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A Study for the Measurement of the Minimum Clearance Distance between the 500 kV DC Transmission Line and Vegetation

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Abstract: High voltage direct current (HVDC) transmission is being widely implemented for long-distance electrical power transmission due to its specific benefits over high voltage alternating current (HVAC) transmission. Most transmission lines pass through forests. Around the HVDC lines, an arc to a nearby tree may be produced. Thus, there should be a minimum possible clearance distance between a live conductor and a nearby tree, named the minimum vegetation clearance distance (MVCD), to avoid short-circuiting. Measurement of minimum clearance distance between the conductor and trees is a significant challenge for a transmission system. In the case of HVAC transmission, a large amount of research has been undertaken in the form of the Gallet equation for the measurement of this distance, whereas for HVDC transmission no substantial work has been done. An equivalent AC voltage value can be derived from the DC voltage value in order to use the Gallet equation. This paper presents an experimental measurement technique for determining the MVCD at 500 kV to verify the results obtained from the Gallet equation in the case of DC voltage. Performing the experiment with a 500 kV DC line is not possible in the laboratory due to safety concerns. Therefore, an experiment up to 60 kV is conducted to measure the MVCD for DC voltage. The measured results achieved from the experiment are then extrapolated to calculate the MVCD at 500 kV.

Keywords: Gallet equation; HVDC transmission; minimum vegetation clearance distance (MVCD)

1. Introduction

High voltage direct current (HVDC) transmission system is widely considered as having technical, economic and environmental benefits. The first electricity, generated by Thomas Alva Edison in the 1880s, was low-level DC [1]. The first HVDC transmission was introduced in Sweden in 1950 and put into operation in 1954 [2]. The HVDC transmission system has technical advantages in producing an asynchronous interconnection and long-distance bulk power delivery [3–5]. There are also some other advantages of DC transmission: there is no reactive power loss in this system [6,7]; no bulky tower structure is needed [8]; it does not require intermediate switching stations [9]; and, skin and corona effects disappear in the transmission [10]. As a result, the number of HVDC projects is steadily increasing, showing that HVDC technology plays a vital role in the power transmission system.

Insulation or line clearance is a big challenge for transmission systems. AC and DC voltage both can produce an electric field around the transmission line; the greater the magnitude of voltage, the greater the strength of the electric field. This explains why HVDC has a very strong electric field. When the electric field increases, it affects the electrons in the atomic orbitals and may cause atoms or molecules to polarize or release electrons. The maximum electric field that a dielectric material—for example, air—can withstand without conduction is known as the dielectric strength of that material, and is denoted by kV/m or kV/cm. When the electric field becomes more than the dielectric strength, breakdown happens and the air becomes a conductor, whereby electrons collide with the atomic or molecular structure, releasing more electrons that cause a further breakdown of the air. Large currents are possible at the breakdown. The dielectric strength of air at normal temperature and pressure is 30 kV/cm [11]. After crossing this limit, air ionizes rapidly [12,13]. This ionization phenomenon can create an arc with any nearby obstacles. These obstacles can be any building or vegetation (e.g., a tree). In practice, many transmission lines run through forests. Although the lines have no direct contact with trees that grow beneath, there is a chance of producing an arc because of extremely high voltages [14]. This situation may cause the blackout of the whole power system. To avoid this situation, there must be a minimum optimal distance between the HVDC transmission line and the tree. This distance is called the minimum vegetation clearance distance (MVCD). This paper focuses on the measurement of MVCD in the DC transmission system.

2. MVCD and Gallet Equation

A lot of work has previously been undertaken to find the minimum vegetation clearance distance (MVCD) in AC high voltage transmission systems. However, there has been no significant work carried out to calculate MVCD for HVDC transmission systems. The Gallet equation has been used by North American Reliability Corporation (NERC) to find the MVCD for the AC system. This method has the ability to consider different air gap geometries and non-standard atmospheric conditions. The critical flashover voltage (CFO) and gap factor are important in explaining the Gallet equation. The voltage at which a surge is 50% likely to cause a flashover is called CFO. The word "critical" here means that the rise time of the surge is at the value known to result in the lowest flashover voltage. The ratio of the CFO of a test object to the CFO of a rod-plane gap for the same spacing is known as the gap factor. For any given spacing, a rod-plane gap gives the lowest CFO voltage [15]. This approach is well known for its conservatism and was used to design the first 500 kV and 765 kV lines in North America [16]. The transient overvoltage factor is also considered in this equation. For 362 kV and above, 1.4 p.u. is selected as the overvoltage factor. There is no prominent information about MVCD calculation in the case of DC transmission in this equation. The Gallet equation is explained in [17–19] and can be shown as:

$$CFO_A = k_w \cdot k_g \cdot \delta^m \cdot \frac{3400}{1 + \frac{8}{D}} \tag{1}$$

where:

k_w is defined as the factor that takes into account wet or dry conditions (dry = 1.0, wet = 0.96) and phase arrangement (multiply by 1.08 for outside phase) (e.g., for outside phase and wet conditions, $k_w = 0.96 \times 1.08 = 1.037$).

k_g is defined as the gap factor (1.3 for a conductor to large structure).

D is the strike distance (m).

CFO_A is the CFO for the relative air density (kV).

δ is defined as the relative air density and is approximately equal to Equation (2) where A is the altitude in km.

$$\delta = e^{\frac{-A}{8.6}} \tag{2}$$

$$m = 1.25G_o(G_o - 0.2) \quad (3)$$

$$G_o = \frac{CFO_s}{500.D} \quad (4)$$

$$CFO_s = k_w \cdot k_g \cdot \frac{3400}{1 + \frac{8}{D}} \quad (5)$$

where CFO_s is the CFO for standard atmospheric conditions (kV). Using (1)–(5), the value of D for a specific value of CFO_A can be computed using an iterative process [17].

Equation (6) can be determined if the maximum switching overvoltage is set equal to the withstand voltage of the air gap (CFO_A–3σ).

$$CFO_A = \frac{V_m}{1 - 3\left(\frac{\sigma}{CFO_A}\right)} \quad (6)$$

where:

V_m is equal to the maximum switching overvoltage.
σ is the standard deviation of the air gap insulation.
CFO_A is the critical flashover voltage of air gap insulation under non-standard atmospheric conditions.

The ratio (σ/CFO_A) in Equation (6) can be taken to be 0.05 based on the literature and can, therefore, be written as:

$$CFO_A = \frac{V_m}{1 - 3(0.05)} \quad (7)$$

$$CFO_A = \frac{V_m}{1 - 0.15} \quad (8)$$

$$CFO_A = \frac{V_m}{0.85} \quad (9)$$

Using the value of CFO_A from Equation (9) in Equation (1), we have:

$$V_m(AC) = 0.85 \cdot k_w \cdot k_g \cdot \delta^m \cdot \frac{3400}{1 + \frac{8}{D}} \quad (10)$$

By using this equation, the required clearance distance for any air gap can be determined.

The above equation was used for determining the clearance distance between the vegetation and the conductor in case of AC transmission. However, it is possible to change DC voltage into AC-equivalent voltage. Equation (11) provides the AC-equivalent voltage value for any DC voltage value [20].

$$\text{AC Voltage} = \text{DC Voltage} \times \sqrt{3} \div \sqrt{2} \quad (11)$$

For example, to find the MVCD at DC 500 kV, the AC equivalent voltage will be 613 kV.

500 kV for DC = 613 kV for AC

We can then determine the MVCD value by using AC-equivalent voltage value in the Gallet equation.

The Gallet equation method has been explained in detail. Equating the magnitude of DC voltage to AC voltage with the help of a formula has also been discussed. We have performed Gallet equation calculations using Matlab in order to determine the MVCD. Tables 1 and 2 show MVCD values at different voltages for a gap factor equal to 1 and altitude of 0 km.

Table 1. Minimum vegetation clearance distance (MVCD) by the Gallet equation for different low DC voltages.

Voltage (kV)	MVCD (m)	Voltage (kV)	MVCD (m)
2.5	0.0055	32.5	0.0715
5	0.0109	35	0.077
7.5	0.0164	37.5	0.0826
10	0.0219	40	0.0881
12.5	0.0273	42.5	0.0937
15	0.0328	45	0.0993
17.5	0.0383	47.5	0.1049
20	0.0438	50	0.1105
22.5	0.0493	52.5	0.1161
25	0.0549	55	0.1217
27.5	0.0604	57.5	0.1273
30	0.0659	60	0.1329

Table 2. MVCD by the Gallet equation for different DC voltages from 100 kV to 900 kV.

Voltage (kV)	MVCD (m)	Voltage (kV)	MVCD (m)
100	0.22	600	1.16
200	0.45	700	1.58
300	0.67	800	1.80
400	0.90	900	2.03
500	1.13	—	—

3. Proposed Idea

A minimum vegetation clearance distance is essential to avoid flashover between trees and the HVDC conductor. Korea Electric Power Corporation (KEPCO) is motivated to establish its own rules for the determination of MVCD for the construction of 500 kV DC transmission lines. This paper proposes that MVCD values can be determined based on some defined rules.

The Gallet equation can be used for AC voltage for the determination of MVCD; however, by using Equation (11), DC voltage can be represented in terms of AC-equivalent voltage. In this way, the Gallet equation can also be used, via Matlab, for determining MVCD in the case of HVDC. This equation has not previously been used and tested for DC voltage. Therefore, in order to verify the equation in the case of DC voltage, experimentation is required. The comparison between the Gallet equation results (for DC voltages) and experimental results will provide verified MVCD values in the case of HVDC.

4. Experimental Setup

For MVCD measurement for a DC system, experimental work was undertaken at a maximum voltage of 60 kV DC. Although the central theme of this work is to calculate MVCD for a voltage of 500 kV DC, there are many restrictions to undertaking laboratory experiments at very high voltages. The main issue is that HVDC of 500 kV requires a high level of insulation. Another issue is that special regulatory permission is needed for performing such a high voltage experiment.

Therefore, this study is based on an experiment performed at different voltage levels ranging from 2.5 kV to 60 kV. At each level of voltage, the MVCD was measured. The graph of these measured MVCD values provided a clear picture of how MVCD values increase as voltage level increases. An equation based on these measured values could then be used to identify the MVCD at each voltage level.

A schematic of the experimental configuration is shown in Figure 1. The implementation of this configuration is shown in Figure 2. It can be seen in Figure 1 that a power supply of 100 kV was used with 2 mA to energize the conductor. A capacitor bank was also used parallel to the power supply for its protection. This capacitor bank consisted of two capacitors, each with a capacity of 30 kV. These were connected in series to make a 60-kV capacitor bank. This capacitor bank was first charged from 2.5 kV to 60 kV, and then used to supply power to the conductor. Each voltage level created an electric field of different strength around the conductor.

The tree and the speed control motor can also be seen in Figures 1 and 2. The tree was placed on a moving platform and could be moved up and down using the speed control motor. The distance between the conductor and the basement was already specified. When the tree was moved upward, the distance between the basement and the moving platform on which the tree was placed increased, while the distance between the tree and the conductor decreased. At some specific distance between the tree and the conductor, the electric field around the conductor caused ionization in the air and generated an arc that caused short-circuiting. The distance between the tree and the conductor just before the arc was produced is the MVCD. The MVCD depends upon the voltage level: the greater the voltage level, the greater the MVCD, and vice versa. This distance could be measured easily with the help of a scale attached to the sliding mechanism. Before starting the experiment, at some specific voltage, the distance between the tree and the conductor was measured. When the conductor was energized and the platform moved upward by some distance, an arc was produced between the tree and the conductor. At this point (just before the arc was produced), the vegetation clearance distance could be measured by subtracting the distance traveled by the tree from the initial distance between the tree and conductor before the experiment was begun. At each voltage level, this MVCD had a different value. Figure 3 shows an arc produced between the conductor and the tree just after crossing the MVCD.

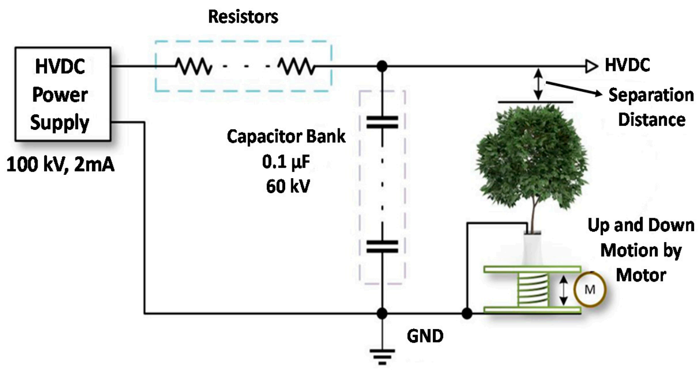

Figure 1. Experimental configuration.

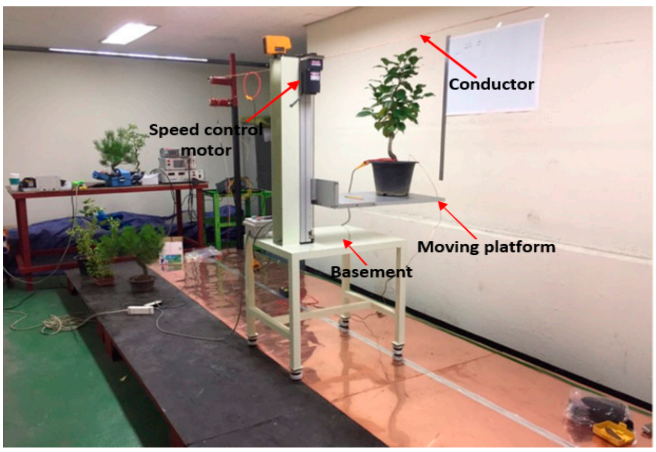

Figure 2. Experimental setup.

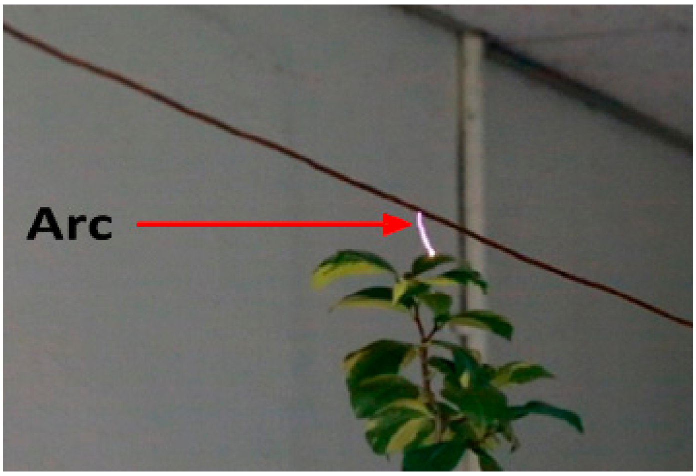

Figure 3. Arc between the conductor and the tree.

5. Experimental Results for MVCD

5.1. Experimental MVCD Values

The MVCD was measured using the procedure discussed above. Different MVCD values at different voltages are shown in Table 3. The graph of these MVCD values is shown in Figure 4.

Table 3. Experimental values of MVCD at different voltages.

Voltage (kV)	MVCD (m) Experiment	Voltage (kV)	MVCD (m) Experiment
2.5	0.001	32.5	0.022
5	0.003	35	0.025
7.5	0.005	37.5	0.027
10	0.006	40	0.031
12.5	0.007	42.5	0.033
15	0.008	45	0.035
17.5	0.01	47.5	0.038
20	0.012	50	0.041
22.5	0.013	52.5	0.042
25	0.015	55	0.046
27.5	0.017	57.5	0.049
30	0.019	60	0.052

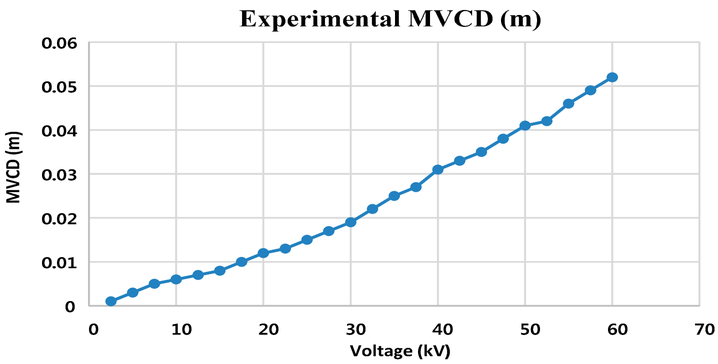

Figure 4. Experimental MVCD values at different voltages.

5.2. Comparison of Experimental MVCD, Experimental (Compensated) MVCD and MVCD from the Gallet Equation (for DC Voltage)

The Gallet equation results showed a significant deviation from the experimental results, as shown in Figure 5. However, when the experimental values of the MVCD were used with a correction factor of 1.8 (i.e., maximum switching or transient overvoltage factor [17,21]) to derive a compensated MVCD, the MVCD values became closer to the Gallet equation results (Figure 6). This shows the verification of the experiment.

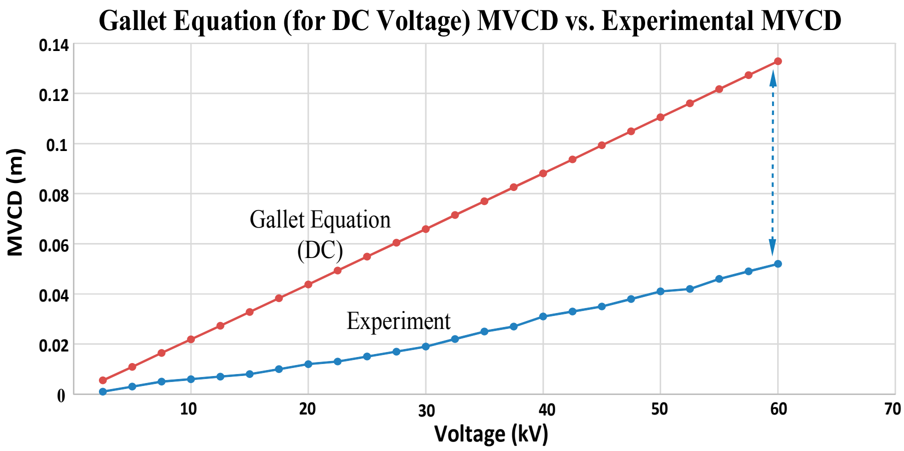

Figure 5. Experimental MVCD vs. Gallet MVCD.

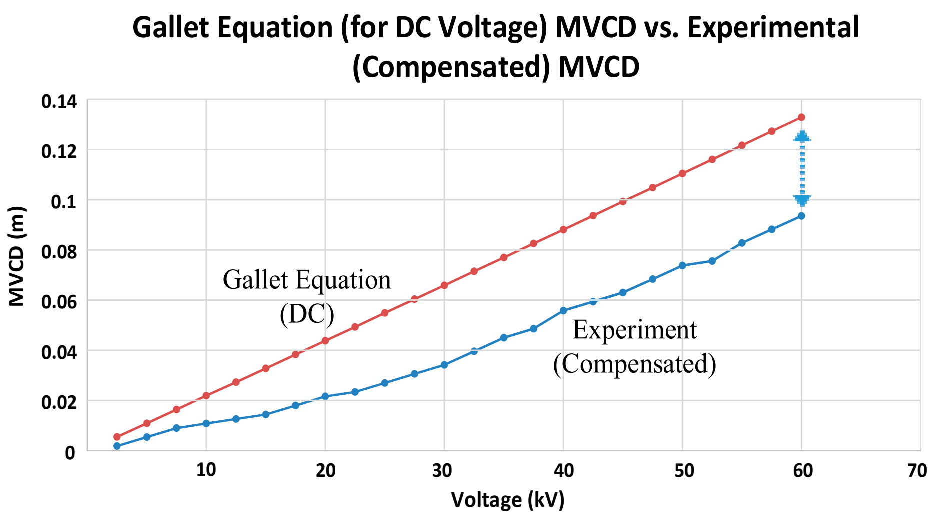

Figure 6. Experimental (Compensated) MVCD vs. Gallet MVCD.

5.3. Extended MVCD Results

Figure 7 shows the compensated experimental results up to 900 kV. As discussed above, the experimental MVCD values were determined up to 60 kV. These results were compensated and extended up to 900 kV. In this way, an equation satisfying these MVCD values at the voltage level from 100 kV to the voltage level of 900 kV is obtained. The equation is an exponential approximation as it showed the best curve fit:

$$y = 0.0007\, x^{1.1933} \tag{12}$$

In this equation, y represents the MVCD (m) and x represents DC voltage. Using this equation, the MVCD value at each level of voltage can be calculated.

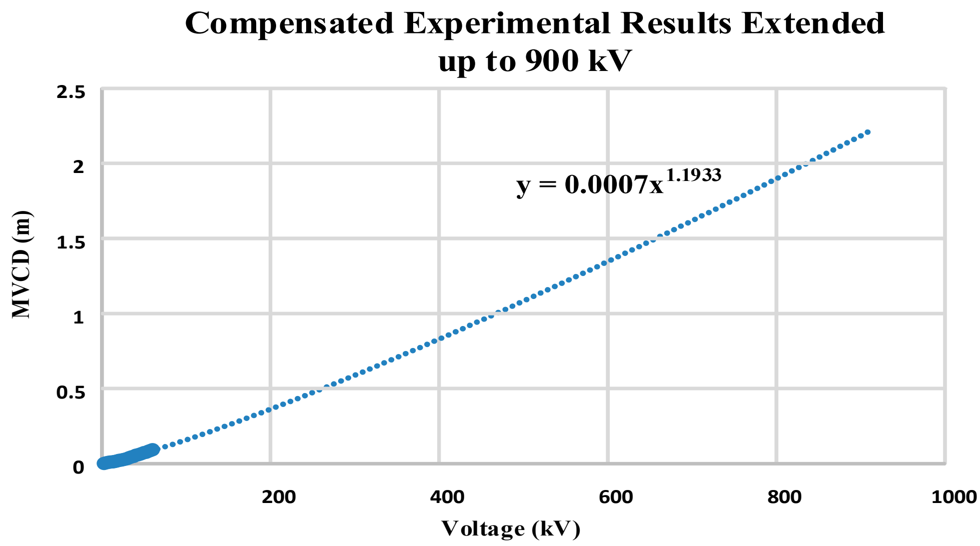

Figure 7. Compensated Experimental Results Extended up to 900 kV.

5.4. Comparison between the MVCD Results from the Gallet Equation for DC Voltage and Experimental (Compensated-Extended) Results

Table 4 shows the experimental (compensated-extended) MVCD and the MVCD from the Gallet equation at DC voltages. These table data for the compensated and extended experimental MVCD values are obtained from Equation (12). It can be seen from the table that the MVCD values are similar at each voltage level. This demonstrates verification of the MVCD values obtained from the Gallet equation for DC voltage with the help of the experiment.

The purpose of this work was to find the MVCD value at DC 500 kV. The table shows that the MVCD value of 1.16 m at 500 kV obtained from the experiment (compensated-extended) is very close to the MVCD value of 1.13 m obtained from the Gallet equation for DC voltage.

Table 4. Experimental (compensated-extended) MVCD values vs. MVCD values from the Gallet equation at different voltages.

Voltage (kV)	MVCD (m) from Experiment (Compensated-Extended Equation)	MVCD (m) from Gallet Equation for DC Voltage
100	0.17	0.22
200	0.39	0.45
300	0.63	0.67
400	0.89	0.90
500	1.16	1.13
600	1.45	1.36
700	1.74	1.58
800	2.04	1.80
900	2.34	2.03

6. Discussion and Conclusions

It is important to establish a minimum vegetation clearance distance (MVCD) in the case of HVDC transmission to avoid flashover between trees and transmission lines. Each country has its own parameters to determine this clearance distance. The Gallet equation is one of the most famous methods for the determination of MVCD, especially in the case of HVAC transmission. No significant work has previously been undertaken for the measurement of MVDC for HVDC transmission.

In the present work, an effort has been made to determine the MVCD in the case of HVDC transmission. This work dealt first with the determination of the MVCD by the Gallet equation in the case of HVAC transmission and the different factors that affect the MVCD. Using a conversion formula, any DC voltage value can be converted into an equivalent AC voltage value. The MVCD from the Gallet equation has been determined for both low and high DC voltages.

Experimental verification was also needed. An experiment was performed at DC voltages up to 60 kV. Thereafter, compensated results were obtained by using a correction factor. These results were extended up to 900 kV. An equation was obtained that was used to achieve the MVCD values at different DC voltage levels beyond those employed in the experiment.

Finally, a comparison between the results from the Gallet equation (for DC voltage) and the experimental (compensated-extended) results has been carried out. The MVCD results obtained from the Gallet equation for DC voltage have been verified by the experimental (compensated-extended) work, because the two sets of results have been shown to be very close to each other. At 500 kV, both the MVCD values were almost equal. For future work, the authors are planning modeling and simulations of this experiment.

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References

1. Moran, R. *Executioner's Current Thomas Edison, George Westinghouse, and the Invention of the Electric Chair, Chapter: The Battle of the Currents*; Vintage Books: New York, NY, USA, 2003.
2. Setreus, J.; Bertling, L. Introduction to HVDC technology for reliable electrical power systems. In Proceedings of the Probabilistic Methods Applied to Power Systems 2008 PMAPS the 10th International Conference, Rincon, Puerto Rico, 25–29 May 2008.
3. Wang, H.; Redfern, M.A. The advantages and disadvantages of using HVDC to interconnect AC networks. In Proceedings of the Universities Power Engineering 45th International Conference (UPEC), Cardiff, Wales, UK, 31 August–3 September 2010.
4. Barnes, M.; Van Hertem, D.; Teeuwsen, S.P.; Callavik, M. HVDC systems in smart grids. *Proc. IEEE.* **2017**, *105*, 2082–2098. [CrossRef]
5. Pourbeik, P.; Bahrman, M.; John, E.; Wong, W. Modern countermeasurus to blackouts. *IEEE Power Energy Mag.* **2006**, *4*, 36–45. [CrossRef]
6. Padiyar, K.R. *HVDC Power Transmission Systems: Technology and System Interactions*; New Age International: New Delhi, India, 1990.
7. Arrillaga, J.; Liu, Y.H.; Watson, N.R. *Flexible Power Transmission: The HVDC Options*; John Wiley & Sons: Hoboken, NJ, USA, 2007.
8. Paulinder, J. Operation and Control of HVDC Links Embedded in AC Systems. Ph.D. Thesis, Chalmers Tekniska Högsk, Gothenburg, Sweden, 2003.
9. Bahrman, M.P.; Johnson, B.K. The ABCs of HVDC transmission technologies. *IEEE Power Energy Mag.* **2007**, *5*, 32–44. [CrossRef]
10. Kamakshaiah, S.; Kamaraju, V. *HVDC Transmission*; TATA McGraw-Hill: New York, NY, USA, 2011.
11. Hong, A.; Dielectric Strength of Air. The Physics Factbook. 2000. Available online: https://hypertextbook.com/facts/2000/AliceHong.shtml (accessed on 29 September 2018).
12. Yu, Z.; Huang, K.; Zeng, R.; Gao, Z.; Li, M.; Liu, L.; Lou, B.; Ma, Q.; Wang, Z.; Zhang, B.; et al. Research on DC Electric Field Measurement Considering Ion Flow Near HVDC Transmission Line. In Proceedings of the 12th IET International Conference on AC and DC Power Transmission (ACDC 2016), Beijing, China, 28–29 May 2016.

13. Panicker, P.K. Ionization of Air by Corona Discharge—Aerodynamics Research Center. Master's Thesis, The University of Texas at Arlington, Arlington, TX, USA, 2003.
14. Motomura, T.; Hirao, M.; Nakamura, K.; Kikuchi, T. Development of the heliborne separation measuring system and its practical application. In Proceedings of the Transmission & Distribution Construction, Operation & Live-Line Maintenance ESMO'98 IEEE 8th International Conference, Orlando, FL, USA, 26–30 April 1998.
15. Kirkham, H. *Applicability of the "Gallet Equation" to the Vegetation Clearances of NERC Reliability Standard FAC-003-2*; Pacific Northwest National Laboratory: Oak Ridge, TN, USA, 2012.
16. Hileman, A.R. *Insulation Coordination for Power Systems*; CRC Press: Boca Raton, FL, USA, 1999.
17. The North American Electric Reliability Corporation Vegetation Management Standard Drafting Team. *Transmission Vegetation Management Standard FAC-003-2 Technical Reference*; North American Electric Reality Corporation: Princeton, NJ, USA, 2009.
18. 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]
19. *FAC-003-3 Minimum Vegetation Clearance Distances*; North American Electric Reliability Corporation: Atlanta, GA, USA, 2015.
20. Hill, H.L.; Capon, A.S.; Ratz, O.; Renner, P.E.; Schmidt, W.D. *Transmission line Reference Book HVDC to ±600 kV*; OSTI: Anderson, TN, USA, 1976.
21. *516-2003 IEEE Guide for Maintenance Methods on Energized Power Lines*; IEEE Std: Piscataway, NJ, USA, 2009.