the electric field, ion mobility, and space charge density.

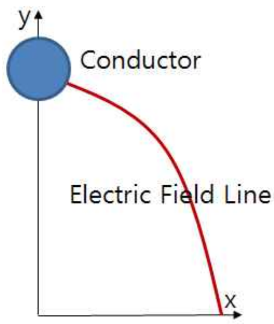


Figure 1. Electric flux line method

The electric flux line method does not consider the effect of wind, and a complicated arrangement of conductors results in a complex electric flux line structure which might increase the difficulty during calculation. There are advantages in that it does not require division of the analysis space and setting of a virtual boundary. Additionally, analytic formulae can be used without numerical differentiation for the electric field calculation. Therefore, errors due to numerical differentiation are absent. The electric flux line method can also be applied to an ion flow field analysis under the HVDC overhead transmission line where both positive and negative ions are present. In conclusion, the procedure for calculating the ion flow field around the HVDC transmission line is as follows. According to the Deutsch assumption, a two-dimensional problem can be transformed into a one-dimensional problem, and it can be analyzed assuming that it only affects the magnitude of the electric field in the absence of generation of ions in the HVDC line and it does not affect the direction. In the absence of ions, electric field analysis is performed using the charge superposition method, which includes image charges because the ground acts as the ground plane, and the space potential, electric field, and electric flux lines are obtained. When ions are generated, the corona onset voltage and potential on the surface of the conductor, which is the starting point of the electric flux line for each electric flux line, are set as boundary conditions. The related equation is solved to obtain the electric field at the surface of the ground, which is the end of the electric flux line. The process of calculating along the electric flux lines requires the double integral of the related quantities. It should be noted that the integrand of this integral is considered as quantities to be calculated numerically. In particular, a double integral for the potential has to be performed while calculating the charge density on an electric flux line with an average charge density determined by the initial condition. Therefore, the integrand can be considered as a function of the potential, and the integral variable is treated as a potential to perform double integration. Based on the above basic theory, it is possible to analyze the ion flow field near DC overhead transmission lines of various configurations such as a monopole, bipole, two-bipole, AC/DC hybrid.

III. REDUCED-SCALE MODEL

The scale factor of the reduced-scale model is determined by the applied voltage, the experimental space, and the size of the conductor. The one-dimensional geometric scale factor K_l of the reduced-scale model can be expressed using Equation 5.

$$K_\ell = \frac{r_{reduced}}{r_{full}} = \frac{h_{reduced}}{h_{full}} = \frac{S_{reduced}}{S_{full}} \tag{5}$$

where r is the radius of the sub-conductor, h is the height of the pole, and S is the conductor spacing. Additionally, the reduction factor K_v for the applied voltage can be expressed using Equation 6.

$$K_V = \frac{V_{reduced}}{V_{full}} \tag{6}$$

The reduction factor of the surface electric field strength in the reduced-scale model can be expressed as in Equation 7.

$$K_e = \frac{E_{reduced}}{E_{full}} = \frac{V_{reduced}\,/h_{reduced}}{V_{full}\,/h_{full}} = \frac{V_{reduced}\,h_{full}}{V_{full}\,h_{reduced}} = \frac{K_v}{K_\ell} \tag{7}$$

The charge density ρ at the ground surface is expressed using Equation 8, where ε is the permittivity, E is the electric field strength at the ground surface, A is the area, and V is the volume.

$$\rho = \epsilon E \times A/V \tag{8}$$

Therefore, the reduction factor of charge density, K_ρ, is expressed as in Equation 9.

$$K_\rho = \frac{\rho_{reduced}}{\rho_{full}} = \frac{\epsilon E_{reduced} \times A'/V'}{\epsilon E_{full} \times A/V} = \frac{E_{reduced}\,VA'}{E_{full}\,V'A} = \frac{K_e K_\ell^2}{K_\ell^3} = \frac{K_e}{K_\ell} = \frac{K_v}{K_\ell^2} \tag{9}$$

Using Equation 9, the reduction factor K_j of the surface ion current density J can be obtained as follows:

$$K_j = \frac{J_{reduced}}{J_{full}} = \frac{(k\rho E)_{reduced}}{(k\rho E)_{full}} = K_k K_\rho K_e = \frac{K_v^2}{K_\ell^3} \tag{10}$$

In this study, the hybrid reduced-scale model was designed with the standard electric tower shape of an AC 765 kV transmission line as the basic target to simulate the parallel operation of ±500 kV DC with a 765 kV AC transmission line. Considering the maximum distance from the ground to the center of each phase, the height from the ground to the center of each phase was in the range of 23–72 m, and the horizontal distance from the center of the tower to the center of each phase was in the range of 13–15 m. Figure 2 shows the shape of the AC/DC hybrid line in which the single-circuit part of the 765 kV double-circuit transmission line is replaced with a ±500 kV DC line.

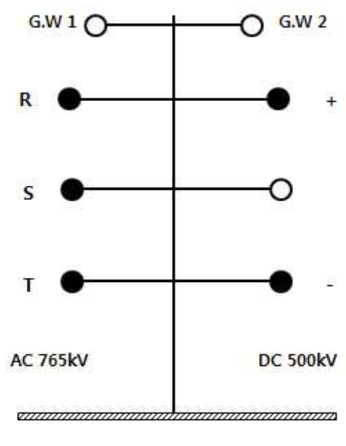


Figure 2. 765 kV/±500 kV hybrid line configuration

Assuming that the additional ±500 kV DC line is installed to the existing arm, the full-scale line was determined using the reduction factor by applying the pole height, spacing of the AC line, and the insulator length. The results are shown in Table 1. The calculated results for each reduction factor according to the sub-conductor specification of the AC and DC lines are shown in Table 2. The similarity between size of the reduced-size model and the full-scale model increases with an increase in the reduction factor. Therefore, it is advantageous in terms of reliability of the evaluation. However, when the actual model is reduced by 1/25, the height of the uppermost arm of the reduced-scale model is approximately 2.88 m, which increases the difficulty while simulating various line configurations. Therefore, it is suitable to reduce the full-scale model to a 1/40 ratio for simulation tests and evaluation, where the height of the uppermost arm is approximately 1.8 m.

Table 1. Pole configuration of reduced-scale model according to reduction factor

Reduction factor		765kV full-scale line	Reduced-scale model
0.04	Pole Spacing	27 ~ 29 m	1.08 ~ 1.16 m
	Pole Height	23 ~ 72 m	0.92 ~ 2.88 m
0.03	Pole Spacing	27 ~ 29 m	0.82 ~ 0.88 m
	Pole Height	23 ~ 72 m	0.70 ~ 2.18 m
0.025	Pole Spacing	27 ~ 29 m	0.68 ~ 0.73 m
	Pole Height	23 ~ 72 m	0.56 ~ 1.8 m

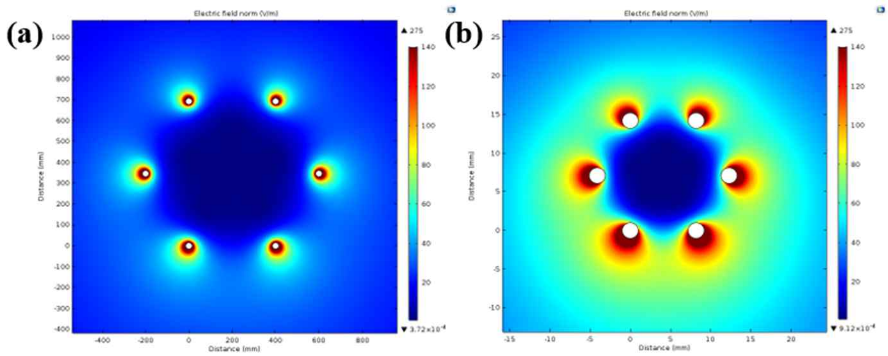
Table 2. Design parameters of reduced-scale model

Conductor type	CARDINAL 480 mm^2			
Number of Sub-conductors	6			
Line	Full-scale	Reduced-scale		
Sub-conductor diameter, mm	30.42	2.01	2.01	2.01
Sub-conductor spacing, mm	400	14.4	10.37	8.23
Equivalent diameter, mm	625.35	24.9	18.95	15.62
Reduction factor	1	1/25	1/33	1/40
Conductor type	CARDINAL 480 mm^2			
Number of Sub-conductors	4			
Line	Full-scale		Reduced-scale	
Sub-conductor diameter, mm	30.42	2.01	2.01	2.01
Sub-conductor spacing, mm	400	13.5	9.34	7.23
Equivalent diameter, mm	385.24	15.38	11.67	9.63
Reduction factor	1	1/25	1/33	1/40
Conductor type	CARDINAL 480 mm^2			
Number of Sub-conductors	2			
Line	Full-scale	Reduced-scale		
Sub-conductor diameter, mm	30.42	2.01	2.01	2.01
Sub-conductor spacing, mm	400	9.68	5.55	3.78
Equivalent diameter, mm	156	6.24	4.72	3.90
Reduction factor	1	1/25	1/33	1/40

If the diameter of the sub-conductor of the reduced-scale model and the distance between the sub-conductors are the same as the geometric reduction factors such as the pole height, it is possible to simulate the ion flow phenomenon in a full-scale line including its conductor surface electric field strength and the ground electric field. However, if the diameter of the cardinal (483 mm^2) wire, which is a sub-conductor mainly used in the current transmission line, is reduced to 1/40, it is difficult to develop a new wire with a thickness of 0.76 mm. Therefore, the smallest wire produced according to the current Korea Industrial Standard (2.01 mm) was applied to the reduced-scale model. The sub-conductor specification of the reduced-scale model is selected using the formula to convert the sub-conductor bundle into a single conductor with an equivalent diameter.

$$d_{eq} = D\sqrt{\frac{nd}{D}} \tag{11}$$

where d_{eq} is the equivalent diameter of a single conductor, D is the bundle diameter, n is the number of sub-conductors, and d is the diameter of the sub-conductor. When the equivalent diameter simulating the sub-conductor configuration of the reduced-scale model as a single conductor is applied, the voltage applied to the reduced-scale model should be calculated to simulate the conductor surface electric field in the full-scale line equally. Figure 3 shows the conductor surface electric field strength of the reduced-scale model designed by applying a full-scale line and an equivalent diameter. Calculation results demonstrated that the ion generation characteristics in a full-scale line and in a reduced-scale model exhibit similarity when 4.6% voltage of the full-scale line was applied as shown in Table 3.



(a) Full-scale model (b) Reduced-scale model

Figure 3. Conductor surface electric field intensity distribution of full-scale and reduced-scale models

Table 3. Applied voltage in reduced-scale model

	Full-scale	Reduced-scale #1	Reduced-scale #2
Pole Height (%)	(100)	(2.5)	(2.5)
Sub-conductor diameter, mm (%)	30.42 (100)	0.76 (2.5)	2.01 (6.6)
Sub-conductor spacing, mm (%)	400 (100)	10 (2.5)	8.2 (2.1)
Equivalent diameter, mm (%)	625.4 (100)	15.6 (2.5)	15.6 (2.5)
Voltage (%)	(100)	(2.5)	(4.6)
Conductor surface electric field (%)	(100)	(100)	(100)

Figure 4 shows the configuration used to perform the electrical environmental characteristics test of the hybrid transmission line in a reduced-scale model. Four types of tests were conducted according to the pole arrangement and operating conditions.

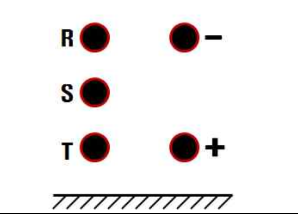
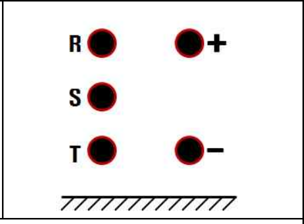
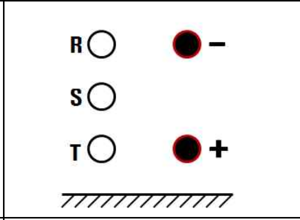
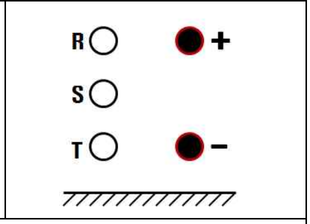
Case A	Case B	Case C	Case D
			
AC/DC voltage applied		DC voltage applied	

Figure 4. Hybrid test line configuration

IV. HARDWARE SETUP OF REDUCED-SCALE MODEL

A variable arm of reduced-scale model was designed and tested by changing the coordinates for each pole height and pole spacing. The materials of the reduced-scale model were designed with insulators. An epoxy insulated plate was used for the lower support plate, and fabric bakelite material was used for the supports to prevent deformation in the state where the metal fittings and wires are installed. Additionally, the variable arm which was used to change the distance between the poles and the pole height was designed with MC-Nylon insulator. Figure 5 shows the overall shape of the reduced-scale model and the diagram of the support, respectively. Figure 6(a) shows the front view of the deformable arm.

Figure 6(b) shows the designs of the yoke and spacer used in the reduced-scale model, respectively. Except for the bolts and nuts connecting the test conductor and the yoke, the bolts and nuts used for the assembly of the reduced-scale model were made of an insulator such as epoxy to prevent noise including gap discharge.

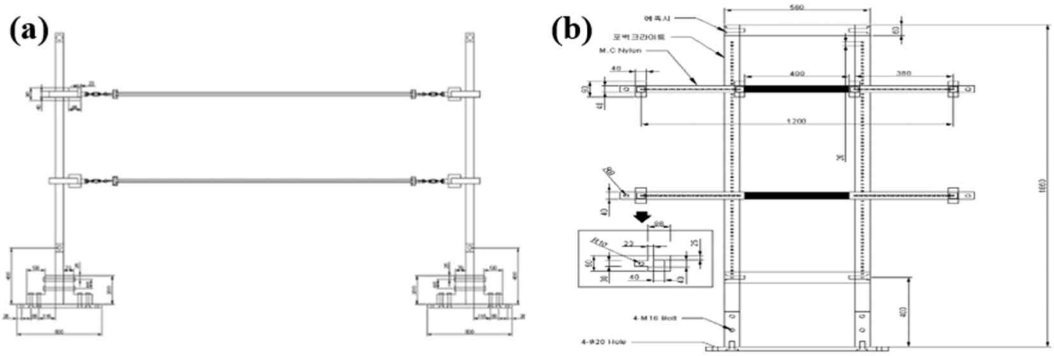


Figure 5. Schematic view of the reduced-scale model (a) Front view (b) Side view

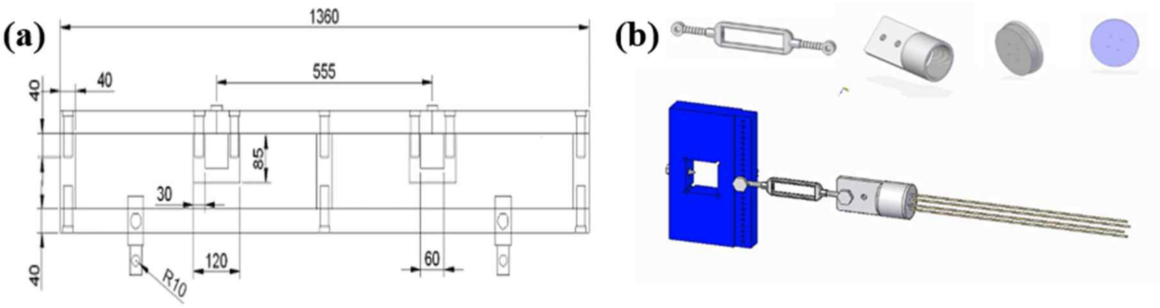


Figure 6. (a) Variable arm of the reduced-scale model (b) Design of fittings for the hybrid reduced-scale model

The DC power supply was designed to generate a maximum of ±60 kV to simulate the corona discharge phenomenon of the conductor for each voltage, and the specifications are shown in Table 4. Table 5 shows the specification of the AC power supply.

Table 4. Specifications of the DC power supply

	Specification	Note
Input voltage	AC220V, 50～60 Hz	
Output voltage	0～±120kV	Variable
Output current	0～±10mA	Variable
Ripple	0.1%	RMS at maximum output
Line Regulation	0.01% at±10% input change	
Load Regulation	0.01% at full load	
Efficiency	80% or more at maximum output	

Table 5. Specifications of the AC power supply

	Specification	Note
Input voltage	3-phase AC380V, 60Hz	
Output voltage	3-phase 0~30kV	Variable
Output current	580mA	Rating
Rated capacity	3-phase 30kVA	

The reduced scale-model and evaluation system are shown in Figure 7. The reduced-scale model was designed to reduce AC 765 kV/DC ±500 kV by 1/40 ratio, and the applied voltage was AC 29 kV RMS and DC ±19 kV. A 765 kV HVAC one-circuit and a 500 kV HVDC one-bipole were installed on the left and right sides, respectively, in a vertical configuration. The evaluation system can measure the DC and AC electric fields, and ion current density.

Figure 7. Photograph of the reduced-scale model

V. REDUCED-SCALE MODEL OF HVDC TRANSMISSION LINE

Before performing the HVAC/HVDC hybrid reduced-scale model test, the evaluation of the HVDC transmission line was initially performed in the reduced-scale model test to verify the reliability of the measured value. The values converted from measured values of the HVDC double-bipole transmission lines in the reduced-scale model to the full-scale lines were compared to the measured values of the 500 kV DC double bipole in the full-scale lines that were used in a long-term evaluation test at the Gochang Electric Power Testing Centre in South Korea as shown in Figure 8. Additionally, the values measured by the reduced-scale model were compared with those calculated by the simulation software based on the electric flux line method.

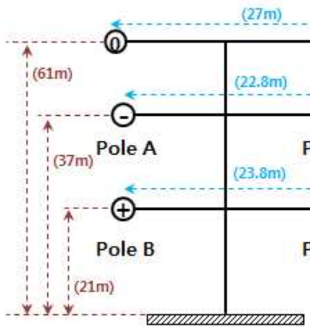


Figure 8. HVDC double-bipole in the full-scale line

Table 6 shows the results of measuring the DC electric field and ion current density by voltage-variation in a reduced-scale model (reduction ratio: 1/40) of the Gochang Electric Power Testing Centre ±500 kV double-bipole. The data measured in the reduced-scale model were converted to those of a full-scale line by applying the reduction factor of the electric field and ion current density. As corona discharge occurred slightly in the present line configuration, the DC electric field was converted to approximately -4.6 and +4.5 kV/m, regardless of the applied voltage of the reduced-scale model. Because the value in the reduced-scale model was measured in a short duration under limited weather conditions, it was assumed that the values of the corona discharge characteristics were smaller than the measured values of the long-term full-scale line reflecting seasonal changes. Therefore, the measured data in the reduced-scale model should be converted using the correction factor to predict the electric field at the surface of the full-scale line considering actual conditions such as seasonal variations. Thus, when L50 was applied to the value converted to the full-scale line by applying the reduction factor in the reduced-scale model, it appeared to be similar to the value generated in the full-scale line when a correction factor of 1.69 was applied. The simulation value was similar to the value generated in the full-scale line when a correction factor of 1.21 was applied in the reduced-scale model.

Table 6. Comparison between converted and measured values of ±500 kV double-bipole full-scale transmission line

		Full-scale*	1/40 Reduced-scale**		
DC Voltage, kV (converted value)		500	20(500)	24.4(500)	30(500)
Number of sub-conductor		6	6		
Sub-conductor diameter, mm		30.48	2.01		
Sub-conductor spacing, mm		400	8.23		
Equivalent diameter, mm		625.35	15.62		
Lower part pole height, m		21	0.525		
Upper part pole height, m		37	0.925		
Lower part pole spacing, m		23.8	0.595		
Upper part pole spacing, m		22.8	0.57		
Conductor surface electric field, kV/cm		17.42 /17.61	14.26 /14.42	17.43 /17.62	21.39 /21.63
Electric field reduction factor K_e		1	1.6	1.95	2.4
Ion current density reduction factor K_ρ		1	64	78	96
Measured value Negative pole/Positive pole (converted value)	Electric field L50, kV/m	-7.2/6.9	-7.3(-4.6) /7.1(4.4)	-9.0(-4.6) /8.8(4.5)	-11.1(-4.6) /10.8(4.5)
	Ion current	-7.0/2.8	-2(0)/2(0)	-3(0)/2(0)	-7(0)/2(0)

	density, nA/m^2				
Simulation value Negative pole/Positive pole (converted value)	Electric field L50, kV/m	-9.85/7.45	-13.01(-8.1) /13.01(8.1)	-15.88(-8.1) /15.88(8.1)	-20.66(-8.6) /19.52(8.1)
	Ion current density, nA/m^2	-3.53/1.57	0(0)/0(0)	0(0)/0(0)	-77.73(-0.8) /0(0)

* The maximum point of the full-scale line ±14m, **Evaluation point of reduced-scale line ±0.4m

VI. REDUCED-SCALE MODEL OF HYBRID TRANSMISSION LINE

The corona discharge characteristic test of the AC/DC hybrid line was performed using the previously developed HVDC reduced-scale model. An AC line was installed on the left and a DC line was installed on the right. The generation characteristics of the DC electric field and ion current density were tested. The negative pole of the DC line was placed at the bottom as shown in Figure 9, and the detailed specifications and results are shown in Table 7. A negative electric field was measured even at a position where the AC line was located by installing a negative pole at the bottom. The converted value with the reduction factor applied was compared with the simulation result of the full-scale line. When a reduction factor 1.6 was applied, an electric field of -13.44 kV/m was expected to be measured at the bottom of the negative pole, whereas an electric field of -11 kV/m was calculated in the simulation. Since the corresponding reduced-scale model test results in a value measured using a short-term scale model in an indoor space where corona discharge is limited, only the geometric scale factor was considered and converted into a full-scale line. An error occurred with the long-term measurement value that was statistically processed.

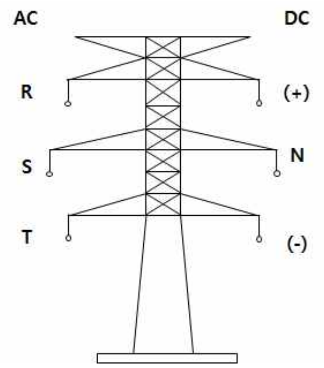


Figure 9. AC/DC hybrid line configuration

Table 7. Comparison between converted and measured values of AC 765 kV/±500 kV hybrid transmission line

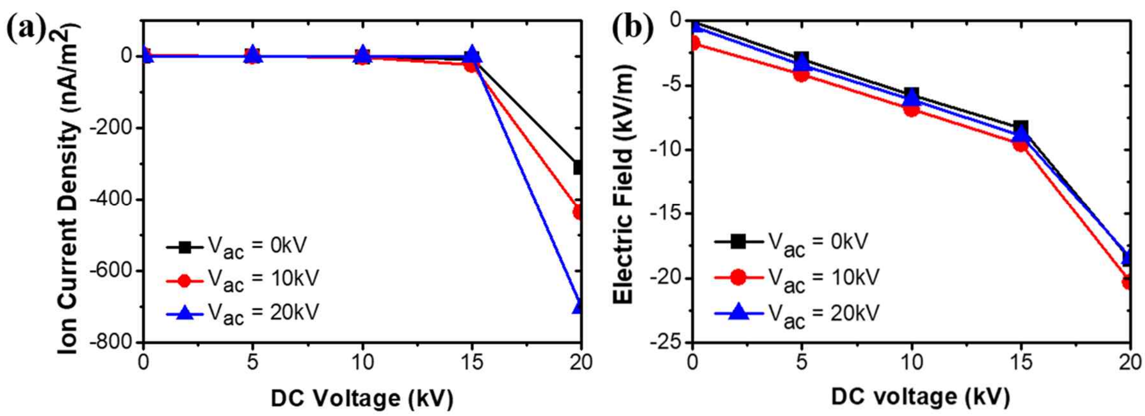
	Simulation value* (full-scale)	1/40 Reduced-scale**
Voltage (converted value)	DC500kV with AC765kV	DC20kV(500) with AC30kV
Number of sub-conductor	6	6
Sub-conductor diameter, mm	30.48	2.01
Sub-conductor spacing, mm	400	8.23
Equivalent diameter, mm	625.35	15.62
Lower part ground height, m	23	0.58
Middle part ground height, m	40	1.01

Upper part ground height, m		56	1.40
Lower part pole spacing, m		28.8	0.72
Middle part pole spacing, m		28.4	0.71
Upper part pole spacing, m		27.2	0.68
Electric field reduction factor K_e		1	1.6
Ion current density reduction factor K_ρ		1	64
Negative pole/Positive pole (converted value)	Electric field L50, kV/m	-11/-3.35	-8.4(-13.44) /-1.9(-3.04)
	Ion current density, nA/m^2	-5.2/-0.5	-1(0)/0(0)

* The maximum point of the full-scale line ±14m, **Evaluation point of reduced-scale line ±0.4m

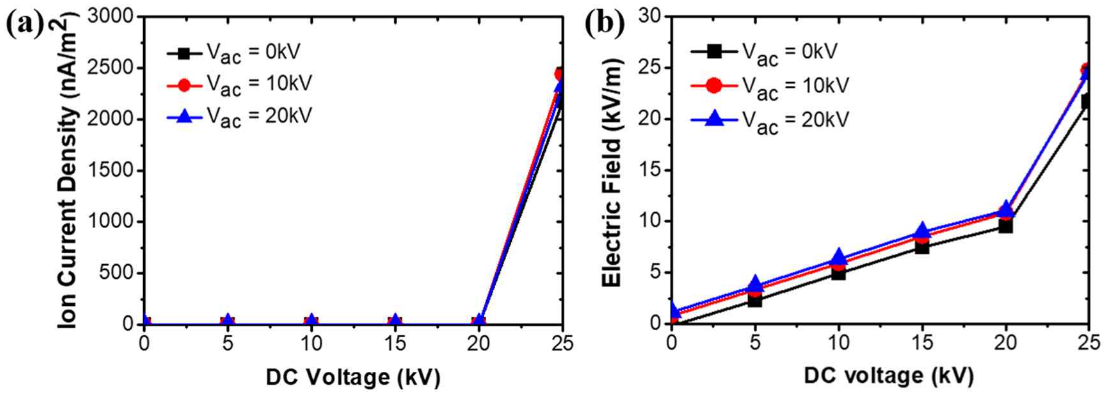
A needle-shaped electrode was installed on the DC conductor to generate more corona discharge. Additionally, the corona discharge generation characteristic test was performed under the condition that the corona onset voltage was lower. This was performed to determine the effect on DC and AC conductors by forcibly generating corona as the most severe environmental condition. The experimental conditions were evaluated for AC voltages of 0, 10, 20, and 25 kV to understand the corona discharge characteristics of DC voltage with respect to the magnitude of the AC voltage. The cases with AC and DC conductors were individually evaluated.

The AC voltage applied to the AC conductor affected the corona onset voltage of the DC conductor as shown in Figure 10 and Figure 11. Additionally, when the AC voltage was significantly high, corona discharge occurred even at a low voltage applied to the DC conductor. Furthermore, the configuration of the line with the negative pole at the bottom exhibited a higher electric field and ion current density due to the difference in corona discharge onset voltage for each polarity. This was observed because the corona onset voltage of the negative pole is usually lower than that of the positive pole. Therefore, from the viewpoint of space charge directly under the DC transmission line, when the AC/DC hybrid line is operated, placing the positive pole at the bottom causes less corona discharge under the same line configuration and operating conditions. However, when the positive pole was located at the bottom, the occurrence of audible noise and radio disturbance due to corona discharge was higher than that of the line configuration with the positive pole at the top. Therefore, the effect of ion flow, corona noise, and radio disturbance should be studied [5].



(a) Characteristics of ion current density by DC voltage (b) Characteristics of DC electric field by DC voltage

Figure 10. Corona discharge characteristics of negative pole with negative pole at the bottom



(a) Characteristics of ion current density by DC voltage (b) Characteristics of DC electric field by DC voltage

Figure 11. Corona discharge characteristics of positive pole with positive pole at the bottom

The corona discharge characteristics of the AC conductor changed slightly according to the operating conditions of the DC line when the voltage of the DC conductor was varied while a constant voltage was applied to the AC conductor as shown in Figure 12. Additionally, the DC electric field characteristics that change when an AC conductor is installed around the DC line were measured as shown in Figure 13. When the AC conductor and the DC conductor were parallel, it can be observed that the surface gradient of the DC conductor changes depending on whether the AC conductor is installed or not.

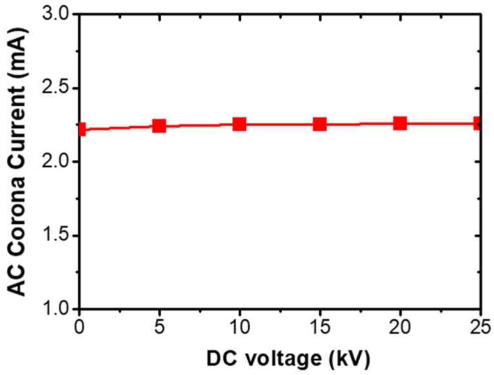
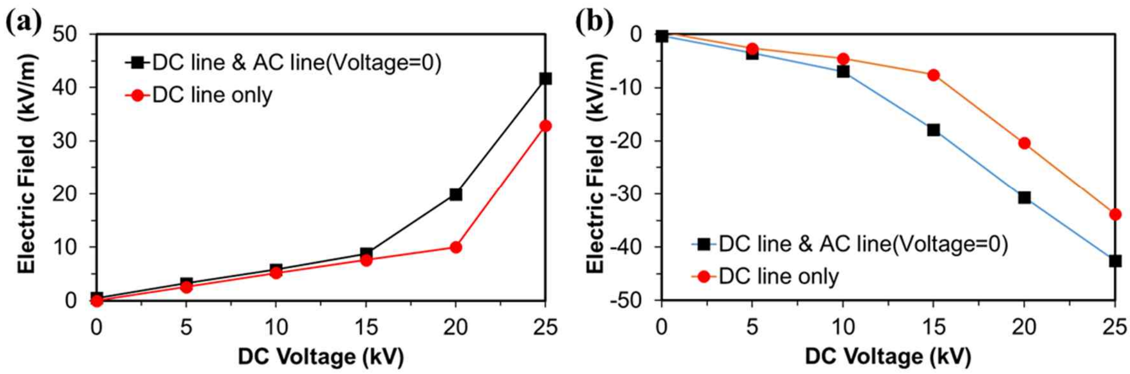


Figure 12. Corona discharge characteristics of the AC conductor according to operating conditions of DC conductor (V_{ac} = 25 kV)



(a) Positive pole at the bottom (b) Negative pole at the bottom

Figure 13. DC electric field effect depending upon the presence of AC conductor

VII. CONCLUSION

A reduced-scale model was designed to reduce AC 765 kV/DC ±500 kV by a reduction factor of 1/40. The evaluation of the HVDC transmission line was performed before conducting the HVAC/HVDC hybrid reduced-scale model test. However, the scale model test had a few limitations because the reduced-scale model test was conducted for a short duration of time under limited weather conditions. Therefore, the correction factor was applied to convert the measurement data from the reduced-scale model. In the hybrid test, an electric field of -13.44 kV/m was measured at the bottom of the negative pole when a reduction factor 1.6 was applied, whereas an electric field of -11 kV/m was calculated in the simulation. A corona discharge enhanced test was performed to verify the effect on DC and AC conductors. It was observed that the AC electric field was unaffected by the DC electric field. However, the DC electric field changed with variation in AC voltage. The corona onset voltage of the DC conductor was affected by the presence of the AC conductor even without AC voltage bias.

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