NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

August 12, 2015

Ms. Kimberly D. Bose
Secretary
Federal Energy Regulatory Commission
888 First Street, NE
Washington, D.C. 20426

Re: Electric Power Research Institute 2015 Technical Report
Docket No. RM12-4-000

Dear Secretary Bose:

The North American Electric Reliability Corporation ("NERC")[1] hereby submits the 2015 Technical Report prepared by the Electric Power Research Institute entitled *Supplemental Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances ("MVCD"): Tests: Results and Analysis* ("EPRI Report"). This report explains testing that was performed to determine the switching impulse strength of the air gap between a conductor and natural trees to validate revision of the gap factor to 1.0 in order to determine the MCVD in the NERC FAC-003-2 Reliability Standard.

Also attached is a summary prepared by NERC staff of the EPRI Report. As explained in NERC's summary, NERC anticipates using the findings from the EPRI report to initiate a Standards Authorization Request to adjust the MVCD values in the FAC-003-2 standard. NERC staff anticipates that this work will be completed by the end of the first quarter 2016.

Should you have any questions, please do not hesitate to contact the undersigned.

---

[1] The Commission certified NERC as the electric reliability organization ("ERO") in accordance with Section 215 of the FPA on July 20, 2006. *N. Am. Elec. Reliability Corp.*, 116 FERC ¶ 61,062 (2006).

Respectfully submitted,

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CERTIFICATE OF SERVICE

I hereby certify that I have served a copy of the foregoing document upon all parties listed on the official service list compiled by the Secretary in this proceeding.

Dated at Washington, D.C. this 12th day of August, 2015.

/s/ Holly A. Hawkins
Holly A. Hawkins
Associate General Counsel for the North American
Electric Reliability Corporation

ELECTRIC POWER
RESEARCH INSTITUTE

Supplemental Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances (MVCD)

Tests: Results and Analysis

2015 TECHNICAL REPORT

Supplemental Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances (MVCD)

Tests: Results and Analysis

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3002006527
Final Report, June 2015

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Acknowledgments

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Supplemental Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances (MVCD): Tests: Results and Analysis. EPRI, Palo Alto, CA: 2015. 3002006527.

Product Description

Testing was performed to determine the switching impulse strength of the air gap between a conductor and natural trees to validate revision of the gap factor to 1.0 in order to determine the minimum vegetation clearance distance (MVCD) in North American Electric Reliability Corporation (NERC) Standard FAC 003-2. These tests complement those reported in EPRI's *Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances (MVCD): Test Results and Analysis* (3002006078, April 2015). The present report provides utilities, the North American Electric Reliability Corporation (NERC), and the Federal Energy Regulatory Commission (FERC) with the information necessary to validate the proposed revision of the gap factor used for MVCD calculations.

Background

In response to FERC Order No. 693, NERC submitted the reliability standard FAC-003-2, *Transmission Vegetation Management*. In the submittal, NERC proposed a methodology for calculating the MVCD based on the Gallet equation and the use of a gap factor of 1.3 pursuant to FAC-003-2.

On March 21, 2013, FERC issued its Final Rule of the *Revisions to Reliability Standard for Transmission Vegetation Management*. In this document, the NERC Reliability Standard FAC-003-2 was approved and NERC was directed "to conduct or contract testing to develop empirical data regarding the flashover distances between conductors and vegetation," and to use an approach based on "statistical analysis [that] would then evaluate the test results and provide empirical evidence to support an appropriate gap factor to be applied in calculating minimum clearance distances using the Gallet equation."

A research project was subsequently initiated to provide empirical evidence to support the selection of an appropriate gap factor that would be applied in calculating the MVCD using the Gallet equation. The results showed, however, that the values based on a gap factor of 1.3 are not conservative. Based on this finding, NERC issued an Industry Advisory (Alert ID: A-2015-05-14-01), which highlighted the anticipated adjustments utilizing a gap factor of 1.0 for the MVCD specified in NERC Reliability Standard FAC-003-3.

Objectives

To confirm, or if necessary, advise NERC of the adequacy of the revised gap factor (k_g) of 1.0 as a basis for the MVCD calculation using the method documented in NERC Reliability Standard FAC-003-3.

Approach

Switching impulse tests were designed and executed at EPRI's High-Voltage Laboratory in Lenox, Massachusetts. The goal of this testing was to determine the critical flashover voltage (CFO, U_{50}) for the revised MVCD applicable to a 230-kV system and a natural, vase-shaped tree for a tree-to-conductor distance calculated using a gap factor of 1.0. The gap factor (k_g) is calculated and compared against the 1.0 value proposed by FERC and NERC. Testing involved a range of tree canopy diameters in order to confirm that the choice of gap factor is acceptable for all tree diameters.

Results

This report provides a detailed description of the switching impulse tests performed on natural trees. Included is a description of the test setups, the procedure used, and test results. Based on the results of testing, the following conclusions may be drawn:

- Within the confines of the testing performed (resulting in a large confidence region), the gap factor of a conductor over a large flat top tree approaches that of a conductor-plane gap, which is k_g = 1.1.
- The results confirm the adequacy of using a gap factor (k_g) of 1.0 as a conservative basis for the calculation of MVCD according to the method documented in NERC Reliability Standard FAC-003-3.

Applications, Value, and Use

This research is performed to provide an empirical basis to verify the MVCD values in the NERC Reliability Standard FAC-003-3. It is expected that these results will be incorporated in the NERC writing process as part of a review of the present standard.

Keywords

Minimum vegetation clearance distance (MVCD)
Impulse testing
Flashover distance
Trees
Gap factor
Critical flashover voltage

Abstract

NERC proposed a methodology for calculating the minimum vegetation clearance distances (MVCD) based on the Gallet Equation and the use of a gap factor. EPRI's approach was to validate the gap factor used in the NERC standard using empirical evidence through switching impulse testing between trees and conductor bundles. The project pursued a statistically valid scientific approach.

These test results complement those reported in EPRI Report 3002006078, *Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances (MVCD): Test Results and Analysis*. The results were analyzed and compared against the value listed in the NERC FAC-003-3 Standard.

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Section 1: Introduction

Background

In response to FERC Order No. 693, NERC submitted the reliability standard FAC-003-2 (Transmission Vegetation Management) for Commission approval. In the submittal, NERC proposed a methodology for calculating the minimum vegetation clearance distances (MVCD) based on the Gallet Equation and the use of a gap factor described within FAC-003-2. The NERC Standard contained a table of minimum vegetation clearance distances (MVCD) using a gap factor equal to 1.3.

On March 21, 2013, FERC issued its Final Rule of the "Revisions to Reliability Standard for Transmission Vegetation Management[1]," in which NERC Reliability Standard FAC-003-2 was approved. In the approval Order, NERC was directed "to conduct or contract testing to develop empirical data regarding the flashover distances between conductors and vegetation," and to use an approach based on "statistical analysis [that] would then evaluate the test results and provide empirical evidence to support an appropriate gap factor to be applied in calculating minimum clearance distances using the Gallet equation."

NERC retained EPRI to conduct these empirical tests designed to evaluate the appropriate gap factor within the Gallet equation for determining MVCDs in NERC FAC-003-2. An overall three stage empirical testing plan was designed and executed, based on NERC oversight and industry subject matter experts as well as FERC observers that included a range of switching impulse tests to validate the gap factor.

The tests were performed at EPRI's Lenox High Voltage Laboratory in Lenox, Massachusetts from June 23 through September 2, 2014, and are documented in a written report [10]. The tests were all performed on MVCD distances based on a gap factor of 1.3. Based on the test results, and the detailed analysis thereof, NERC concluded that the proposed minimum vegetation clearance distances (MVCD), based on a gap factor of 1.3, should be increased and the corresponding gap factor reduced to a more conservative value of 1.0.

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[1] *Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances (MVCD): Test Results and Analysis* April, 2015 3002006078

Revisions to Reliability Standard for Transmission Vegetation Management, Order No. 777, 142 FERC 61,208 (2013).

More specifically, the 230 kV MVCD to a vase shaped natural tree, based on gaps and impulses calculated for a gap factor of 1.3, did not pass the withstand test performed at expected transient overvoltage level given in the MVCD FAC003-2. Photographs of the flashovers that occurred during the withstand test are shown in Figure 1-1.

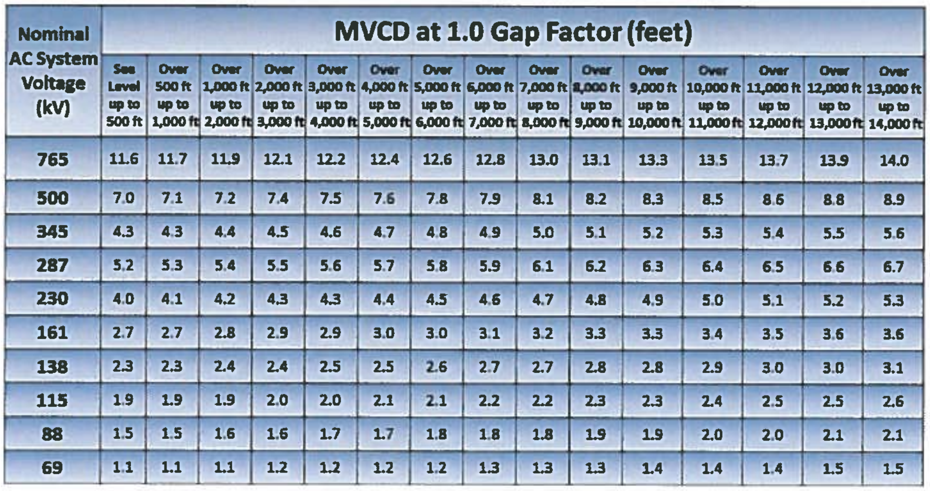
Figure 1-1
Flashovers to Vase, 230 kV, Vertical, Natural Vegetation

A series of communications and webinars were completed in early 2015, and an "Industry Advisory FAC-003-3 Minimum Vegetation Clearance" was issued in early May containing the revised MVCD tables (see Table 1-1) [11] based on a gap factor of 1.0.

NERC staff retained EPRI to perform these supplementary impulse tests to validate that a MVCD based on a gap factor of 1.0 is empirically able to statistically withstand the expected transient overvoltage level provided in FAC-003-2. The testing plan used the configuration that yielded the lowest withstand strength in the original testing, which was the vase shaped tree at 230 kV in a vertical configuration. The tests were performed in the spring of 2015, when the trees at the Lenox facility are in full leaf bloom.

This document is intended to document the empirical testing plan and results for validating the adjusted gap factor of 1.0 at the Lenox facility to confirm the appropriate MVCD values within the FAC-003 standard. Accordingly this document supplements the earlier testing conducted by EPRI.

Table 1-1
Table of MVCD values at a 1.0 gap factor (in U.S. customary units) [11]



Nominal AC System Voltage (kV)	MVCD at 1.0 Gap Factor (feet)														
	Sea Level up to 500 ft	Over 500 ft up to 1,000 ft	Over 1,000 ft up to 2,000 ft	Over 2,000 ft up to 3,000 ft	Over 3,000 ft up to 4,000 ft	Over 4,000 ft up to 5,000 ft	Over 5,000 ft up to 6,000 ft	Over 6,000 ft up to 7,000 ft	Over 7,000 ft up to 8,000 ft	Over 8,000 ft up to 9,000 ft	Over 9,000 ft up to 10,000 ft	Over 10,000 ft up to 11,000 ft	Over 11,000 ft up to 12,000 ft	Over 12,000 ft up to 13,000 ft	Over 13,000 ft up to 14,000 ft
765	11.6	11.7	11.9	12.1	12.2	12.4	12.6	12.8	13.0	13.1	13.3	13.5	13.7	13.9	14.0
500	7.0	7.1	7.2	7.4	7.5	7.6	7.8	7.9	8.1	8.2	8.3	8.5	8.6	8.8	8.9
345	4.3	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6
287	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.1	6.2	6.3	6.4	6.5	6.6	6.7
230	4.0	4.1	4.2	4.3	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.3
161	2.7	2.7	2.8	2.9	2.9	3.0	3.0	3.1	3.2	3.3	3.3	3.4	3.5	3.6	3.6
138	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.7	2.7	2.8	2.8	2.9	3.0	3.0	3.1
115	1.9	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.5	2.5	2.6
88	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.1
69	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	1.5

Objective

The objective of this project is to confirm, or if necessary, advise NERC of the adequacy of the gap factor (kg) of 1.0 as a basis for the calculation of minimum vegetation clearance distances (MVCD) utilizing the method documented in NERC Reliability Standard FAC-003-3.

Approach

Switching impulse testing was performed to determine the critical flashover voltage (CFO, U_{50}) for the revised MVCD applicable to a 230 kV system and a natural, vase-shaped tree, for a tree to conductor distance calculated using a gap factor of 1.0. The gap factor (k_g) is calculated and compared against the 1.0 value proposed by FERC and NERC. A range of canopy diameters was tested to confirm that the choice of gap factor is acceptable for all tree diameters.

Overview of Report

The test methodology is described in Chapter 2 and the test results are presented and compared in Chapter 3. The conclusions are summarized in Chapter 4.

Section 2: Switching Impulse Testing

Objective

Switching Impulse tests have been performed to determine the flashover strength of a representative conductor-to-natural vegetation gap configuration to validate the revision of the gap factor used in determining minimum vegetation clearance distances (MVCD). The critical flashover voltage (CFO) was determined for each configuration.

Approach

Switching impulse testing was performed on natural trees under the Lenox test line to determine the critical flashover voltage (CFO) of the air gap between a conductor and natural trees. The distance between the conductor and the tree was calculated using a gap factor of 1.0. The gap factor (k_g) was then calculated based on test results and compared against the value utilized in the revised MVCD calculation [11].

Test location and connections to test object

Switching impulse tests were performed on a natural, vase-shaped tree, and a conductor to tree distance applicable to a Nominal System Voltage of 230 kV [11]. For these tests a tree with an appropriate shape was selected from the specimens available at the test location under the Lenox UHV span, across the river from the impulse generator as shown in Figure 2-1. The test location was selected to replicate the withstand tests performed during the 2014 minimum vegetation clearance tests [10].

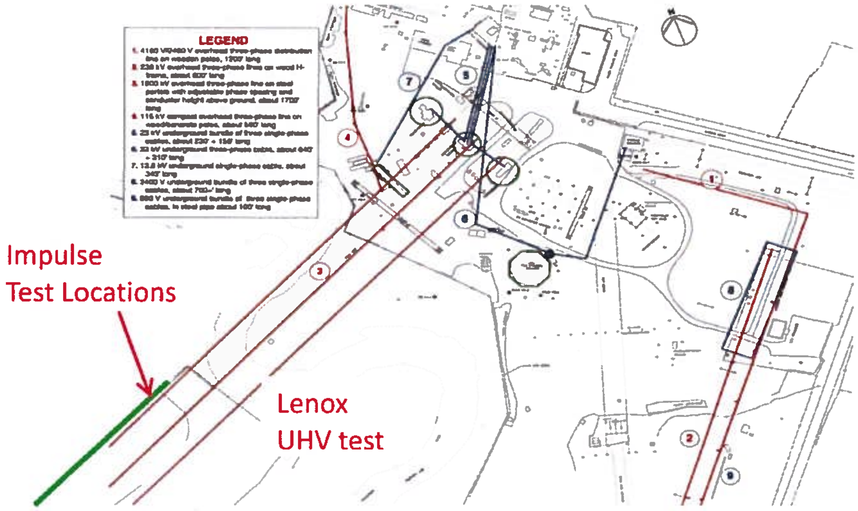


Figure 2-1
Test Location for Natural Trees

Test setup

The test ***setup*** was the same as that previously used for the withstand tests during the 2014 minimum vegetation clearance distance tests [10]. The tree was tested without the addition of a metal rod or wooden dowel to serve as ground electrode. A general view of the test setup is shown in Figure 2-2.

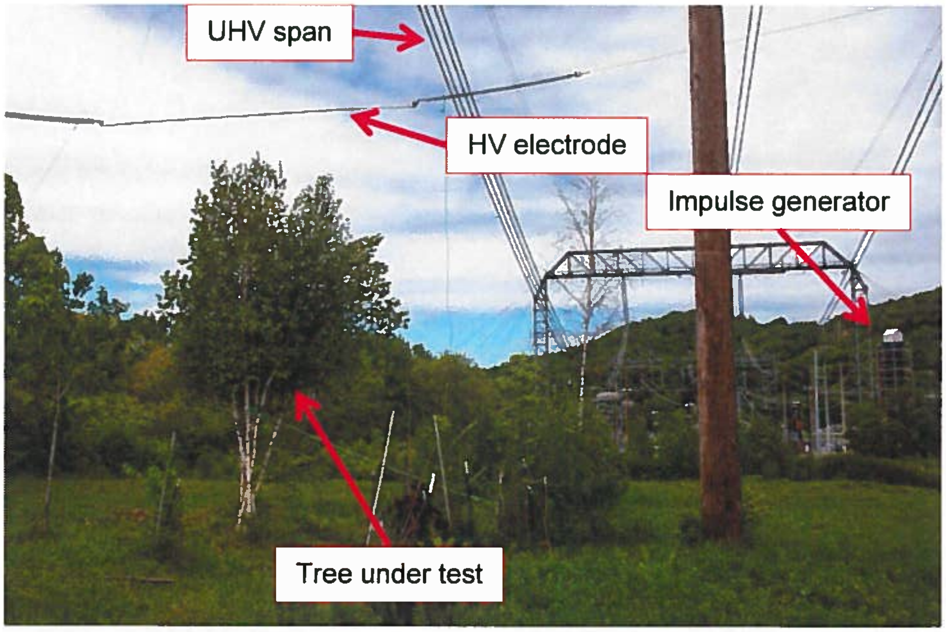


Figure 2-2
Photograph of test set up. Vertical gap distances were set using a winch.

Energized electrode definition:

The energized electrode was an aluminum tube representing a typical phase conductor of a 230 kV system voltage level. The characteristics and dimensions of the aluminum tube were the same as was used for the 2014 minimum vegetation clearance tests and are given in Table 2-1.

Table 2-1
Phase conductor definition for the supplemental minimum vegetation clearance tests

	230 kV
Bundle (# conductors per phase)	1
Bundle spacing	n/a
Bundle height above ground (NESC)	Minimum 25.2 feet
Conductor size (Outer Diameter)	1.0 in

To minimize interference with the electric field profile between the simulated conductor and the tree, the connection from the impulse generator to the electrode were made as far as practical from the Artificial Vegetation Configuration as shown conceptually in Figure 2-3. The length of the aluminum tube was chosen to be sufficient to minimize any end effects.

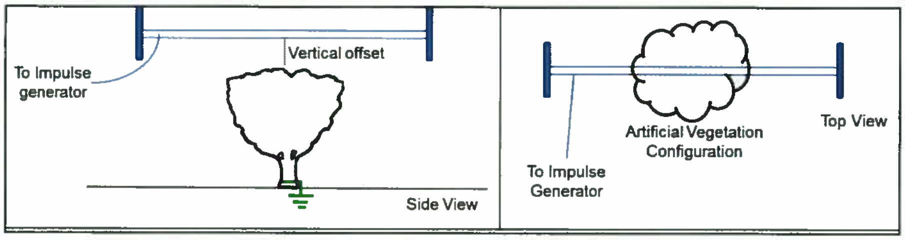


Figure 2-3
Connections to the conductor for the supplemental minimum vegetation clearance tests simulating the Grow-in condition (i.e. vertical gap to artificial vegetation)

Gap Size

The shortest distance from the bottom/side of the conductor to the top of the tree crown is defined in Table 2-2.

Table 2-2
Gap sizes for the supplemental minimum vegetation clearance tests.

	230 kV
Gap (feet)	4.2
Gap (m)	1.30

Note: This distance was obtained from the "Industry Advisory FAC-003-3 Minimum Vegetation Clearance Distances": Table 1 – Table of MVCD value at a 1.0 gap factor (in U.S. customary units) [11]. The values "Over 1,000 ft. up to 2,000 ft." applies as the Lenox test site is 1200 feet above sea level

Test circuit

Applicable Standards

IEEE Std. 4 – 2013

Wave shape

The switching impulse tests have been performed with the critical wave shape defined for the 2014 MVCD tests [10]. The following wave shape parameters apply:

- Time to peak (T_p): 100 µs ± 20%
- Virtual time to half-value (T_2): 2500 µs ± 60%

The definition of these wave parameters are presented in Figure 2-4.

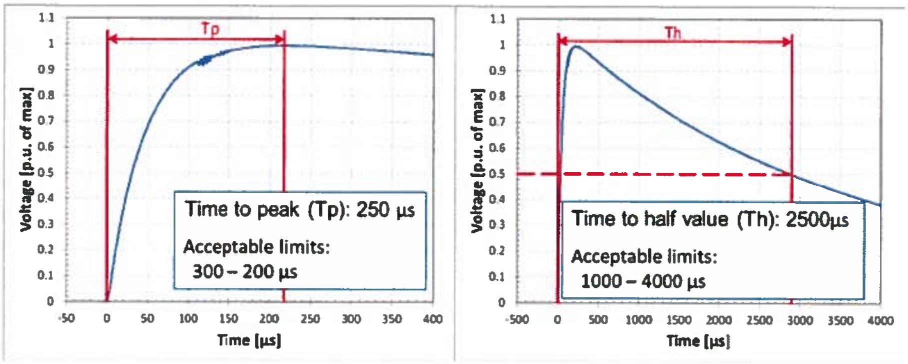
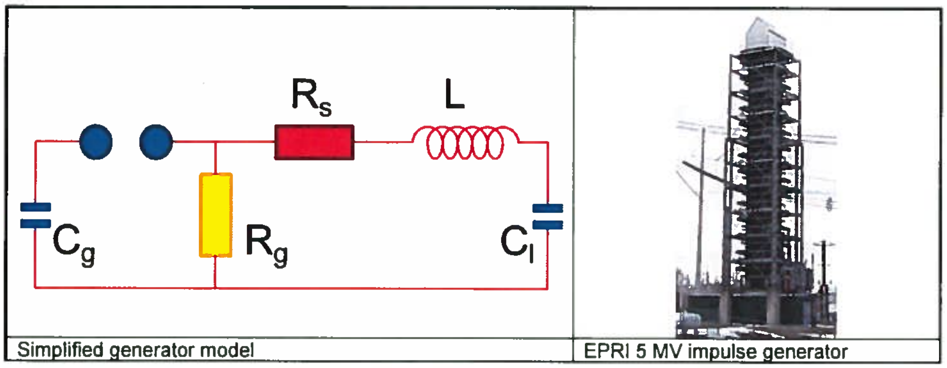


Figure 2-4
Definition of the Standard Switching Impulse as per IEEE Standard 4.

Marx Generator setup

The lightning impulse tests have been performed with the EPRI 28 stage conventional Marx generator circuit as shown in Figure 2-5. It has the following internal parameters:

- Capacitance per stage: 0.5 µF
- Self-inductance per stage: 3.64 µH
- Internal resistance per stage: 0.2 Ω



Simplified generator model

EPRI 5 MV impulse generator

Figure 2-5
The test circuit for Lightning Impulse Tests

The following circuit component values have been selected for the impulse generator to produce required lightning impulse wave shapes:

- Number of Stages: 17
- Generator capacitance C_g: 29.4 nF (0.5 µF per stage)
- Assumed Capacitance for test setup C_l: 6.2 nF
- Front shaping resistance R_s: 3.42 kΩ
- Discharge resistance R_g: 105 kΩ

Test Ambient Conditions

The tests were performed under dry conditions. This means:

- No precipitation of any kind is allowed.
- Relative humidity less than 80%
- The ratio of the absolute humidity (h) to the relative air density (δ) shall not exceed 15 g/m^3.
- The ambient temperature shall be between 0°C (32°F) and 40°C (104°F).
- Wind: The tree top was stabilized with rope approximating an inverted V so that the relative distance between electrode and tree top did not vary significantly during windy conditions.

Test methodology

The critical flashover voltage (CFO, or U_{50}), was determined by the Up-Down method (UDM). For the UDM at least 20 impulses shall be applied including the first flashover. The applied voltage was increased by one step after each withstand and lowered by one step after each flashover. The step size was selected so that there was at least 4 voltage levels between full withstand and complete flashover.

During the test the development of the CFO estimate was monitored to determine if the flashover characteristics change during the test.

Evaluation of the results

The outcome of each test was analyzed in accordance with IEEE Std. 4, to determine estimates for the critical flashover voltage. This is done by fitting a normal distribution function through the test data points with the method of maximum likelihood. The fitted normal distribution function is described in terms of the 50% flashover voltage (Critical Flashover Voltage, CFO) and standard deviation. This method also provides an estimation of the 95% confidence interval, which is the interval for which there is a 95% probability that the true CFO will fall within. As such it gives an indication of the reliability of the CFO estimate.

The gap factor (k_g) was determined by expressing the CFO of the MVCD [CFO_{SOV} *(MVCD)*] relative to the flashover strength of a rod-plane gap [CFO_{SOV} *(Rod-Plane)*] with the same dimensions as follows.

$$CFO_{SOV}\,(MVCD) = k_g \times CFO_{SOV}(Rod\text{-}Plane) \qquad Eq.\ 2\text{-}1$$

Where the CFO_{SOV} *(Rod-Plane)* is calculated with the Gallet Equation:

$$CFO_{SOV}(Rod\text{-}Plane) = 3400 / (1+8 / S) \qquad Eq.\ 2\text{-}2$$

Where S is the gap size in meter [m].

Test specimens

The 2014 tests revealed the tree size (i.e. diameter of the crown) as an important parameter that may influence the flashover strength of the vegetation clearance. The results showed that wider trees resulted in lower flashover values. Furthermore, based on these results it was expected that the effect of diameter on flashover value would become less for very wide tree sizes as the gap factor approach that of a conductor-plane – i.e. $k_g = 1.1$. What constitutes a wide tree is related to the size of the air gap. The largest tree tested during 2014 (for the 230 kV, grow-in, vase shaped tree) had a ratio of tree diameter to gap length of 3.2:1. The test on this tree resulted in a gap factor in the range 1.08 to 1.11, which indicates that the diameter effect may have already saturated at this diameter to gap ratio.

For this testing, which is aimed at confirming the adequacy of the gap factor (k_g) of 1.0 as a basis for the calculation of MVCDs, it was thus important to perform the test on a large enough tree that the diameter effect no longer plays a significant role in withstand strength. The test on such a large tree would result in the lowest gap factor for that tree-conductor configuration. Considering the 2014 results it was decided to perform the verification tests on two tree sizes:

1. A "large tree" with a ratio of diameter to the gap length in the order of 4:1 For the gap size of 50" (4.2 ft.) this means that the diameter of the tree should be about 200"
2. A "small tree" with a diameter which is at least 50" less than that of the large tree. Based on a large tree diameter of 200", the diameter of small tree should be no larger than 150"

The supplemental tests were performed on a Natural, Vase-shaped tree, which was selected from the trees available for this purpose at the Lenox facility. This tree is shown in Figure 2-6 on the left. Additional freshly cut trees were lashed to the selected tree to achieve the required tree shape and size. This tree was also trimmed by cutting back the outgrowth to produce the characteristic "flat top" of a vase shaped tree. The modified tree, subjected to testing, is shown in Figure 2-6 on the right. Furthermore, steps were taken to ensure that all the trees used to build up the test specimen were bonded together electrically with copper wires and screws.

Before Modification

After Modification

Figure 2-6
Vase Shaped Tree selected for testing.

As shown in Table 3-1, the switching impulse tests were performed on two tree diameters. The large tree, with a target diameter of 200", comprised a total of 7 trees lashed together. For the smaller diameter tree, two of the additional trees were removed. The dimensions of test object "as tested" were measured before and after the test and are presented in Figure 2-7.

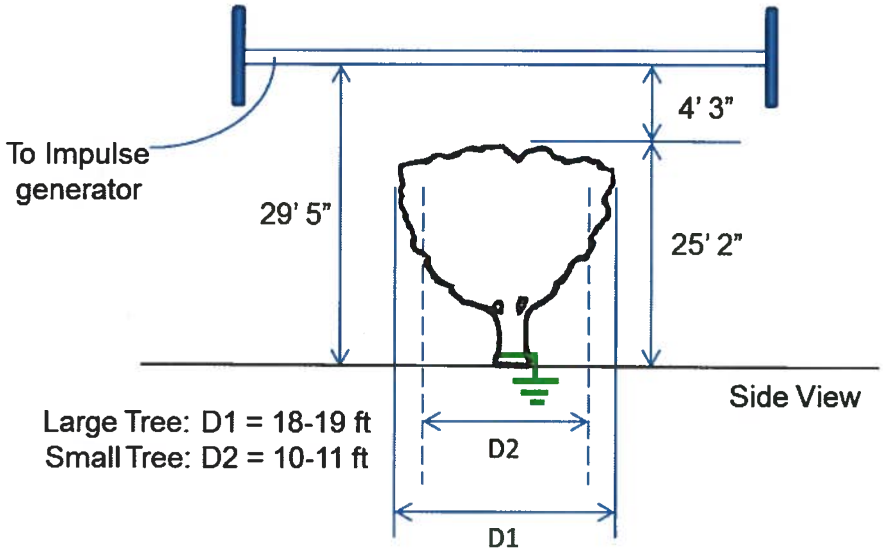


Figure 2-7
Actual test object dimensions and gap size

Section 3: Results

Overview of the tests performed

Testing was performed on May 21, 2015 as specified in Table 3-1.

Table 3-1
Overview of the switching impulse tests performed on natural trees.

Test #	Impulse	Voltage level (kV)	Gap configuration	Polarity	Diameter of tree top
1	Switching Impulse (≈100/2500 µs)	230 kV Nominal Voltage	Vase-shape tree	Positive	Large Tree D1 ≈ 220″
2			Grow-In (Vertical)		Small Tree D2 ≈ 125″

Wave shape

The following wave shape parameters were measured during testing:

- Time to peak (T_p): 107 µs
- Virtual time to half-value (T_2): 2470 µs

The applied impulse wave shape conformed therefore to the imposed requirements set out in Chapter 2. The definition of these wave parameters are again as presented in Figure 2-5.

Large Diameter Vase Shape: D1= 220″

The test sequence applied to the large diameter tree is presented in Figure 3-1. During this test a total of 36 impulses were applied to the test object. The first part of this test, comprising 15 impulses with increasing amplitude, is aimed at finding the voltage amplitude necessary for flashover. The next 21 impulses (from the first flashover onwards) form the up-down test. The data of these impulses are used to estimate the CFO (U_{50}).

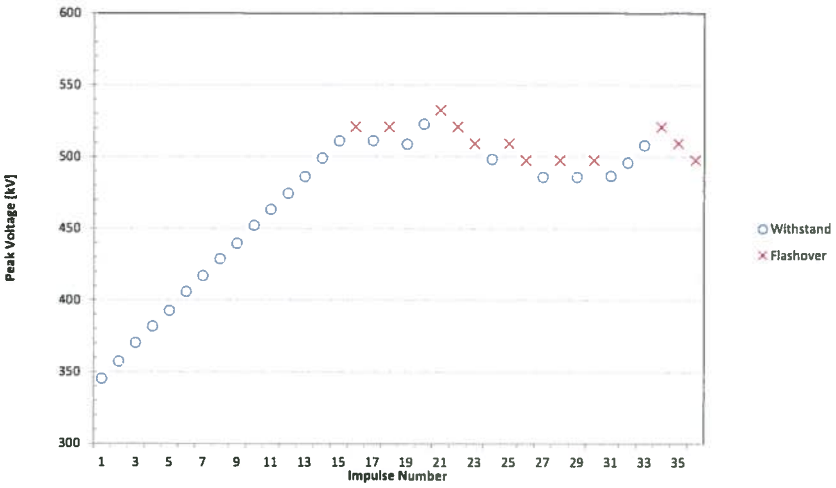


Figure 3-1
Test sequence for the up-down test on the large diameter tree

The results from the up-down test were analyzed with the method of maximum likelihood to estimate the critical flashover voltage (also named the V_{50}; or the voltage with a 50% flashover probability), and the standard deviation of the flashover characteristic. The 95% confidence interval of these parameters was also calculated.

The test results are presented in Table 3-2. Both the un-corrected and corrected values are presented. The corrected values refer to the flashover values which are corrected for atmospheric conditions as defined in IEEE Std. 4. The results are also presented graphically in Figure 3-2. Direct observation of impulse withstands and flash-overs indicate that the flashover characteristics do not change during this test.

The CFO, at sea-level, is therefore determined as 518 kV. This CFO is now compared to that of a rod-plane gap with the same gap length of 4.25 feet (1.30 m) which according to the Gallet equation is a CFO of 475 kV. The gap factor is therefore calculated as $k_g = 518/475 = 1.09$.

Photographs were taken of each flashover to the tree. The discharge channels were however not sufficiently luminous to be registered by the digital cameras used. Flashover was recognized by the sound and by the change in the impulse wave shape. The impulse wave shape associated with flashover had a notably shorter time to half value – on average $T_2 \approx 1000$ µs instead of the 2470 µs registered when no flashover occurred. This behavior is similar to that observed during the MVCD withstand tests performed in 2014[10].

This testing did not result in any visible damage to the tree.

Table 3-2
Estimate of the CFO of the test on the large diameter tree.

Porcelain Disc		**As tested**		**Corrected to Standard conditions**	
		U_{50} [kV]	**Std. dev.[kV]**	**U_{50} [kV]**	**Std. dev.[kV]**
STD Impulse	95% Conf. Min	477	8	488	9
	Estimate	**506**	**19**	**518**	**20**
	95% Conf. Max	534	-*	547	-

Note: * Too few data points were available to estimate the upper 95% confidence limit for the standard deviation.

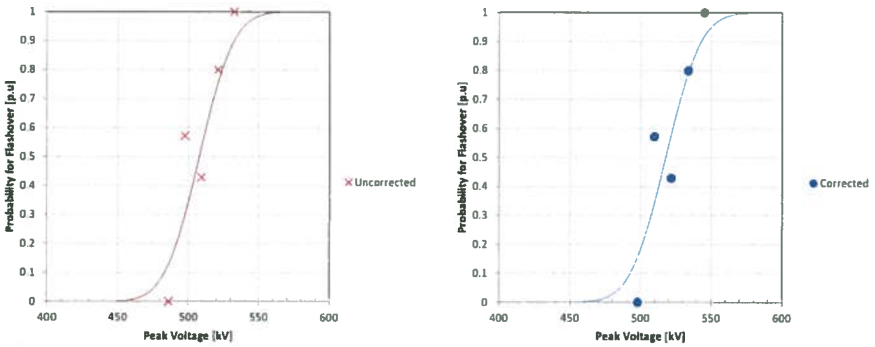


Figure 3-2
Test on the large diameter tree: Probability for Flashover as a Function of the Applied Switching Impulse Voltage.

Small Diameter Vase Shape: D2 = 125"

The test sequence applied to the small diameter tree is presented in Figure 3-3. During this test a total of 25 impulses were applied to the test object. The first part of this test, comprising 5 impulses with increasing amplitude, is aimed at finding the voltage amplitude necessary for flashover. The next 20 impulses (from the first flashover onwards) form the up-down test. The data of these impulses are used to estimate the CFO (U_{50}).

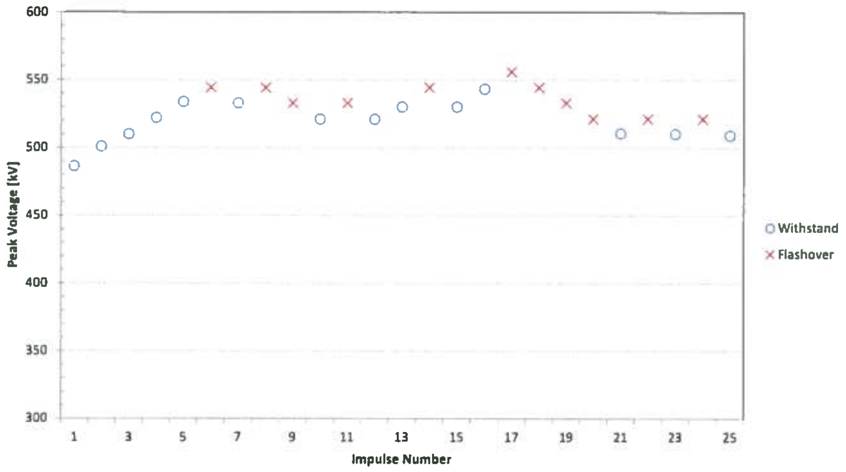


Figure 3-3
Test sequence for the up-down test on the small diameter tree

The results from the multiple level test were analyzed with the method of maximum likelihood to estimate the critical flashover voltage (also named the V_{50}; or the voltage with a 50% flashover probability), and the standard deviation of the flashover characteristic. The 95% confidence interval of these parameters was also calculated. The test results are presented in Table 3-3. Both the un-corrected and corrected values are presented. The corrected values refer to the flashover values which are corrected for atmospheric conditions as defined in IEEE Std. 4. The results are also presented graphically in Figure 3-2. Direct observation of impulse withstands and flash-overs indicate that the flashover characteristics do not change during this test.

Table 3-3
Estimate of the CFO of the test on the small diameter tree.

Porcelain Disc		**As tested**		**Corrected to Standard conditions**	
		U_{50} [kV]	**Std. dev.[kV]**	**U_{50} [kV]**	**Std. dev.[kV]**
STD Impulse	95% Conf. Min	507	7	523	8
	Estimate	**530**	**17**	**546**	**17**
	95% Conf. Max	556	-*	574	-*

Note: * Too few data points were available to estimate the upper 95% confidence limit for the standard deviation.

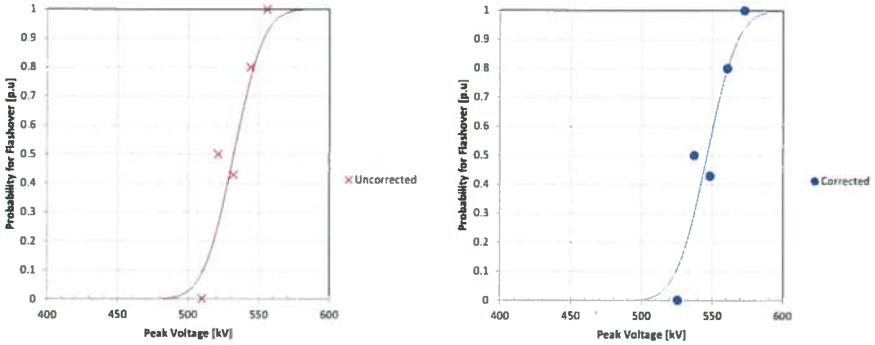


Figure 3-4
Test on the small diameter tree: Probability for Flashover as a Function of the Applied Switching Impulse Voltage.

The CFO, at sea-level, is therefore determined as 546 kV. This CFO is now compared to that of a rod-plane gap with the same gap length of 4.25 feet (1.30 m) which according to the Gallet equation should have a CFO of 475 kV. The gap factor is therefore calculated as $k_g = 546/475 = 1.15$.

The flashovers to the small diameter tree also did not have sufficient luminosity to be photographed and as before, flashover was recognized by the sound and the change in the impulse wave. Also during this test series no visible damage to the tree was observed.

After all tests were completed, a series of additional impulses were applied to the tree to determine if there was a change in flashover behavior at higher impulse amplitudes. It was found that visible discharges started occurring for voltage amplitude of 788 kV and above. An example of such a discharge is presented in Figure 3-5. While still faint, a discharge could be seen across the air gap and following along the tree stem to the ground – see detail photos on the right in Figure 3-5.

After these discharges a clear flashover path was observed on the tree stem. An example is shown in Figure 3-6.

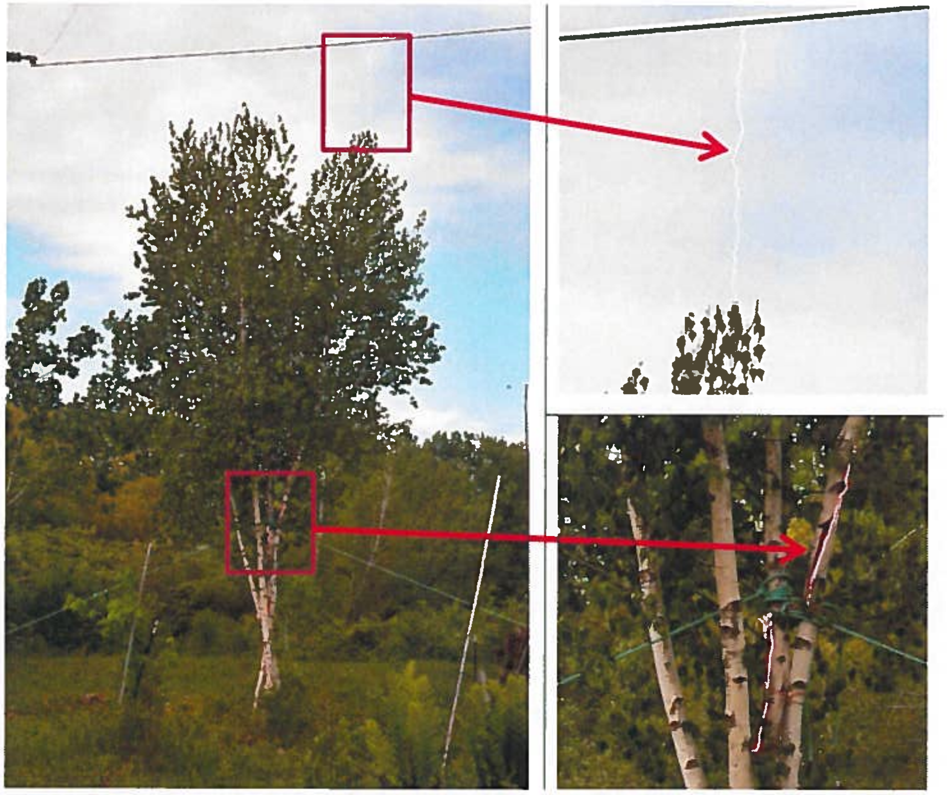


Figure 3-5
An example of a visible flashover to the tree that occurs at impulse voltages with amplitude of over 780 kV.

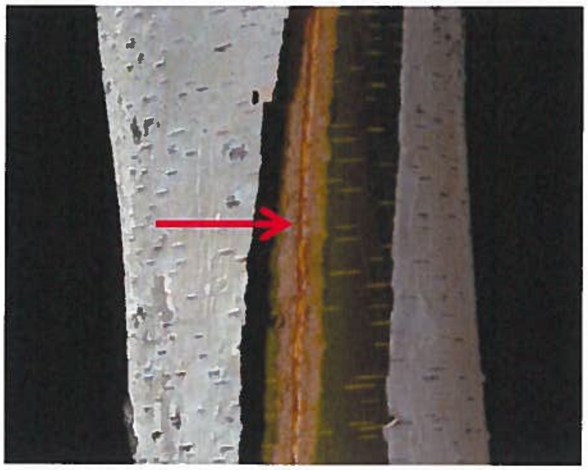


Figure 3-6
An example of the flashover track along the tree stem.

Comparison of results

For comparison purposes the test results. Corrected to standard atmospheric conditions are presented side by side in Table 3-4. From these values it can be seen that the flashover strength of the gap to the small diameter tree was 5.4% over that of the large diameter tree. The results are also shown graphically in Figure 3-7.

Table 3-4
Comparison of the flashover strength under switching impulse of two tree diameters: 230 kV Vertical Configuration, Vase Shaped Tree.

		Large Diameter	**Small Diameter**
Canopy Diameter	Feet	18-19	10-11
Critical flashover Voltage	[kV]	518	546
95% Confidence interval of the CFO estimate	[kV]	488 - 547	523 - 574
Normalized Standard Deviation*	[%]	4	3
Gap Factor	[p.u.]	1.09	1.15

Note: * a typical standard deviation for switching impulse tests is 6%.

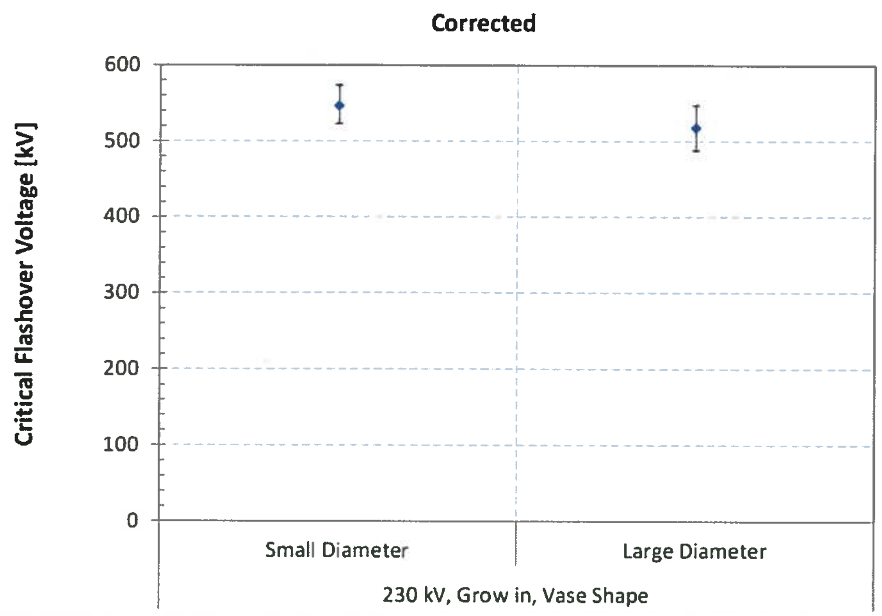


Figure 3-7
Comparison of the flashover strength under switching impulse of two tree diameters: 230 kV Vertical Configuration, Vase Shaped Tree. (The 95% confidence intervals of the CFO estimates are indicated by the error bars)

In Figure 3-8 a comparison is made of the 2014 and 2015 results for the 230 kV; grow in – vase shaped tree. This comparison is made on the basis of the ratio of the canopy diameter to the gap length because different gap lengths were tested in 2014 and 2015. The 95% confidence intervals for each gap factor are also shown to indicate the reliability of the estimated CFO values.

This comparison indicates that the gap factor stabilizes around 1.1 for ratios of the canopy diameter to the gap length greater than 3. It may therefore be concluded that the gap factor of a conductor over a wide tree approaches that of a conductor-plane gap, which is $k_g = 1.1$. This conclusion is made with some reservation considering the relatively few tests performed that resulted in a relatively large confidence region (i.e. 1.03 to 1.15). A conservative approach would be, therefore, to base the MVCD calculation on a gap factor which falls below the confidence region.

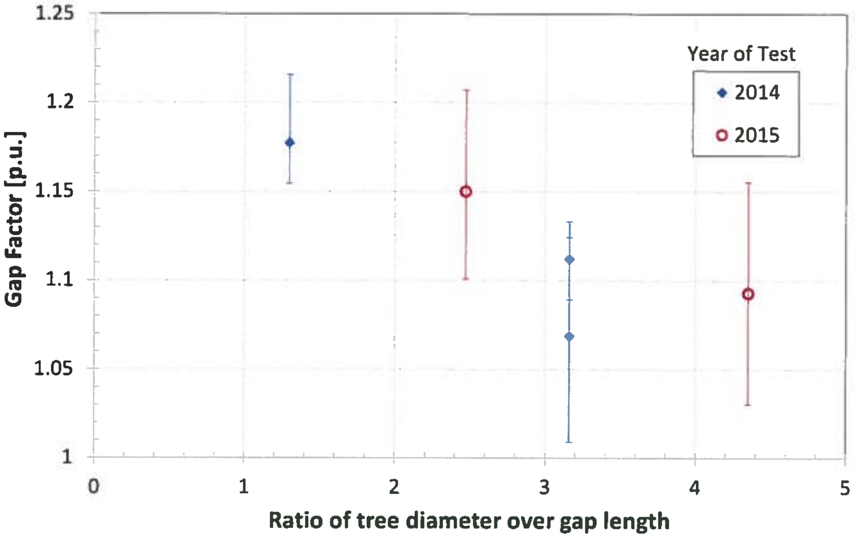


Figure 3-8
Comparison of the flashover strength under switching impulse for various tree diameters: 230 kV Vertical Configuration, Vase Shaped Tree. (The 95% confidence intervals of the CFO estimates are indicated by the error bars)

Based on these results presented above it can be confirmed that a gap factor (k_g) of 1.0 is an adequate basis for the calculation of minimum vegetation clearance distances (MVCD) according to the method documented in NERC Reliability Standard FAC-003-3.

Section 4: Conclusions

Switching impulse testing was performed to determine the critical flashover voltage (CFO, U_{50}) and associated gap factors for the revised MVCD applicable to a 230 kV system and a natural, vase-shaped tree with a tree to conductor distance based on the NERC approach based on a Gap factor of 1.0. A range of tree diameters were tested to confirm that the choice of gap factor is acceptable for all tree diameters.

Based on the results the following conclusions may be made:

- Within the confines of the testing performed (resulting in a large confidence region), it is concluded that the gap factor of a conductor over a large flat top tree approaches that of a conductor-plane gap, which is $k_g = 1.1$.
- The results confirm the adequacy of using a gap factor (k_g) of 1.0 as a conservative basis for the calculation of minimum vegetation clearance distances (MVCD) according to the method documented in NERC Reliability Standard FAC-003-2.

Section 5: References

[1] IEEE Standard for High-Voltage Testing Techniques IEEE Std. 4-2013 (Revision of IEEE Std. 4-1995) , 2013 , Page(s): 1 - 213

[2] IEEE Standard for the Measurement of Audible Noise From Overhead Transmission Lines, IEEE Std. 656-1992 , 1992

[3] IEC International Standard, Overhead lines - Requirements and tests for fittings, IEC 61284 ed2.0, 1997-09-17.

[4] EPRI, AC Transmission Line Reference Book – 200 kV and Above, Third Edition, EPRI, Palo Alto, CA: 2005. 1011974.

[5] FERC Ruling 777 FAC-003-2

[6] FAC-003-2 Compliance Filing

[7] Transmission Vegetation Management Standard FAC-003-2, Technical Reference 093011

[8] Applicability of the "Gallet Equation" to the Vegetation Clearances of NERC Reliability Standard FAC-003-2, PNNL-21220, 4/23/2012

[9] Transmission Vegetation Management Standard FAC-003-3: Transmission Vegetation Management.

[10] Testing to Confirm or Refine Gap Factor Utilized in Calculation of Minimum Vegetation Clearance Distances (MVCD) - Test Results and Analysis, EPRI, Palo Alto, CA: 2014. #3002006078.

[11] Industry Advisory FAC-003-3 Minimum Vegetation Clearance Distances

Program:

Transmission and Substations

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FAC-003-3 Minimum Vegetation Clearance Distances

August 4, 2015

Executive Summary

In Order No. 777,[1] the Federal Energy Regulatory Commission (FERC) directed NERC to provide empirical data validating the gap factor for flashover distances between conductors and vegetation used in the Gallet equation to calculate Minimum Vegetation Clearance Distances (MVCDs) in NERC Reliability Standard FAC-003-2. In the order, FERC directed NERC to submit: (1) a schedule for testing; (2) the scope of work; (3) funding solutions; and (4) a deadline for submitting a final report on the test results to FERC, along with interim reports if a multiyear study is conducted. NERC contracted the Electric Power Research Institute (EPRI) and performed a collaborative research project to complete the work. NERC submitted a compliance filing on July 12, 2013,[2] which FERC accepted on September 4, 2013.[3]

In January 2014, NERC formed an advisory group to develop the scope of work for the project. This team of subject matter experts assisted in developing the test plan, which included monitoring the testing and analyzing the test results to be provided in a final report. The advisory team was comprised of NERC staff, arborists, and industry members with wide-ranging expertise in transmission engineering, insulator characteristics, and vegetation management. The project's scope of work and the detailed test plan were finalized in March 2014.

The testing project commenced in April 2014 and continued through October 2014. EPRI completed the prescribed tests to validate the gap factor applied in the Gallet equation. NERC filed an informational filing with FERC on July 31, 2014,[4] that contained the results of the testing work completed to date. The initial analysis, containing preliminary conclusions and recommendations, concluded in early 2015. Based on the preliminary results, the gap factor used in the Gallet equation required changing from 1.3 to 1.0, which would increase the MVCD values compared to those specified in the existing standard.

NERC, through EPRI, performed additional tests in 2015 to finalize the gap-factor verification and issued an industry advisory alert in May 2015. This final report includes the final gap-factor testing results that will be used to initiate a focused Standard Authorization Request (SAR) to adjust the MVCD values in NERC Reliability Standard FAC-003-3.

Test Plan

The primary objective of the testing project was the determination of the appropriate gap factor in the Gallet equation. The gap factor is a multiplier that adjusts the MVCD for different configurations of

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[1] *Revisions to Reliability Standard for Transmission Vegetation Management*, Order No. 777, 142 FERC ¶ 61,208 (2013).
[2] Compliance Filing of NERC, Docket No. RM12-4-000 (Jul. 12, 2013).
[3] *N. Am. Elec. Reliability Corp.*, Docket No. RM12-4-001 (Sept. 4, 2013) (delegated letter order).
[4] Informational Filing of NERC, Docket Nos. RM12-4-000 and RM12-4-001 (Jul. 31, 2014).

vegetation and conductors (i.e., conductor-to-vegetation gap configurations) to avoid flashover. A lower gap factor correlates with a higher MVCD.

NERC and EPRI designed a scope of work and detailed test plan for the project that recognized the complex nature of the research. There are a number of variables to consider, including vegetation type, health of the vegetation, condition of the root system and soil, moisture levels, altitude, humidity, and other atmospheric factors. Sufficient empirical data must be gathered to statistically validate the gap factor specified in NERC Reliability Standard FAC-003-3. The testing of the conductor-to-vegetation gap configurations involved selecting representative vegetation geometries, transmission line voltages, and conductor configurations to determine the probability of a flashover occurrence.

Vegetation species vary both regionally and by site type. The test was designed to cover the range of vegetation shapes and types expected in and around transmission rights-of-way for all NERC Regional Entities. It was important to test various vegetation shapes, as they produce varying influences on the electric field between a transmission line conductor and vegetation. These influences were found to affect the probability of flashover between a conductor and vegetation and must be considered to determine the minimum value of the gap factor for a given conductor-to-vegetation gap configuration. The different types of vegetation were organized into three basic shapes, as illustrated in Figure 1:

- Pyramidal – Conifers (e.g., spruce, fir, pine) that have a well-defined central leader.
- Columnar – Deciduous trees that may exhibit less central dominance, commonly referred to as having a random form.
- Broadly vase-shaped – Involves larger trees with crowns that have been maintained by pruning. This is produced by the inability to remove trees within the conductor zone. The crown form would be asymmetrical or perhaps even "flat-topped."

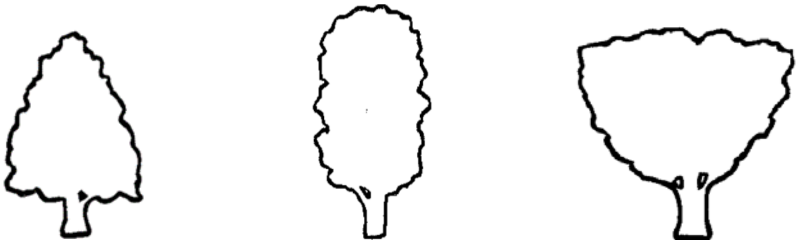

Figure 1: Vegetation Shapes Tested for Vertical Conductor-to-Vegetation Gaps – Pyramidal, Columnar, and Vase

The physical arrangements of both the vegetation and transmission line conductors were also considered when determining the types of conductor-to-vegetation gap configurations that were tested. Encroachment between vegetation and transmission lines could occur vertically (from below) or horizontally (from the side), as illustrated in Figure 2. Both vertical and horizontal conductor-to-vegetation gap configurations were incorporated into the test plan. All three vegetation shapes were tested in the vertical conductor-to-vegetation gap configuration, since they may produce varying electric field influences between a conductor and vegetation, as noted above.

Figure 2: Vertical (Grow-in) and Horizontal (Blow-in) Conductor-to-Vegetation Gap Configurations

Concerning horizontal conductor-to-vegetation gap configurations, vegetation shape varies based on maintenance practices. When viewed from the side, maintained vegetation appears planar in shape. However, vegetation that has not been maintained may have a less-consistent appearance, with branches that protrude out toward a transmission line. The horizontal conductor-to-vegetation gap configurations were tested for both columnar geometry (i.e., maintained look) and modified columnar form of vegetation that simulates a branch protruding toward a transmission line, as illustrated in Figure 3.

Figure 3: Vegetation Shapes Tested for Horizontal Conductor-to-Vegetation Gaps – Branch Protruding Toward Conductor and Columnar

The resulting conductor-to-vegetation gap configurations were used to demonstrate that the gap factor for the representative vegetation (artificial vegetation) represented a conservative estimate of the gap factor for natural vegetation. The artificial vegetation replicated the full crown of a recently harvested tree (including stems, branches, twigs, and leaves) with the permittivity[5] of natural vegetation. The crown of the harvested tree was pruned to represent the particular vegetation shapes for a given system voltage and conductor-to-vegetation gap configuration. The artificial vegetation also included a grounded metal center rod extending through to the crown. The purpose of the metal center rod was to avoid changes to the electrical characteristics of the vegetation tested and to obtain repeatable, statistically valid switching impulse test measurements. Artificial vegetation testing was performed for nominal voltages of 230 kV, 345 kV, 500 kV, and 765 kV. Testing was completed using conductor bundles that represented transmission line

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[5] The ability of a material to permit or maintain an electric field across its body, thereby making it susceptible to electrical breakdown.

construction used at each of the tested voltages (see conductor bundle shown in Figure 4). A sufficient number of test impulses at each voltage level were conducted to produce scientifically and statistically valid conclusions about the critical flashover (CFO) voltage.

The gap factors of the representative conductor-to-vegetation gap configurations were determined by testing for CFO, using positive-polarity switching impulse waveforms[6] as specified by IEEE Standard 4, High-Voltage Testing Techniques.[7] The switching impulse waveform that yielded the highest probability of flashover for the range of conductor-to-vegetation gap sizes was selected for use in testing.

Positive-polarity switching impulses were selected for testing, as they typically create the highest voltage stress at the conductor and yield the lowest values of CFO for an air gap similar to the conductor-to-vegetation gap configurations.[8] EPRI was able to demonstrate that positive-polarity switching impulses resulted in breakdown voltages that were approximately 100 kV lower than the negative-polarity switching impulses applied, proving that positive-polarity switching impulses would yield the most conservative values of CFO. The CFO values obtained during testing were used to calculate the withstand voltages based on the statistically valid methods in IEEE Standard 4, which were used to determine an appropriate gap factor.

In the second phase of testing, the conductor-to-vegetation gap configuration and voltage combination that yielded the lowest gap factor was retested with a wooden electrode at least one meter in length at the end of the grounded metal center rod to simulate a tree branch within the crown. The conductor-to-vegetation gap spacing and statistical testing methods used during the metal electrode tests were the same as for the wooden electrode tests. These tests were performed to validate that the switching impulse strength of a gap between an energized conductor and a wooden electrode was greater than that of an identical gap between an energized conductor and a metal electrode. This configuration behaved more like that of natural vegetation, from a flashover voltage perspective.

Finally, the conductor-to-vegetation gap configurations and voltage combinations that yielded the lowest gap factors based on the aforementioned tests were tested using natural vegetation (third phase of testing). The voltage withstand values calculated were used to statistically verify that the gap factor determined for the artificial vegetation tests represented a conservative estimate of the gap factor for natural vegetation.

Preliminary Results of Scheduled Testing

During the first phase of testing, combinations of representative artificial vegetation, conductor-to-vegetation gap configurations, and system voltages were tested as shown in Figure 4. For both configurations of conductor-to-vegetation gaps, the lowest statistically observed gap factors were at a system voltage of 230 kV. In the vertical conductor-to-vegetation gap configuration, a gap factor of 1.15

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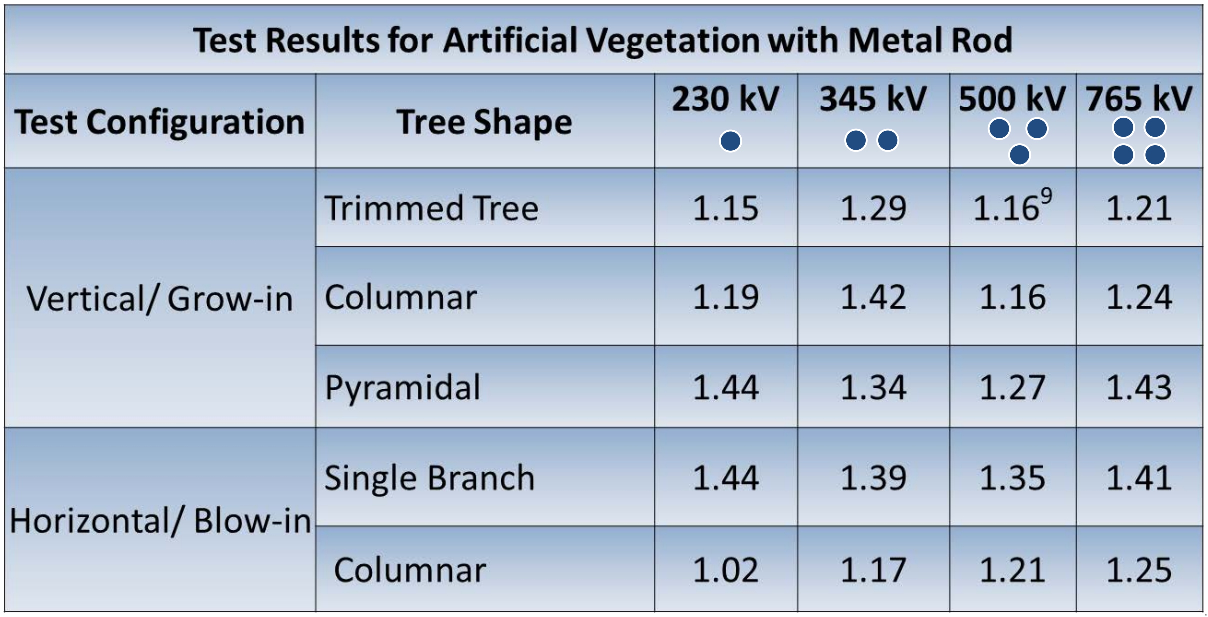
[6] As noted in the *Transmission Vegetation Management Standard FAC-003-2 Technical Reference*, MVCD is determined using the maximum expected switching surge impulse, not a lightning impulse. *See Transmission Vegetation Management Standard FAC-003-2 Technical* Reference at 7, *available at* http://www.nerc.com/pa/Stand/Project%20200707%20Transmission%20Vegetation%20Management/Transmission_Veg_Man_Standard_FAC-003-2_Technical_Ref_093011.pdf.

[7] *IEEE Standard for High-Voltage Testing Techniques*, IEEE Standard 4, 2013.

[8] *IEEE Guide for the Application of Insulation Coordination*, IEEE Standard 1313.2, p. 13, 1999.

was observed when testing a trimmed tree at 230 kV. In the case of the horizontal conductor-to-vegetation gap configuration, a gap factor of 1.02 was observed when testing a columnar tree at 230 kV. The 1.02 gap factor was also the lowest gap factor determined during the first phase of testing. Consequently, the horizontal conductor-to-vegetation gap configuration for a 230 kV system voltage and columnar tree were selected for completion of the second phase of testing. It was noted that the tree shapes that provided the lowest gap factors appeared planar from the perspective of the conductor in both conductor-to-vegetation gap configurations tested.



Test Results for Artificial Vegetation with Metal Rod

Test Configuration	Tree Shape	230 kV ●	345 kV ● ●	500 kV ● ● ●	765 kV ● ● ● ●
Vertical/ Grow-in	Trimmed Tree	1.15	1.29	1.16[9]	1.21
	Columnar	1.19	1.42	1.16	1.24
	Pyramidal	1.44	1.34	1.27	1.43
Horizontal/ Blow-in	Single Branch	1.44	1.39	1.35	1.41
	Columnar	1.02	1.17	1.21	1.25

Figure 4: Gap Factors that Resulted from Testing Representative Conductor-to-Vegetation Gap Configurations at Tested Voltages

In the second phase of testing, substitution of the metal center rod with equivalently sized and wetted wooden dowels resulted in a gap factor of 1.22 when testing a horizontal conductor-to-vegetation gap configuration and columnar-shaped tree at a system voltage of 230 kV, as shown in Figure 5. This demonstrated that the first phase of testing produced conservative results for setting an appropriate gap factor for natural vegetation.

Finally, the third phase involved retesting the two configurations that yielded the lowest gap factors in the first phase of testing, but with the artificial vegetation replaced by natural vegetation that was planted at the EPRI Lenox Test Facility. The horizontal conductor-to-vegetation gap and columnar-shaped tree configuration yielded a gap factor of 1.23. This finding indicated that the method employed for testing the artificial vegetation was consistent with the results obtained when testing natural vegetation (i.e., only a 0.01 difference between the gap factor determined for natural vegetation and the equivalent artificial

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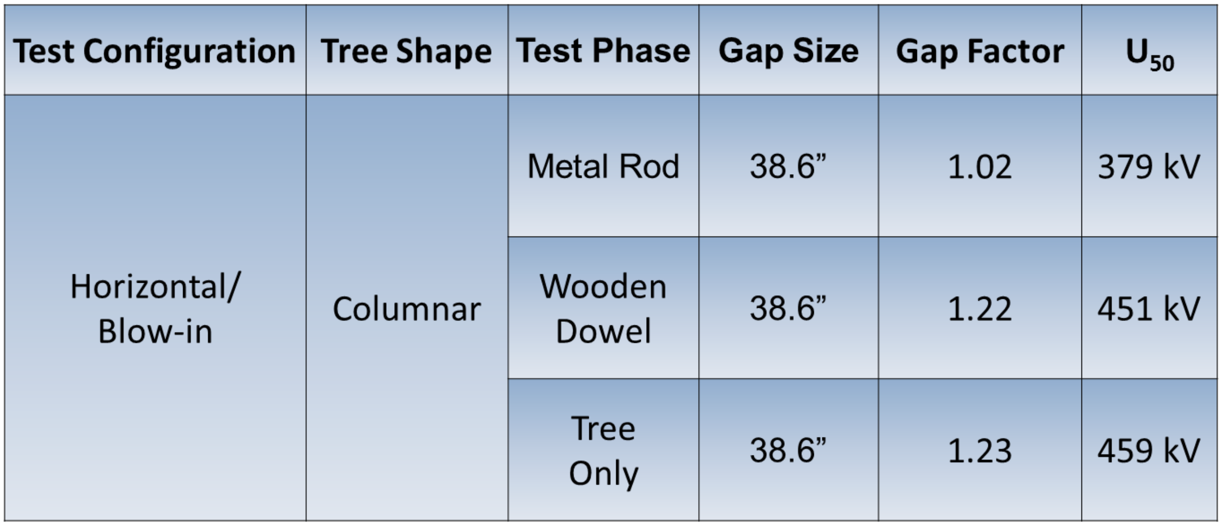
[9] The geometry and orientation of the conductor bundle in relation to the vegetation being tested, for vertical conductor-to-vegetation gaps, influenced perturbation of the electric field and the dielectric strength of the conductor-to-vegetation gap being tested. As such, the single-conductor 230 kV and the lower conductor in the 500 kV conductor bundle arrangements coupled with the vegetation in a manner that resulted in lower gap factors for these configurations.

vegetation/wooden dowel configuration tested in the second phase of testing). Therefore, NERC and EPRI concluded that the test method was practical for determining the appropriate gap factor for use in setting MVCDs for Bulk Electric System transmission lines.

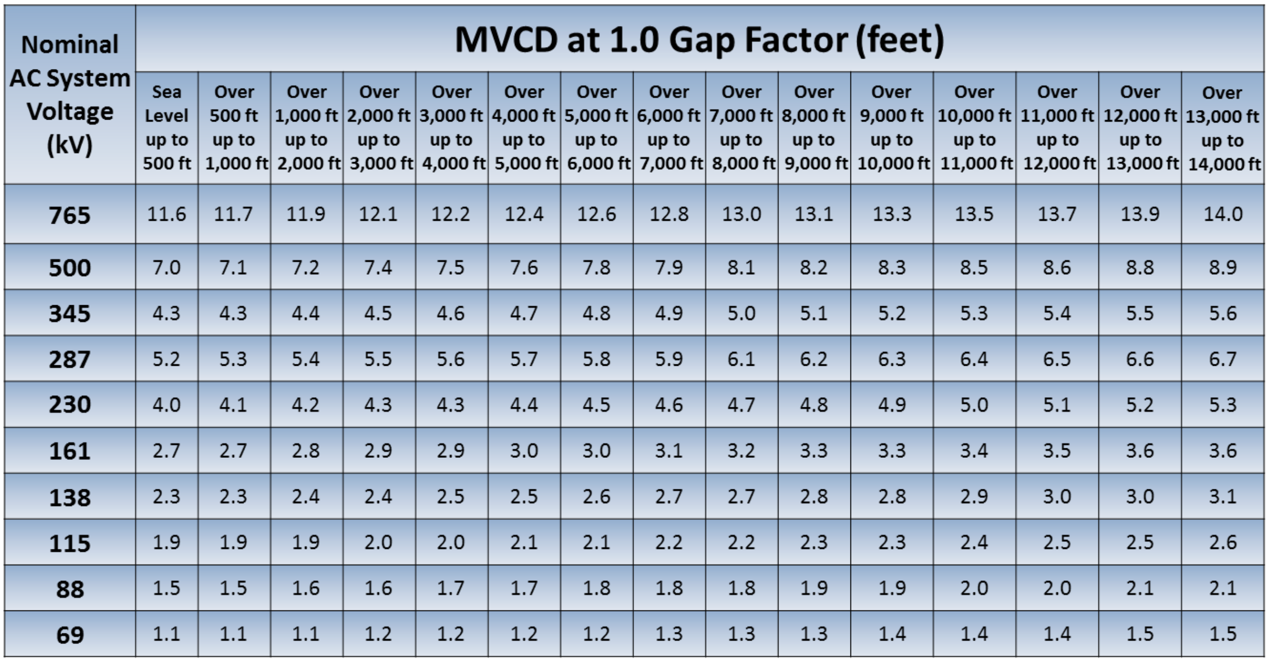
Testing of a second configuration consisting of a vertical conductor-to-vegetation gap and trimmed tree was also conducted using the original test plan for a 1.3 gap factor. Analysis of the testing revealed the need to conduct additional tests with the vertical conductor-to-vegetation gap set for the lower gap factor. Therefore, NERC and EPRI conducted additional tests to verify the gap factor for this configuration in May 2015.



Test Configuration	Tree Shape	Test Phase	Gap Size	Gap Factor	U_{50}
Horizontal/ Blow-in	Columnar	Metal Rod	38.6”	1.02	379 kV
		Wooden Dowel	38.6”	1.22	451 kV
		Tree Only	38.6”	1.23	459 kV

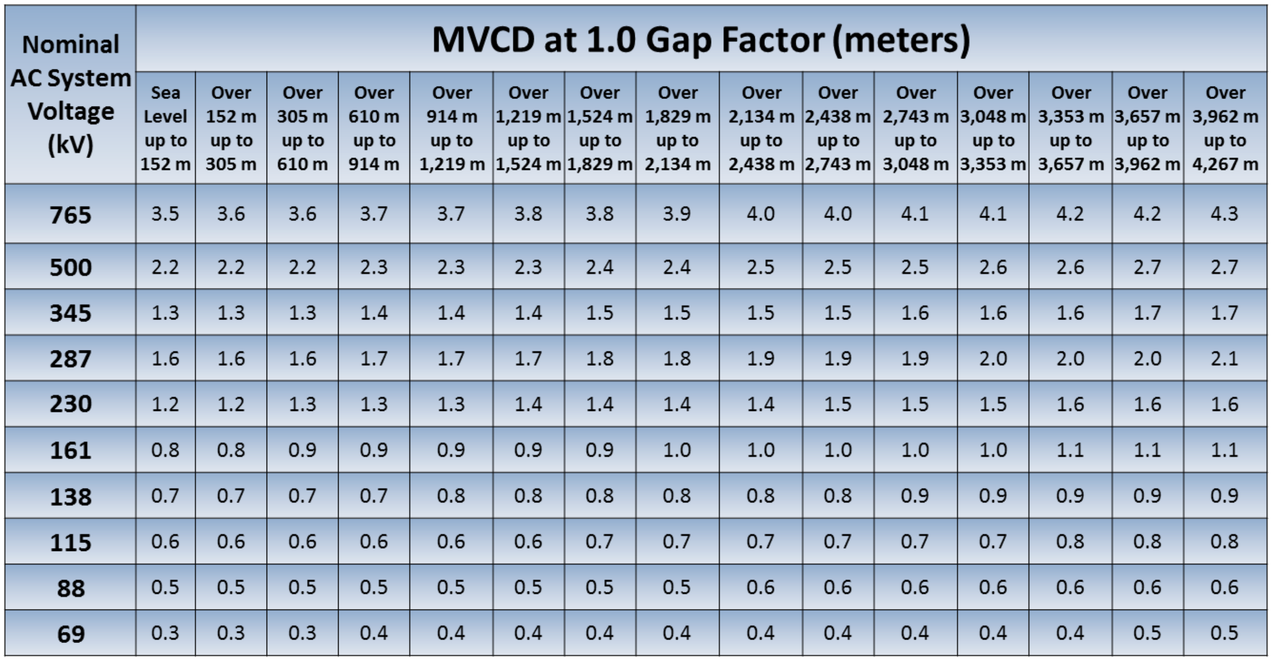
Figure 5: Test Results – Horizontal Conductor-to-Vegetation Gap Configuration, Columnar Tree Shape, and Setup for a System Voltage of 230 kV

Based on the final testing results and findings, NERC has determined that the current gap factor of 1.3 used in the Gallet equation should be adjusted to a value of 1.0. This will result in increased MVCD values for all alternating current system voltages identified in Table 2 of Reliability Standard FAC-003-3. The adjusted MVCD values, reflecting the anticipated 1.0 gap factor, appear in Figures 6 and 7.



Nominal AC System Voltage (kV)	MVCD at 1.0 Gap Factor (feet)														
	Sea Level up to 500 ft	Over 500 ft up to 1,000 ft	Over 1,000 ft up to 2,000 ft	Over 2,000 ft up to 3,000 ft	Over 3,000 ft up to 4,000 ft	Over 4,000 ft up to 5,000 ft	Over 5,000 ft up to 6,000 ft	Over 6,000 ft up to 7,000 ft	Over 7,000 ft up to 8,000 ft	Over 8,000 ft up to 9,000 ft	Over 9,000 ft up to 10,000 ft	Over 10,000 ft up to 11,000 ft	Over 11,000 ft up to 12,000 ft	Over 12,000 ft up to 13,000 ft	Over 13,000 ft up to 14,000 ft
765	11.6	11.7	11.9	12.1	12.2	12.4	12.6	12.8	13.0	13.1	13.3	13.5	13.7	13.9	14.0
500	7.0	7.1	7.2	7.4	7.5	7.6	7.8	7.9	8.1	8.2	8.3	8.5	8.6	8.8	8.9
345	4.3	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6
287	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.1	6.2	6.3	6.4	6.5	6.6	6.7
230	4.0	4.1	4.2	4.3	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.3
161	2.7	2.7	2.8	2.9	2.9	3.0	3.0	3.1	3.2	3.3	3.3	3.4	3.5	3.6	3.6
138	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.7	2.7	2.8	2.8	2.9	3.0	3.0	3.1
115	1.9	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.5	2.5	2.6
88	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.1
69	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	1.5

Figure 6: Table of MVCD Values at a 1.0 Gap Factor (in U.S. Customary Units)



Nominal AC System Voltage (kV)	MVCD at 1.0 Gap Factor (meters)														
	Sea Level up to 152 m	Over 152 m up to 305 m	Over 305 m up to 610 m	Over 610 m up to 914 m	Over 914 m up to 1,219 m	Over 1,219 m up to 1,524 m	Over 1,524 m up to 1,829 m	Over 1,829 m up to 2,134 m	Over 2,134 m up to 2,438 m	Over 2,438 m up to 2,743 m	Over 2,743 m up to 3,048 m	Over 3,048 m up to 3,353 m	Over 3,353 m up to 3,657 m	Over 3,657 m up to 3,962 m	Over 3,962 m up to 4,267 m
765	3.5	3.6	3.6	3.7	3.7	3.8	3.8	3.9	4.0	4.0	4.1	4.1	4.2	4.2	4.3
500	2.2	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.5	2.5	2.5	2.6	2.6	2.7	2.7
345	1.3	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.7	1.7
287	1.6	1.6	1.6	1.7	1.7	1.7	1.8	1.8	1.9	1.9	1.9	2.0	2.0	2.0	2.1
230	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.6
161	0.8	0.8	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1
138	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9
115	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8
88	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
69	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5

Figure 7: Table of MVCD Values at a 1.0 Gap Factor (in Metric Units)