

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. NERC will file a final report with FERC that includes the final gap-factor testing results and will initiate a focused Standard Authorization Request (SAR) to adjust the MVCD values in NERC Reliability Standard FAC-003-3.

Test Plan

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).

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 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.”

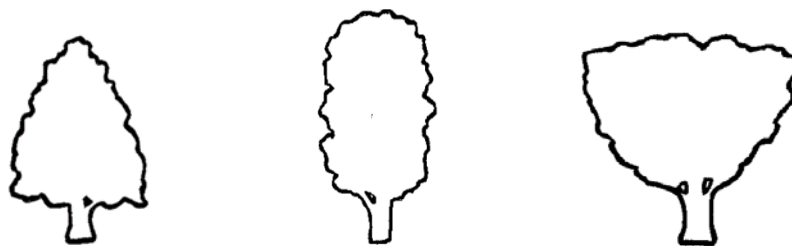


Figure 1: Vegetation Shapes Tested for Vertical Conductor-to-Vegetation Gaps – Pyramidal, Columnar, and Vase

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 permittivity⁵ 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

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

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 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 waveforms⁶ 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

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_FA_C-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.

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 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

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.

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 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)