Experimental Approach to Shielding and Reducing Effects on Ion Currents and Electric Fields at Earth Level under a DC Transmission Line

By

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Abstract

Use of a d. c. transmission line to find a way to reduce ion currents and electric fields at earth level is a most important matter for environmental safety.

This paper discusses the relation between the ion currents and the electric fields at earth level, measured by using a unipolar d. c. transmission line scale model and a bipolar d. c. transmission line. Electric fields at earth level were calculated by means of the image charge method without taking into consideration the space charge caused by the d. c. line. The middle scale models for the unipolar and the bipolar d. c. lines were set at the height of the d. c. lines at 2 m. Both types of scale models were set up in a sufficiently spacious room. Two small scales for the unipolar and the bipolar d. c. lines, with the height of the d. c. lines set at 20 cm above the earth and the separating distance between the two d. c. lines set at 35 to 75 cm, were placed in a suitable roomo. Both the experimental results are discussed here in comparison with the calculated fields. As a conclusion, in using the model unipolar d. c. line with a shielding wire, the shielding effects for both the electric fields and the ion currents at earth level nearly coincided with the calculated fields. However, in using the model bipolar d. c. lines, the reducing effect for the ion currents dind't coincide with the ealculated fields, actually not quite half of the calculated fields. In particular, the ion currents, at earth level on the positive voltage side were reduced very well, relative to those on the negative voltage side. They were measured in relation to the ratio of the separating distance of the bipolar d. c. lines to the the height of the d. c. line from earth level.

1. Introduction

In the problem of environmental safety in the use of d. c. transmission lines, reductions of ion currents and electric fields at earth level have to be considered. To solve this problem, much information on ion currents and electric fields at earth

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level has been given by many researchers using mock-ups[1)~5)], model equipments in the laboratory[6)], and calculation[7)] of the fields.

In this paper, the reductions of ion currents and electric fields have been studied using two types of model transmission lines. One of them, an arrangement of two perpendicular lines consisting of a d. c. line, an aerial ground wire, and an earth plane, was adopted as a model of the unipolar d. c. transmission line system. Here, an aerial ground wire set directly under the d. c. line was treated as a shielding wire, and it's shielding effects were measured under it's various geometrical conditions.

The other type, an arrangement consisting of two parallel lines and an earth plane, was adopted as a model of the bipolar d. c. trasmission line system. The ion currents cancelled each other by the polarity effects produced from the opposite arrangements of two parallel lines to which were applied d. c. voltages of different polarities. As a result, the electric fields and ion currents were sufficiently reduced.

2. Shielding Effects on Ion Currents and Electric Fields under the Model Unipolar DC Line

Ions, departing from a model unipolar d. c. line, flow toward the earth plane, so an ion current distribution at earth level is similar to the distribution of an electric field intensity on the earth plane, excluding the effect of wind.

These phenomena are brought about by the ion currents resulting from the electric fields produced by applied voltage, a geometrical arrangement consisting of a d. c. line, a grounded shielding wire and earth plane electrodes.

Fundamentally, reductions of ion currents and electric fields on the earth are brought about effectively by making higher the height of the d. c. line and by making larger the diameter of the d. c. line. Another method for such a reduction uses a shielding wire set under the d. c. line, which absorbs the ion currents and shields the electric field in the area under itself.

In this section, we calculated the electric fields by the use of a shielding wire, and measured the ion currents and electric fields in the laboratory using two scale models.

2.1. Theoretical calculations of the electric field at earth level

Before this series of experiments, the theoretical calculations of the electric fields were done for various geometric conditions. Therefore, experimental conditions were selected and adopted which give the most clearly different effects. Electric fields for various geometric conditions in the gap, consisting of a smooth surfaced d. c. line, a shielding wire and an earth plane, were calculated by means of the image charge method without taking into consideration the spece charge effect.

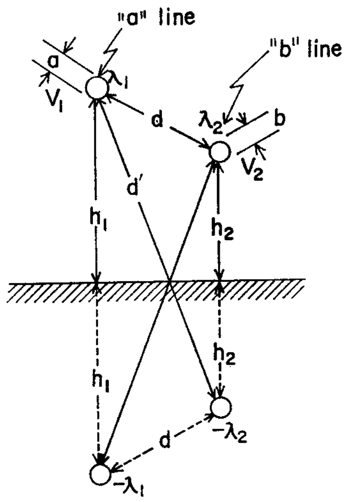

Fig. 1. The schema for the calculation of the electric fields in case of parallel lines and the earth plane.

In these calculations, two parallel lines with an infinitely long length over the earth plane, as shown in Fig. 1, were used. The surface potential of each line was calculated by the following equations:

$$\left.\begin{aligned} V_1&=\frac{1}{2\pi\varepsilon_0}\left(\lambda_1\log\frac{2h_1}{a}+\lambda_2\log\frac{d'}{d}\right)\\ V_2&=\frac{1}{2\pi\varepsilon_0}\left(\lambda_1\log\frac{d'}{d}+\lambda_2\log\frac{2h_2}{b}\right)\end{aligned}\right\} \qquad 1)$$

V_1: surface potential of the d. c. line

V_2: surface potential of the shielding wire

a : diameter of the d. c. line

b : diameter of the shielding wire

h_1: height of the d. c. line from earth level

h_2: height of the shielding wire from earth level

d : distance between the d. c. line and the shielding wire

d': distance between the d. c. line and the image of the shielding wire

λ_1, λ_2: coupling constants

Here, if "a" line is a d. c. line applied, "b" line is a shielding wire, $V_1=v$ and $V_2=0$. Then, λ_1, λ_2, are given as follows:

$$\lambda_1=2\pi\varepsilon_0 v\frac{\log\dfrac{2h_2}{b}}{\log 2\left(\dfrac{h_1}{a}+\dfrac{h_2}{b}\right)+\log\dfrac{2d'}{d}} \qquad 2)$$

$$\lambda_2 = 2\pi\varepsilon_0 v \frac{\log \frac{d'}{d}}{\log 2\left(\frac{h_1}{a}+\frac{h_2}{b}\right)+\log\frac{2d'}{d}}$$

The potential of any point (x, z) in the gap is given by the following equation, using λ_1, λ_2 as given by Equation 2):

$$V(x, z) = \frac{v}{2\pi\varepsilon_0}\left\{\lambda_1 \log \frac{\sqrt{x^2+(h_1+z)^2}}{x^2+(h_1-z)^2} + \lambda_2 \log \frac{\sqrt{x^2+(h_2+z)^2}}{x^2+(h_2-z)^2}\right\} \quad 3)$$

If we try to give the potential gradient at the earth level, where $z=0$ and the electric line of force is perpendicular to the plane, then:

$$\left.\begin{aligned} &\frac{\partial V(x, 0)}{\partial x} = 0 \\ &\frac{\partial V(x, 0)}{\partial z} = \frac{v}{\pi\varepsilon_0}\left\{\lambda_1 \frac{h_1}{x^2+h_1^2} + \lambda_2 \frac{h_2}{x^2+h_2^2}\right\} \end{aligned}\right\} \quad 4)$$

where the electric fields at the earth level are given by the following equation:

$$E(x, 0) = \sqrt{\left(\frac{\partial V(x, 0)}{\partial z}\right)^2} \quad 5)$$

In Equation 5), the electric field distributions and the various geometrical parameters of the shielding wire were given as shown in Fig. 2. In this figure, there are shown three distribution curves. One of them, marked by "○", was given where the height of the d.c. line (h_1) was 2 m, and was without a shielding wire. Another one marked by "●" was given where the height of the shielding wire (h_2) was 1.0 m, and the last one marked by "×" was given where $h_2 = 0.5$ m.

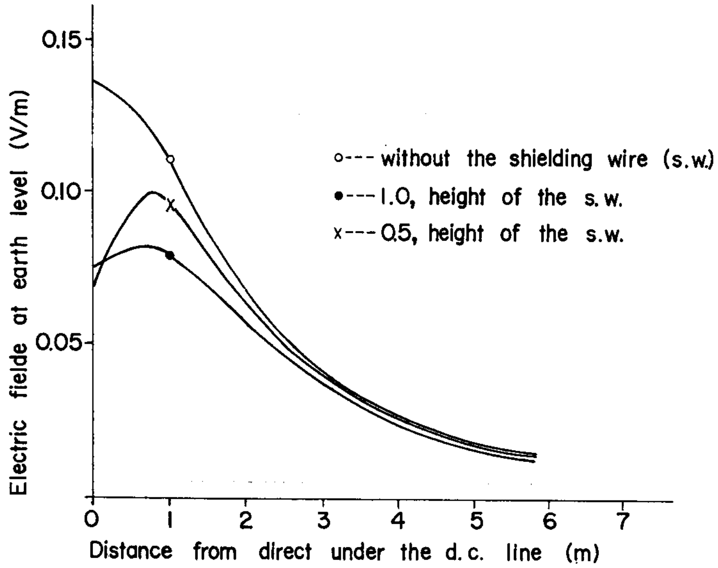

Fig. 2. The electric fields for each position of the shielding wire (by calculation).

2.2. Experimental instrumentation and setting up a d.c. line and a shielding wire

We used two scale models, a middle scale model and a small scale model, for the unipolar d.c. line. The middle scale model was set up with the 5 mm in diameter d.c. lines 2 m above the earth plane, and was used for configurations up to +350 kV. The small scale model was set up with the 0.8 mm in diameter d.c. line 20 cm above the earth plane, and was used for configurations up to +30 kV.

Both scale models were equipped with a provision for some variations in the shielding wire's position (distance between the d.c. line and the grounded shielding wire).

On the middle scale model, the change in the height of the shielding wire, which had a diameter of 1 cm and a length of 5 m, was accomplished by post insulators and balancing weights installed at both ends of the d.c. line and shielding wire.

The earth plane, made from aluminium, with an area of $3.6\times 14.4\ m^2$, had many holes of 6.2 cm diameter with a spacing of 80 cm between the holes for use in measuring the electric fields. Many insulated metal plates of $40\times 50\ cm^2$ were connected to a μA-meter for use in measuring the ion currents. The unipolar d.c. line, the shielding wire, and the earth plane were set in a spacious room which had a floor area of $22\times 26.6\ m^2$ and a ceiling height of 26 m, as shown in Fig. 3 and 4.

In a preparatory experiment, results showed that there remained half of the initial amount of space charge in the room 15 minutes after de-energizing from the d.c. line. Therefore, the measurements of the field intensity and ion currents were

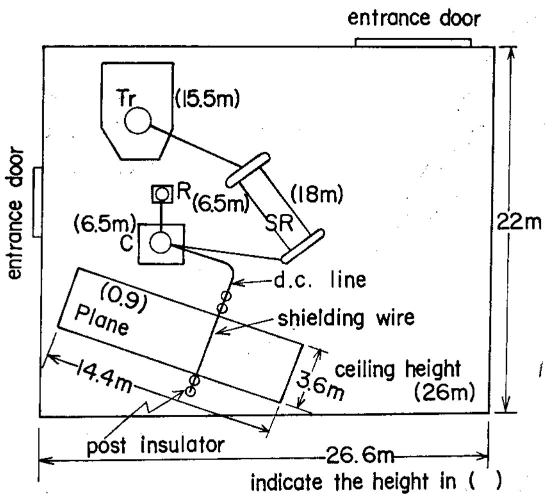

Fig. 3. The schema of the spacious room and the setingof the middle scale model for the unipolar d.c. line.

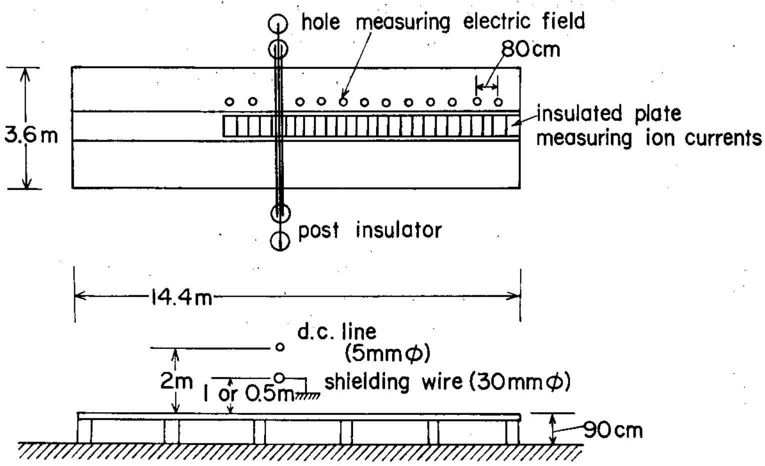

Fig. 4. The arrangement of the middle scale model for the unipolar d. c. line.

taken after sufficient degassing by opening a shutter door the full height of the room, before conditions were changed and the next experiment was conducted. The result of degassing was checked by measurements on the electronmeter.

The experiments in the use of this scale model were done as a part of the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan, at a large scale laboratory belonging to a major electric company. The data obtained in this research series were very few, as the times assigned for our experiment were limited. Nevertheless, the data are of much importance to us.

2. 3. Experimental results

The experimental results for the electric fields and ion currents on the earth are shown in Figs. 5 to 8.

In these figures, the measurement results were shown only on one side because they were measured only on one side as was necessary and sufficient in this case. If the shielding wire had been set directly under the d. c. line, shielded amounts of electric fields and ion currents would have become as large as the height of the shielding wire.

First, the following facts for the electric fields at earth level were arrived at by comparing the experimental results with the calculated values, as shown in Fig. 2.

a) The electric field distributions on the applied negative voltage side, as shown in Fig. 6, were nearly the same as the calculated values, compared with the shielding effects measured on the side of the applied positive voltage, as shown in Fig. 5.

b) Generally, the shielding effects of the electric fields obtained by measurements also follow the theoretical calculations, qualitatively.

Each electric field intensity at the surface of the d.c. line and shielding wire calculated from a change in the arrangement of the shielding wire and the applied voltage is shown in Table 1. In the table, the electric field intensity on the surface

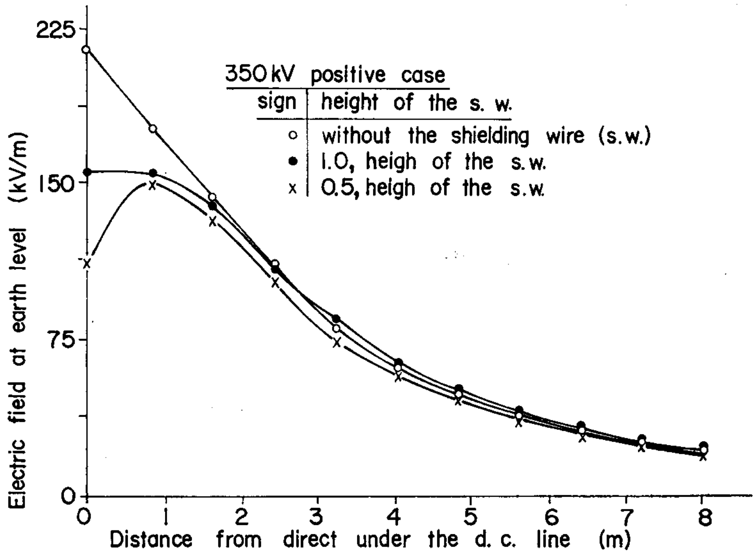

Fig. 5. The electric fields at the earth level for each position of the shielding wire (by measurement, positive).

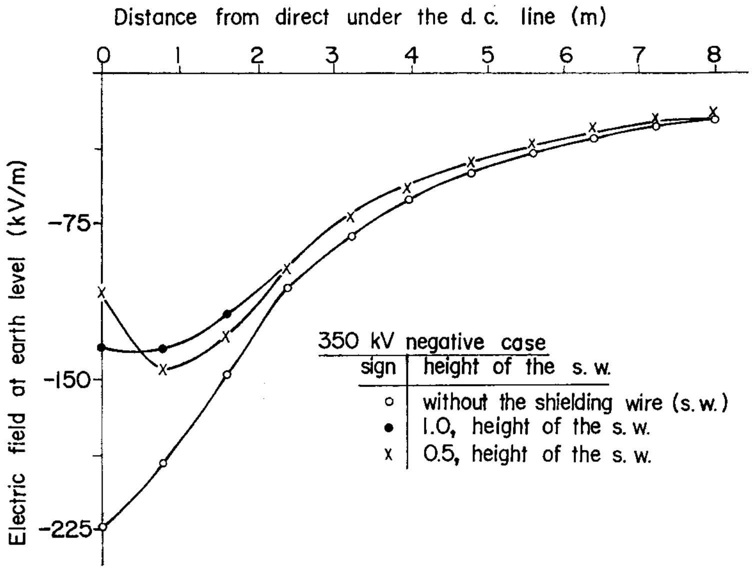

Fig. 6. The electric fields at the earth level for each position of the shielding wire (by measurement, negative).

of the shielding wire set at 1.0 m height from earth level was calculated at 8.1 kV/cm, when the applied voltage on the d.c. line was 350 kV. Under the other geometrical conditions of the experimental configurations, the corona did not depart at

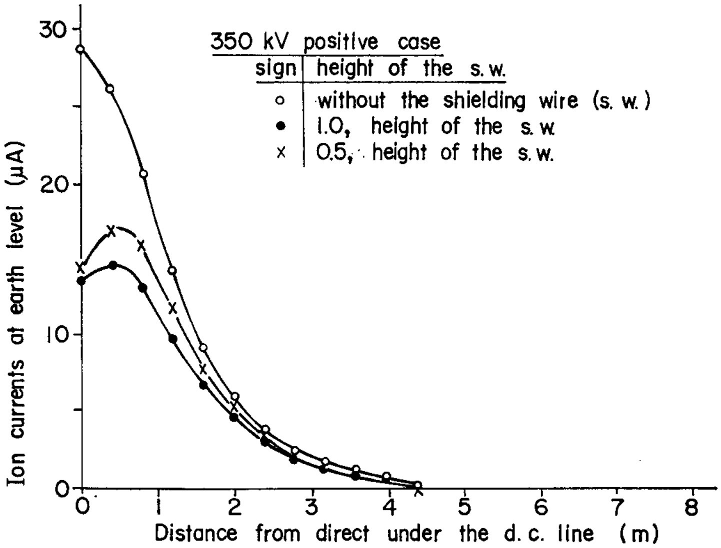

Fig. 7. The ion currents at the earth level for each position of the shielding wire (by measurement, positive).

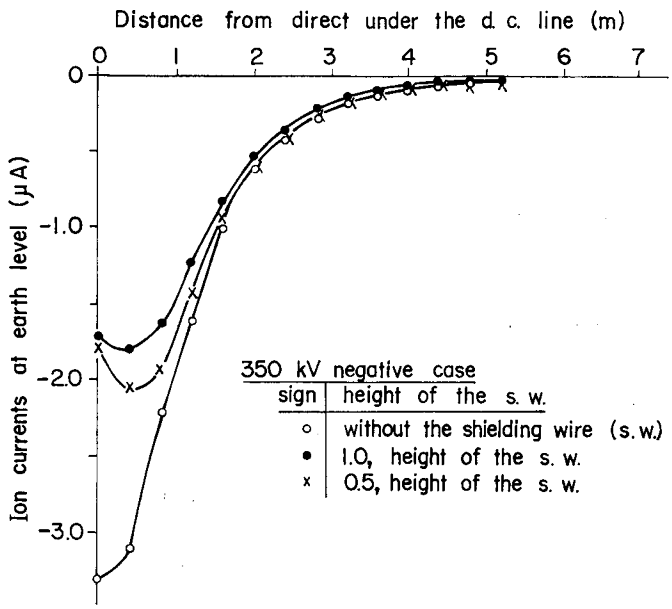

Fig. 8. The ion currents at the earth level for each position of the shielding wire (by measurement, negative).

Table 1. The electric field intensity at the surface of the d.c. line and shielding wire.

Applied Voltage (kV)	on d.c. Line			on S.W.	
	Without S.W.	Height of S.W. 1.0 m	Height of S.W. 0.5 m	Height of S.W. 1.0 m	Height of S.W. 0.5 m
	kV/cm				
50	27.1	28.1	27.4	1.2	0.64
150	(81.3)	(84.2)	(82.1)	3.5	1.9
350	(189.7)	(196.4)	(191.5)	8.1	4.4

all from the shielding wire.

Next, the ion currents at earth level were measured by a μA-meter and many metal plates insulated from each other. The measured results are shown in Fig. 7 for the applied positive voltage, and in Fig. 8 for the applied negative voltage.

The following results for the ion currents on the earth plane were drawn from the experimental data.

a) The ion current distributions at earth level nearly coincided with the distributions of the electric fields, as shown by comparing Fig. 2 with Fig. 7 or 8.

b) The ion current distributions at earth level were gathered to the center compared with the electric field distributions.

c) The ion currents of the applied negative voltage were larger than those of the applied positive voltage, comparing Fig. 7 with Fig. 8.

Each maximum field intensity resulting from a change in the arrangement of the shielding wire was compared with the maximum field intensity in the absence of the shielding wire, as shown in Table 2. The shielding effects are described as follows: when the shielding wire was set at the earth level, it seems that the point indicating the maximum field intensity was located nearly 1.0 m outside the center

Table 2. The relationship of the maximum intensity of the electric field at earth level to the configuration of a d.c. line with a shielding wire compared with the relationship to the configuration consisting of a d.c. line and earth plane without a shielding wire.

Condition \ Applied Voltage	Calcu. (1.0V)	Measurments					
		50(kV)	−50	150	−150	350	−350
	(V/m)	(kV/cm)					
Without S.W.	0.135	2.98	3.39	14.0	14.4	46.7	49.0
Height of S.W. 1.0 m	0.083	2.16	2.10	10.7	10.0	34.1	29.4
R(1.0) (%)	62	72	62	77	70	73	60
Height of S.W. 0.5 m	0.099	1.79	2.22	10.3	11.2	32.6	31.8
R(0.5) (%)	73	60	65	73	78	70	65

line which is directly under the d. c. line and the shielding wire.

The shielded amount of the maximum electric field with the shielding wire in a high position was larger than with the shielding wire in a low position.

The shielding effects for the ion currents were found to be as follows:

a) The ratio (R) of the measured ion current flowing toward the shielding wire to the other flow was calculated, as shown in Figs. 9, 10 and Table 3. ($R=100 \cdot I_s/(I_s+I_{p1})$ Here, I_s: The ion currents flowing toward the shielding wire. I_{p1}: Total ion currents on the earth plane. Both currents were measured per unit width.)

b) The raio (R) increased, linearly, to as higth as the applied voltage. (c. f.

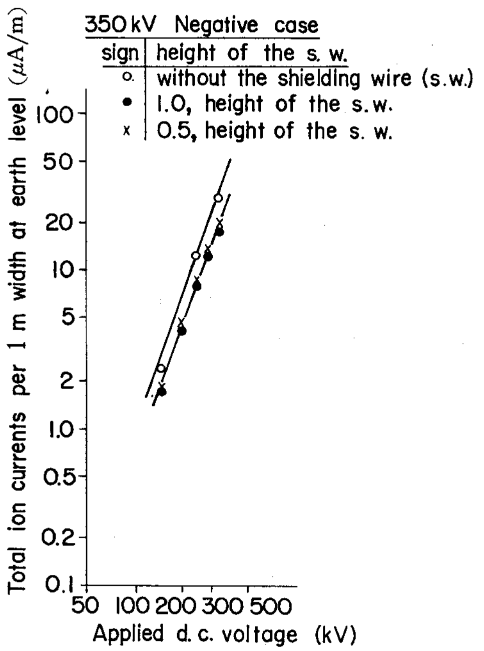

Fig. 9. The relation of the ion currents at the earth level with the applied voltage for each position of the shielding wire (by measurement, positive).

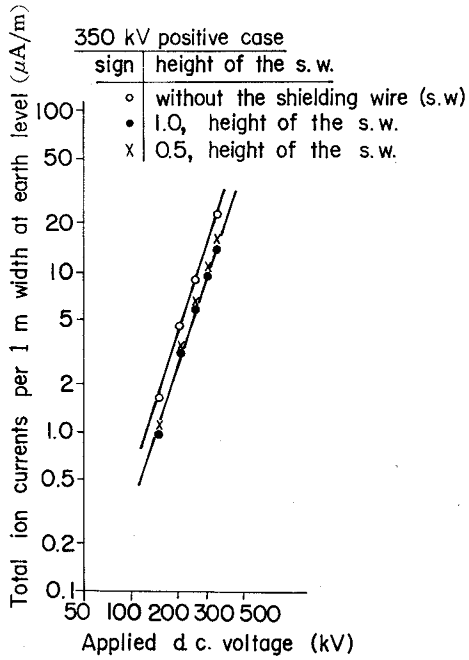

Fig. 10. The relation of the ion currents at the earth level with the applied voltage for each position of the shielding wire (by measurement, negative).

Table 3. The ratio of the maximum ion currents in the absence of the shielding wire and with a full set.

Height of S. W. (m)	Calcu.	Positive		Negative	
	E. Field	E. Field	Ion Carr.	E. Field	Ion Carr.
1.0	62	75	50	65	55
0.5	73	65	60	65	60

(%)

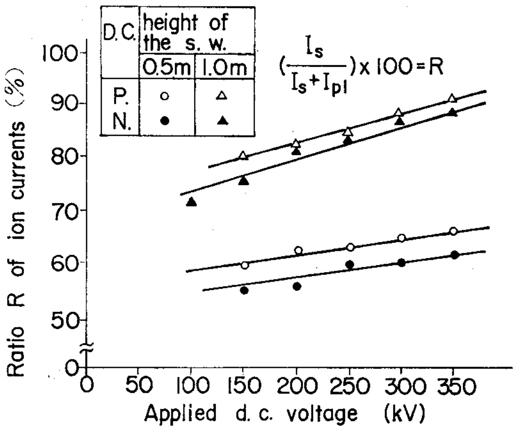

Fig. 11. The shielding effects by the shielding wire on the ion currents at the earth level.

Fig. 11)

c) The ratios of the maximum ion currents in the absence of the shielding wire and with a full setting were calculated, as shown in Table 3. In the table, the characteristics of the shielding effects for the ion currents were almost the same as the shielding effects for the calculated electric fields, qualitatively.

3. Experimental Results and Calculated Results of Electric Fields and Ion Currents at Earth Level for Bipolar DC Lines

3.1. Theorectical calculations of electric field at earth level

The equation for the electric field in this case was shown by using Equations 1 to 5 treated in Section 2.1. The arrangement and dimension of the bipolar d.c.

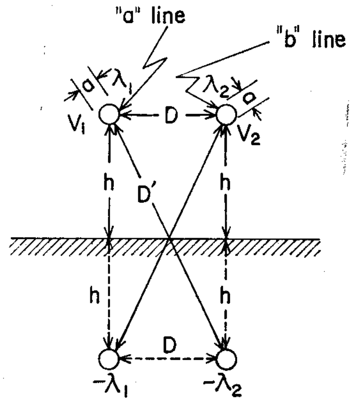

Fig. 12. The schema for the calculation of the electric fields of the bipolar d.c. lines.

lines, the earth plane and the image charge lines are shown in Fig. 12.

Therefore, in Equation 1), in which the spacing distance between the positive and negative charged d. c. lines is given as "D" instead of "d", which is the distance from the unipolar d. c. line to the shielding wire, and $V_1=v$, $V_2=-v$, the gradients of potential are given as follows:

$$\left.\begin{aligned} &\frac{\partial V(x,\ z)}{\partial x}=0 \\ &\frac{\partial V(x,\ z)}{\partial z}=\frac{hv}{\pi\varepsilon_0}\left\{\frac{\lambda_1}{h^2+\left(x-\frac{D}{2}\right)^2}+\frac{\lambda_2}{h^2+\left(x+\frac{D}{2}\right)^2}\right\} \end{aligned}\right\} \quad 6)$$

At the earth level, $z=0$. Therefore, the electric field is given as follows:

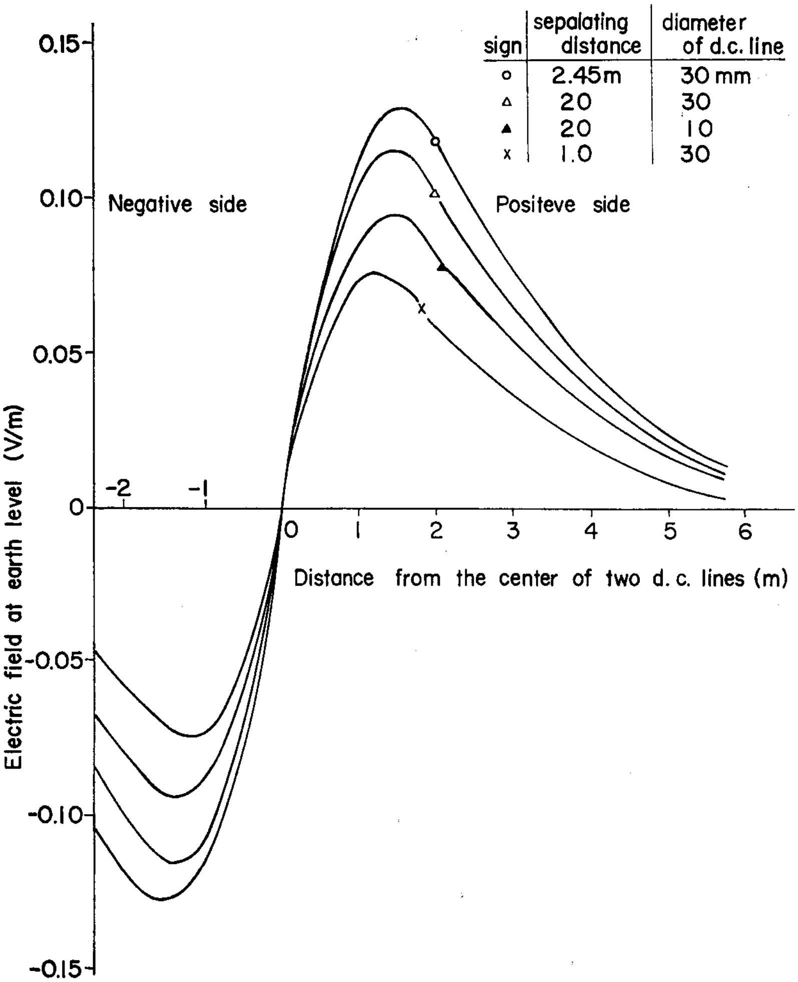

Fig. 13. The electric fields at the earth level for each separate position of the bipolar d. c. lines (by calculation).

$$E(x,\ 0)=\sqrt{\left(\frac{\partial V(x,\ 0)}{\partial z}\right)^2} \qquad 7)$$

The calculated values are given in Fig. 13. In this figure, the calculated fields were given symmetrically on each side of the center of the bipolar d. c. lines spaced for certain conditions, as shown by the table in the figure.

3.2. Experimental instrumentation and setting up the bipolar d.c. lines

We had two models for the bipolar d. c. lines, "the middle scale model" which has both d. c. lines set at 2 m above the earth plane and is used for configurations up to ±350 kV. The other model was "the small scale model" which has both d. c. lines set at 20 cm above the earth plane and is used for configurations up to ±30 kV.

Both scale models were equipped with a provision for some variations in line spacing (distance between the positive and negative lines).

On the middle scale model, the setting of two d. c. lines, which had a diameter of 3 cm, a spacing distance of 2.45 m and a length of 5 m, was accomplished by post insulators and balancing weights. The earth plane, made from aluminium, was arranged the same as the one used when the unipolar configuration was treated in Section 2.2. Both the bipolar d. c. lines and the earth plane were set in a spacious room, as shown in Fig. 14.

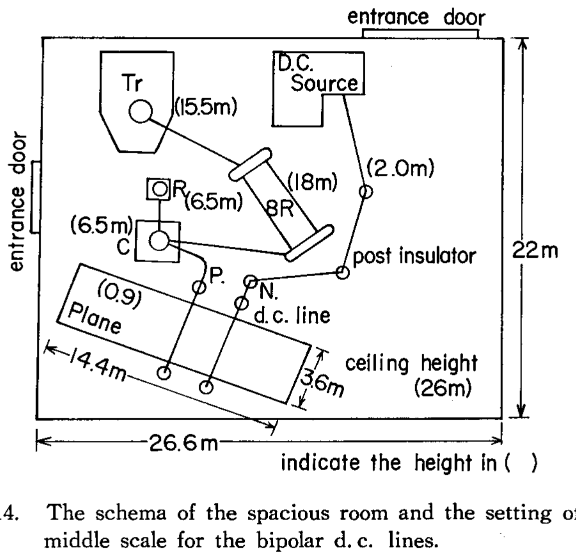

Fig. 14. The schema of the spacious room and the setting of the middle scale for the bipolar d. c. lines.

In the experiments, measurements of the field intensity and ion currents were done after degassing enough to reach the same level as those in the unipolar configuration.

3.3. Experimental results

3.3.1. Experimental examination using the middle scale model

The experimental results for the electric fields on the earth are shown in Figs. 15 and 16. In these figures, the higher negative field intensities were more than the positive field intensities. On the center line of the separating distance between the bipolar d.c. lines, the field was not zero and stayed negative. In other words, the center of the fields dislocated to the positive voltage side away from the geometrical center. It was assumed that this fact was related to the ion current distribution.

The calculated results of the field intensity at the surface of the d.c. lines are show in Table 4. In the table, it is clear that corona from the d.c. line didn't gain sufficiently under the conditions in which the applied voltage was lower than

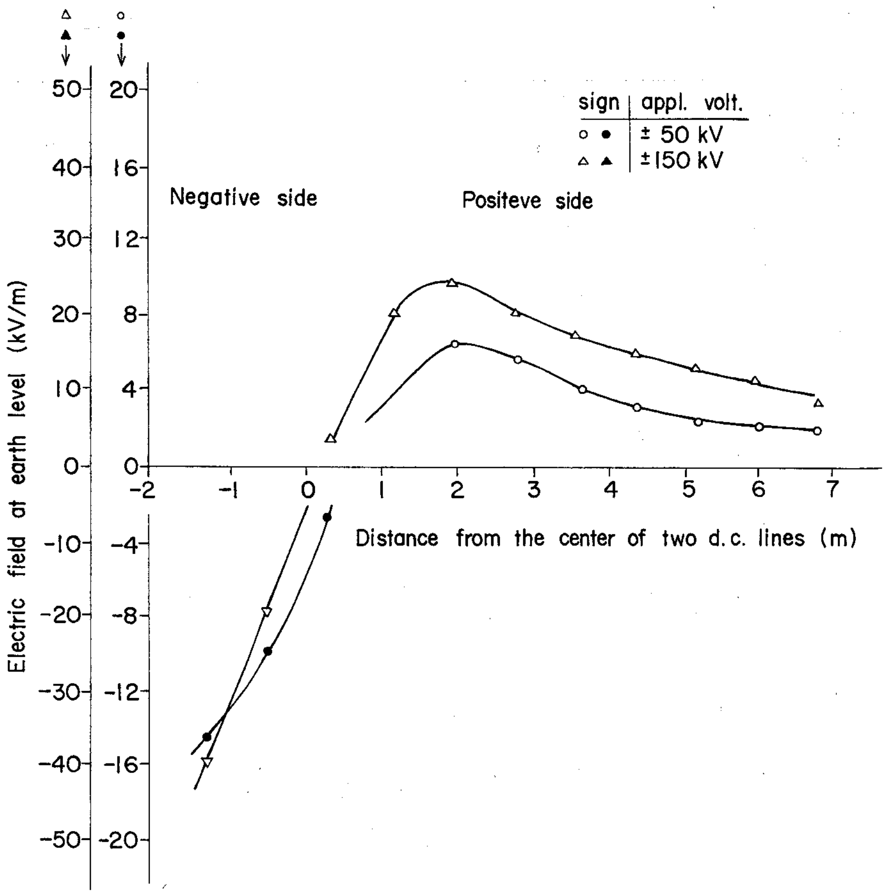

Fig. 15. The electric fields at the earth level for each separate position of the bipolar d.c. lines (by measurement).

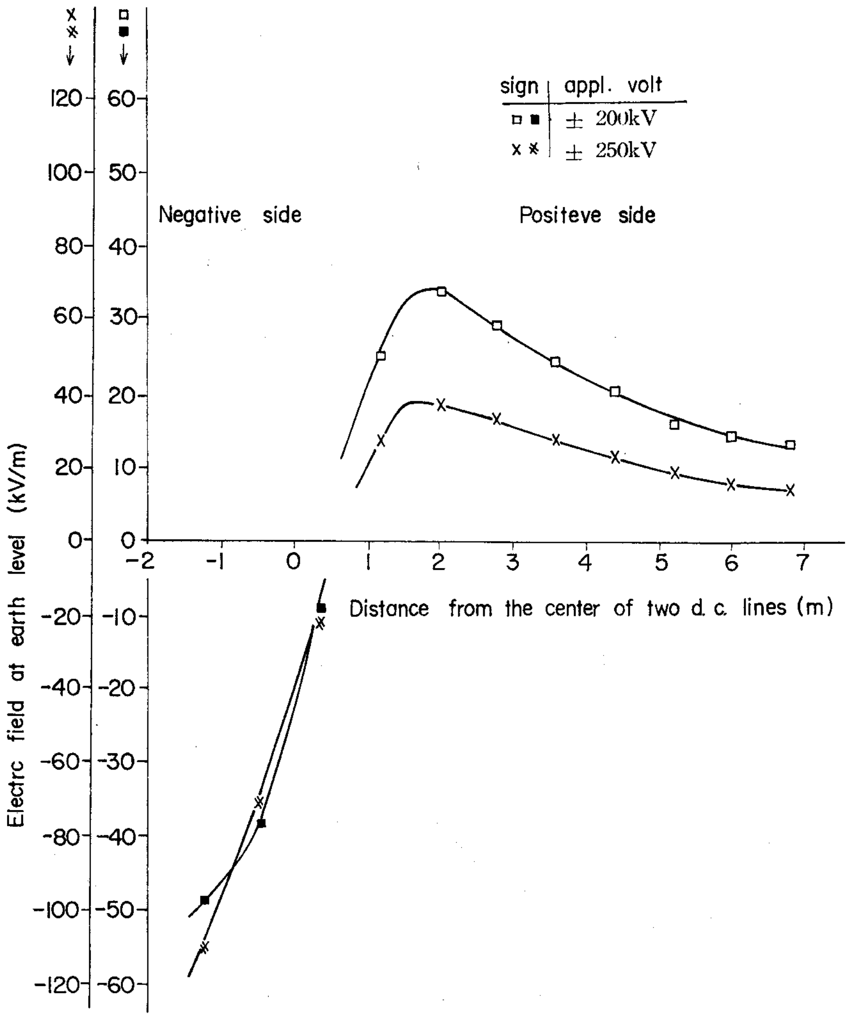

Fig. 16. The electric fields at the earth level for each separate position of the bipolar d. c. lines (by measurement).

Table 4. The electric field at the surface of d. c. line calculated from a change in the applied voltage.

Applied Voltage (kV)	Electric Field at d. c. Line Surface (kV/cm)
± 50	6.8
±150	20.4
±200	27.2

±150 kV.

The contrasts of the measured electric fields at the earth level with the calculated fields in the space between the unipolar line and the earah plane are shown in Table 2. The maximum field intensity in these cases didn't reduce as much as shown by the last column in the table. This small reduction was a result of the specing distance being large compared with the height of the d. c. lines.

The maximum field intensity on the positive voltage side was reduced to nearly half of the calculatted field. However, the maximum field intensity on the negative voltage side was comparable with the field at the earth level in using the unipolar configuration.

Next, the measured results for the ion currents on the earth are shown in Fig. 17. The ion currents at the earth level were measured when the applied voltage was over ±200 kV, but couldn't be measured under ±150 kV because of the absence of the corona. In these figures, enough ion currents on the negative side were measured, but not enough ion currents on the positive side were measured in any of the cases. It appears that ion currents in this case flow as a hypothetical figure,

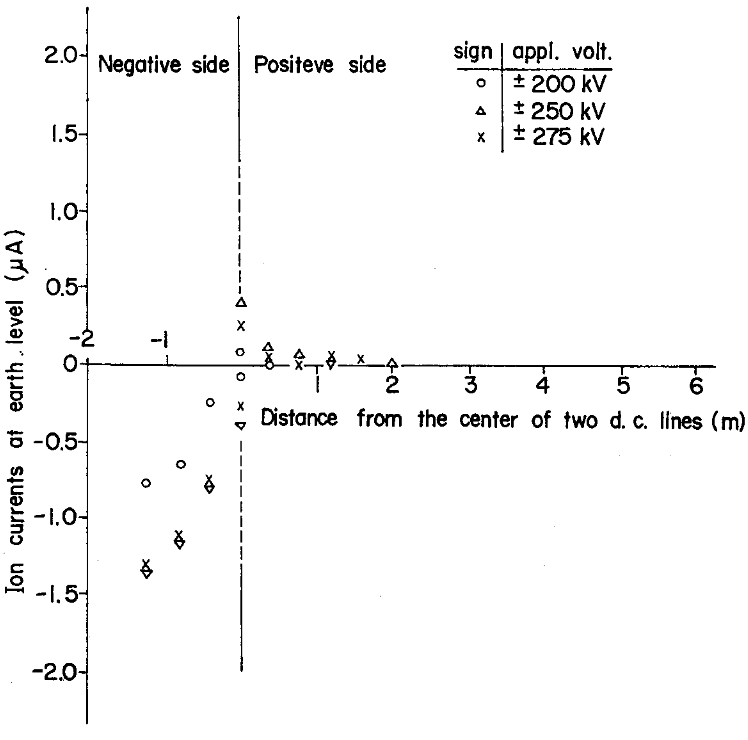

Fig. 17. The ion currents at the earth level for each separate position of the bipolar d. c. lines (by measurement).

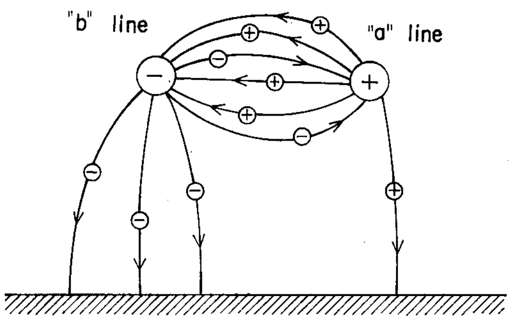

Fig. 18. The imaginary schema for the flow of the positive and negative ion currents.

as shown in Fig. 18.

On the middle scale model, the ion currents at the earth level were nearly zero because the specing disstance (2. 45 m) was just slightly larger than the height (2. 0 m) of the two lines.

These unsymmetrical reductions of ion currents at earth level were measured already by H. L. Hill[8].

3. 3. 2. An experimental examination using a small scale model

Unfortunately, experiments using the middle scale model were not done sufficiently. Therefore, using the small scale model, the relations of ion currents and geometrical conditions were made clear as follows.

The setting dimensions of the small scale model were chosen as follows: the heights of both d. c. lines from the earth level were 20 cm each, the distance between the two d. c. lines was 35 to 75 cm, the diameters of the d. c. lines were 0. 8 mm each, and the applied voltage was set at ± 30 kV constant for all settings.

The ion current distributions at the earth level are shown with the parameter of the separating distance in Fig. 19. In the figure, the ion current distributions on the side of the positive voltage application were very small compared with those on the side of the negative voltage application under all geometrical conditions of the model arreangement.

The maximum value of the ion currents on the positive voltage side, when the broadest separating distance in this series of the experiment was D=75 cm (3. 75 times the height from the earth), was calculated as 79%, based on the maximum value of the ion currents on the negative voltage side. The maximum ion currents on the positive voltage side, when the separating distance was D=35 cm (1. 75 times the height from the earth), was calculated as 45%.

In the setting of the unipolar line, the ion currents at the earth level distributed symmetrically on the right side and the left side with the center directly under

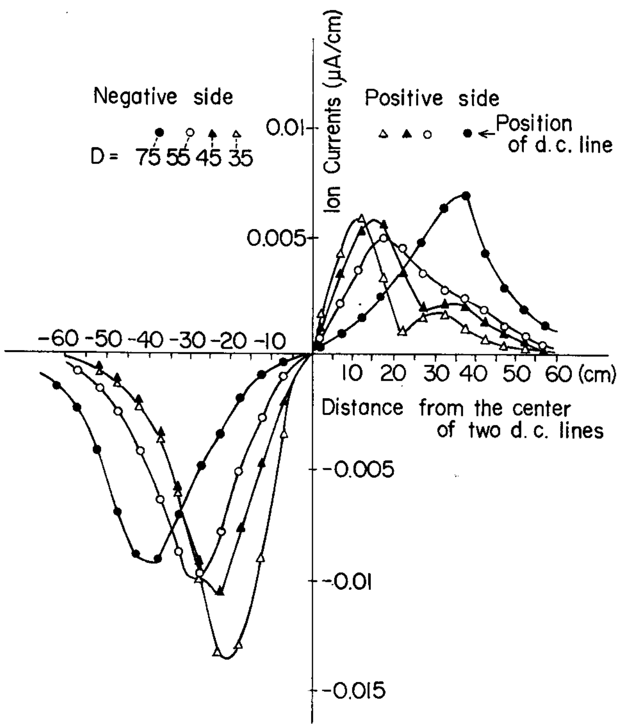

Fig. 19. The ion currents at the earth level for each separate position of the bopolar d. c. lines, using the small scale model.

the d. c. line.

In contrast to the unipolar line, the ion current distribution on the bipolar d. c. lines had a steep slope on the earth plane between one d. c. line and the othe d. c. line. (This space between the d. c. lines is called "the inner side".) This steepness was perhaps created by electric fields in the gap in which ion currents were flowing.

In particular, the peak of the ion currents on the positive voltage side was in "the inner side", and the peak value was very low compared with the one on the negative voltage side. On the positive voltage side, the ion currents at the outside of it's peak grew weak, and a second peak appeared in the narrow separating distance (D).

A comparison of the ion current distribution on the positive voltage side with the one on the negative voltage side is shown in Fig. 20. In the figure, the parts indicated by the shadow mark "▨" show the loss of positive ion currents. These phenomena should be studied in the future by the calculation of electric fields in the gap, in which positive and negative ion currents are flowing. However, in this

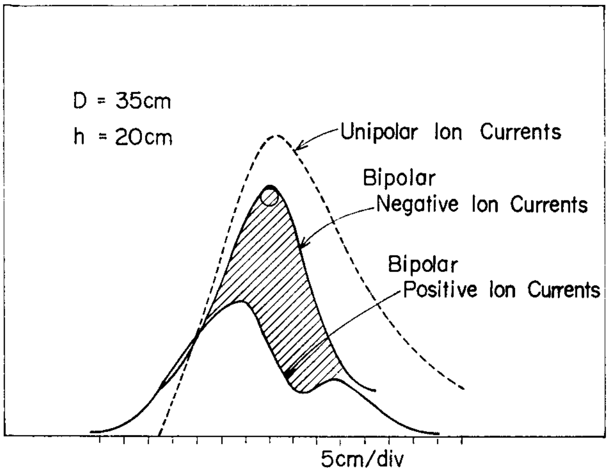

Fig. 20. Comparison of the ion current distribution on the positive voltage side with one on the negative voltage side.

paper, we are showing only the experimental data and the calculated results of the electrical field in the gap in which ion currents were not flowing.

4. Conclusion

The experimental results using the small and middle scale models for the unipolar d. c. line with a shielding wire and bipolar d. c. lines were obtained as folows:

First, for the unipolar d. c. line:

1) The theoretical calculations of the electric fields at the earth level for the unipolar line system with a shielding wire were given by the image method treated without the effects of space charge caused by ion currents.

2) The theoretical calculations of the electric fields on the earth coincided well with the experimental results.

3) The experimental results of the ion currents on the earth were nearly the same as the calculated fields at the center (directly below the d. c. line and shielding wire). However, the farther from the center the farther down toward the earth went the ion currents.

4) The shielding effect becomes as high as the height of the shielding wire, and as high as the voltage of the d. c. line under the constant of the other configurations.

5) The above conclusions hold good under positive or negative voltage application.

Second, for the bipolar d. c. lines:

6) The electric fields at the earth level on the negative voltage side were

nearly the same as the calculated fields, not considering the space charge effects. However, the fields at the earth level on the positive voltage side did not coincide with and were not quite half of the calculated fields.

7) The ion currents on the earth on the positive side were especially reduced.

8) The magnitude of the reducing effects related to the distance separating the bipolar d. c. lines was larger when the distance was shorter.

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