

DESIGN AND APPLICATION OF AERIAL SYSTEMS USING INSULATED AND COVERED WIRE AND CABLE

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I. ABSTRACT

Insulated and covered wires and cables have been used in aerial applications for over fifty years. Despite this long history, the design, application and operation of these different types of conductor constructions are frequently misunderstood and confused with one another.

Utilities have increasing needs for greater reliability and higher quality of service, growing concerns over electromagnetic fields, increased difficulty in obtaining right-of-way and tree trimming, and difficulty in maintaining clearances in congested areas. These challenges have resulted in expanded interest in using covered or insulated cables in aerial systems. This paper (a) describes the differences between the constructions, (b) answers questions, concerns and misconceptions about these aerial designs, and (c) ranks the performance of each relative to desired attributes. A logical system for classifying covered wire and cable is proposed.

II. INTRODUCTION

The term *covered wire* is a generic term used to describe any wire or conductor with a covering, without limitation as to the thickness or properties or the covering. *Weatherproof wire*, *tree wire* and *spacer cable* are three forms of covered conductor. Fully shielded aerial cable is considered as insulated, rather than covered.

Weatherproof (covered) line wire has been in use for many decades to provide weatherability to overhead conductors. The coverings helped to reduce outages due to the storms and wind, where objects might contact the lines or the lines would come in contact with each other. The specification that has most generally been referenced when specifying covered line wire has been ANSI C8.35, which is now out of date. Today's standard is ICEA S70-547-92. Some of the early coverings consisted of a combination of natural rubber compounds and asphalt-saturated cotton braids. These coverings did not weather well; they were subject to cracking and festooning in a relatively short period of time. Other early coverings included gray polyethylene and crosslinked polyethylene that were not

sufficiently sunlight resistant. These also cracked with prolonged exposure to sunlight. Modern covered line wires utilize a thin layer of thermoplastic or crosslinked polyethylene coverings that do not normally crack or festoon.

Tree wire is largely undefined; the term has been applied to covered conductor constructions ranging from weatherproof wire to aerial spacer cable. Some tree wires have a single-layer covering, while others use a dual layer.

Aerial spacer cables utilize a thicker covering than weatherproof wire. The preferred designs for 15kV and higher voltage applications utilize a dual layer construction; an inner layer of natural high-molecular-weight polyethylene overlaid with a track-resistant, high-density polyethylene that is very abrasion resistant. In addition to the dual layer constructions, a conductor shield layer is common at 15kV and is almost always included above 15kV. These covering thicknesses and the abrasion-resistant outer layer provide a greater protection against faults due to incidental (or even sustained), contact by trees or other conductors. The dual-layer construction virtually eliminates the possibility of pinholes through the entire covering wall, minimizing the probability of a fault if contacted by a grounded object.

In the **aerial spacer cable system**, the heavily covered conductors are suspended by spacers from a high-strength, grounded messenger. The messenger serves as a shield wire against lightning strikes and, on grounded-wye systems, commonly serves as the circuit neutral. The spacers are insulators designed to electrically coordinate with the cable covering. Spacers are placed at approximately 10m (30 feet) intervals. The use of the messenger and spacers for conductor support allows very close conductor spacing without any associated problems with phase-to-phase contacts.

Weatherproof wire, tree wire, and aerial spacer cable are all classified as nonshielded, covered conductors. The absence of an insulation shield and the aerial application make it probable that the conductor will remain energized, even if portions of the covering are removed.

Fully shielded cables (having an insulation shield) used for aerial (or underground) purposes are classified as insulated. The insulation is designed and tested to confine full operating voltage continuously and the insulation shield, including metallic component, is designed to provide a defined path for the flow of charging current and fault current in the event of insulation failure. Shielded

aerial cables are commonly lashed to a messenger with wire or tapes and used as an assembly.

III. OPERATING CHARACTERISTICS OF SHIELDED AND NONSHIELDED CABLES

Recognizing that voltage is from conductor to ground, an isolated nonshielded cable might be depicted as shown in Figure 1.

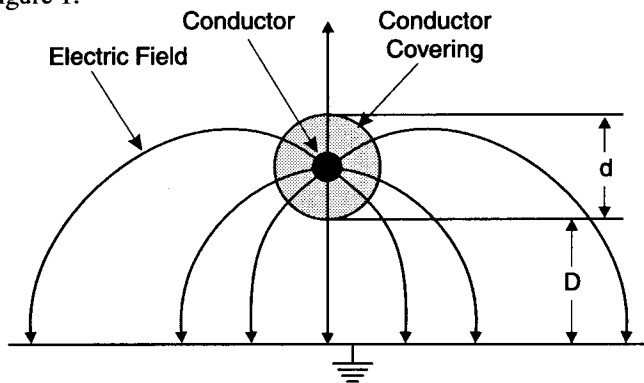


Figure 1. Field Plot

Because of the two different types of insulating materials (air and polyethylene), a distortion of the electric field results in the flux lines arriving at the covering/air boundary at an angle other than 90° . When the distance to ground (D) is large compared with conductor/cable diameter (d), the field distortion is small. However, as the value of D decreases, the distortion increases. This distortion results in significant tangential stresses and/or voltage gradients at the boundary or surface of the covering. Significant voltage gradients on the surface result in a flow of current on the surface which is a source of radio interference voltage (RIV) that will erode the conductor covering. This surface current flow and covering erosion is commonly known as tracking.

Similar stresses are developed to a lesser degree when, instead of a grounded plane, an insulator or spacer made of a material with a dielectric constant significantly higher than that of the cable covering is brought into contact with the covered conductor. Thermoplastic or thermosetting (crosslinked) polyethylene covering has a dielectric constant on the order of 2.3 to 2.5, while typical porcelain ranges from 6-9.

RIV and/or erosion due to tracking has commonly occurred with the use of covered conductors on porcelain insulators. To limit tracking and RIV, many utilities remove the covering at the insulators, defeating the purpose of the covering at every pole attachment. Much the same problem can occur in aerial spacer cable systems if the cable covering and spacer materials are not properly coordinated.

Greater spacing of the air relative to the covering creates a much higher capacitance of the air. Thus, as shown in Figure 2a, under normal conditions and spacing, most of the voltage difference is across the air capacitor (and/or across the spacers in the case of a aerial spacer cable system).

When coverings utilize high dielectric strength materials under normal conditions, the currents involved

are largely due to capacitance, rather than resistance, and the resistance has been ignored for purposes of the calculations in this paper. However, should a grounded object contact the covered cable (as in Figure 2b), the voltage divider would be made up of the series impedance of the covering capacitor and the object impedance (Figure 3). The values would depend upon the impedance of that object to ground.

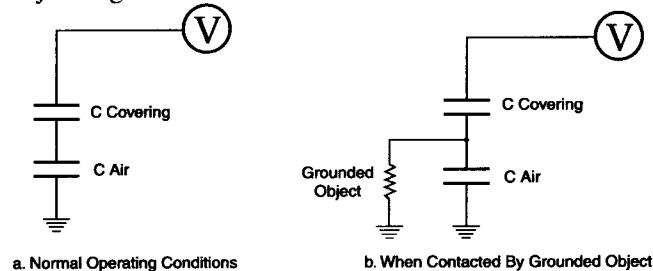


Figure 2. Series Combination of Capacitors

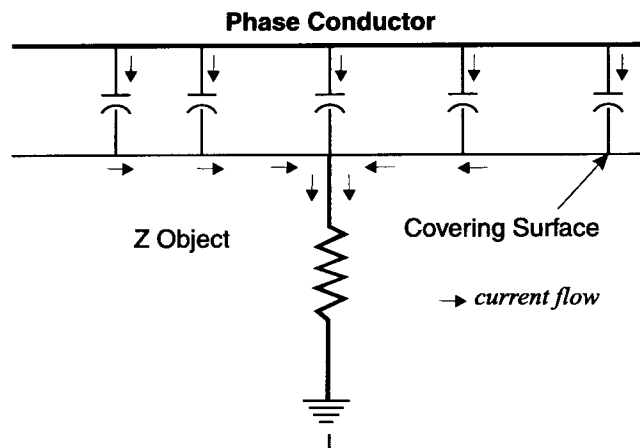


Figure 3. A Grounded Object of Impedance Z Contacting a Covered Cable

If the impedance of the contacting object is relatively small, the majority of the voltage difference is across the conductor covering. In effect the object now becomes the ground lead for the covering capacitor.

The amount of current that can flow is dependent on (a) the level of charge available on the covering surface at the point of contact and (b) the level of current that can be accumulated via tracking across the covering surface to of the point of contact. See Figure 4.

The difference between a shielded cable and a nonshielded cable is that the insulation shield presents a defined path for the flow of the charging current. If the ground plane described previously completely envelops the covering surface, the result is a traditional fully-shielded cable. The shielding is generally accomplished by extruding a layer of semiconducting polymer over the insulation and then adding a metallic component such as tapes or wires over the semiconducting layer. In the case of the fully shielded cable, all of the voltage appears across the insulation and a well-defined cylindrical capacitor appears.

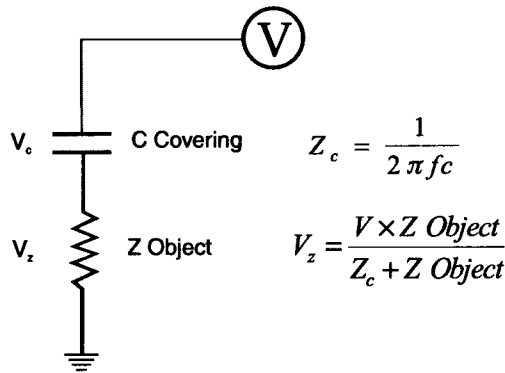


Figure 4. Surface Area Contact Affects Quantity of Capacitive Current at Contact

The key factors in determining the amount of charging current are: (a) Conductor size, (b) Covering thickness, (c) Dielectric constant of covering, (d) Operating voltage, and (e) Operating frequency

The formulas for calculating charging current, per foot, and capacitance for fully shielded cable are:

$$i = 2\pi f c e \quad (1)$$

$$C = \frac{7.354\epsilon}{\log_{10} \frac{Doi}{Doc}} \times 10^{-12} \text{ farads / ft} \quad (2)$$

where: ϵ is the dielectric constant of the covering.

Doc is the diameter over the conductor (or semiconducting conductor shield, if used)

Doi is the diameter over the covering (or insulation in the case of shielded cables)

e is the voltage across the covering or insulation

For a 795 kCmil conductor 6.604 mm (0.260 in) polyethylene insulated fully shielded cable for 25kV service having

$$\begin{aligned} \epsilon &= 2.3 \\ Doc &= 0.0268 \text{ m (1.056 in)} \\ Doi &= 0.0398 \text{ m (1.566 in)} \\ f &= 60\text{Hz} \\ e &= 14.4 \text{ kV Phase-to-grd} \end{aligned}$$

The charging current is calculated to be:

$$i = 2\pi 60 \left(\frac{7.354 \times 2.3}{\log_{10} \frac{1.566}{1.056}} \right) \times 10^{-12} \times 14.4 \times 10^3 = 0.539 \text{ milliamps / ft} \quad (3)$$

In the case of the fully shielded cable, the charging current is drained by a well defined path. However, in the case of a

covered conductor, when a partial shield is created by a ground contact or some conducting contamination on the surface, no well defined path exists.

IV. PROPOSED CLASSIFICATION SYSTEM

Significant differences in the design of covered wires and cable exist under broad generic and colloquial names. This causes confusion in the development of utility standards, purchasing specifications, and field applications. The classification system for covered wires and cables shown in Table 1 is proposed to limit confusion between the designs.

A classification system for insulated, fully shielded cables is available in ICEA standards.

V. APPLICATION

The different characteristics of aerial wires and cables must be considered when making choices for different applications. See Table 2.

A. Weatherproof Wire

Weatherproof wire is generally installed with the same conductor spacing as bare wire. Individual conductor strength requirements, sags, tensions, and span lengths must be considered differently. The covering thickness is independent of operating voltage. At 15kV and above, weatherproof wire should be placed on insulators having a dielectric constant essentially the same as the covering and covered ties are recommended. Weatherproof wire offers some protection against tree branch contacts of short duration, but tree trimming should be essentially the same as for bare wire.

In general, when comparing alternative constructions, weatherproof wire has the lowest material first cost after bare wire.

B. Tree Wire

Depending on covering thickness, the application of tree wire is very similar to weatherproof wire. Thicker coverings afford greater protection against outages due to intermittent contacts. However, the thicker covering results in increased conductor mechanical loading, possibly requiring a reduction in span lengths and/or taller, stronger poles. Since each conductor must be its own strength member, the danger of a broken conductor due to a substantial tree limb falling on the line must be considered (especially for smaller wire sizes). Trimming to reduce overhanging limbs approaches that required for bare and weatherproof wire. As with weatherproof wire, insulators should be matched to covering material and covered ties are recommended.

C. Aerial Spacer Cable

The heavily covered phase conductors are suspended from insulating spacers that are supported on a messenger that is the strength member of the system. The messenger limits the movement of individual phase conductors during changes in operating temperature and ice loading, thus limiting stresses on the covering materials and increasing the longevity of their insulating capabilities.

Table 1—Covered Conductor Classifications

	Conductor Type	Voltage Class	Wire Size	Single-layer Covering Thickness (mil)	Double-layer Covering Thickness (mil)	Conductor Shield	Insulation Shield	NESC Class	NESC "Open"
Self-Supported	Bare	None	All	None		N	N	bare	Y
	Weatherproof*	None	Solid	30-40		N	N	230D	Y
			4	30		N	N	230D	Y
			1/0-4/0	60-80		N	N	230D	Y
			250-350 kcmil	60-80		N	N	230D	Y
			397-556.5 kcmil	80		N	N	230D	Y
			636-1033.5 kcmil	95		N	N	230D	Y
			1500-2000 kcmil	110		N	N	230D	Y
	Tree Wire Type Ia	None		**		N	N	230D	Y
	Tree Wire Type Ib	5 kV		0 + 85 = 85		N	N	230D	Y
		15 kV		0 + 110 = 110		N	N	230D	Y
	Tree Wire Type II	15 kV		0 + 150 = 150	75 + 75 = 150	O	N	230D	Y
		25 kV			125 + 125 = 250	Y	N	230D	Y
35 kV				175 + 125 = 300	Y	N	230D	Y	
Messenger Supported	Aerial Spacer Cable Type I	5 kV		0 + 85 = 85		N	N	230D	Y
		15 kV		0 + 150 = 150		N	N	230D	Y
	Aerial Spacer Cable Type II	15 kV			75 + 75 = 150	O	N	230D	Y
		25 kV			125 + 125 = 250	Y	N	230D	Y
		35 kV			175 + 125 = 300	Y	N	230D	Y
		46 kV			225 + 175 = 400	Y	N	230D	Y

* Thickness does not vary with voltage

** Many thicknesses and types of single layer coverings have been used as "tree wire".

N—No, Y—Yes, O—Optional

The phase conductors of aerial spacer cable systems meet NESC Rule 230D and are generally considered the same as bare wires for clearances to areas accessible to the public. This is because the covered phase conductor is not in intimate contact with a grounded neutral or messenger and cannot be depended upon to trip out of service if the covering insulation fails.

D. Fully Shielded Aerial Cable

The fully shielded aerial cable is by far the most costly of the aerial cable systems and is largely neglected in favor of underground installations. Fully shielded aerial cable is frequently used in alleys and other confined areas where (a) bare or covered conductors cannot meet NESC clearance requirements and (b) underground construction is not practical. Properly installed fully shielded aerial cable meets NESC Rule 230C1 and is allowed to have the same clearances as grounded guys.

The use of shielding increases both diameter and weight, thus placing practical constraints on span lengths and support structure requirements. Lightning protection requirements for shielded aerial cables are the same as for underground primary cable circuits. A major disadvantage to a fully shielded system is the need for voltage stress relief (terminators) at every connection, tap or junction to other conductor types. The shielded aerial cable system

does not lend itself to easy repair or maintenance in the event of cable failure.

Cable construction affects safety, reliability, economy, construction and maintenance costs and time, and environmental interaction. Differences between operating characteristics of shielded and nonshielded cables are discussed above. Table 3 summarizes the performance of bare wire, covered conductors and shielded cables relative to various concerns of utilities.

The presence of a semiconducting conductor shield on aerial spacer cables and tree wires is rare at 5kV, common at 15kV, and almost always occurs at 25kV and above. None of these constructions has an outer insulation shield; therefore all are included in the category of nonshielded cables.

VI. CONCLUSION

1. The various types and designs of bare, covered and insulated conductors and cables have different design and operating characteristics.
2. These differences must be carefully considered when choosing conductors for different applications.
3. The proposed classification system for covered wires and cables will limit confusion among manufacturers, users, and others.

Table 2—Typical Reasons For Choosing Different Conductor Designs

Wire or Cable	Unconstrained Right-of-Way Width				Constrained Right-of-Way Width								
	Cost	Long Span 3 Phase Double Pole	Long Span 3 Phase Single Pole	Reduced EMF	Reduced Initial Tree Trimming	Reduced Maintenance Tree Trimming	Compact Construction	Reliability	Reduced Airborne Contamination Corrosion	Reduced Clearances to Buildings	Long Span 3 Phase Single Pole	Reduced Clearances Between Conductors	Single Phase Long Spans
See Table 3 for covered conductor classifications													
Bare Wire	✓	✓	✓										✓
Weatherproof									✓				
Tree Wire Type Ia									✓				
Tree Wire Type Ib							✓	✓	✓				
Tree Wire Type IIa						✓	✓	✓	✓				
Aerial Spacer Cable			✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Shielded Aerial Cable				✓	✓	✓	✓	✓	✓	✓		✓	

Table 3—Relative Wire Performance Ratings

	Wind Load	Ampacity	Voltage Regulation	Ice Loading	Horizontal Conductor Space	EMF	Tree Trimming	Vertical Space on Pole	Right-of-Way	Abrasion Resistance	Nuisance Trapping	Operate with Ground Contact	Probability of Conductor Burndown With Improper Protection	Probability of Conductor Burndown Without Proper Protection	Ease of Hot Tapping	Ease of Long Span Construction
Bare Wire	1	1	3	1	4	4	4	3	4	No	4	4	1	1	1	2/3
Weatherproof	2	2	3	2	4	4	4	3/4	4	4	2	3	3	3	2	3
Tree Wire Type Ia	2/3	2/3	3	2/3	3/4	3/4	3/4	3/4	3/4	2	2	2/3	3	2/3	2	3/4
Tree Wire Type Ib	2/3	2/3	3	2/3	3	3	3	3/4	3/4	1	1/2	2/3	3	2/3	2	3/4
Tree Wire Type IIa	3	3	3	3	3	3	3	5	3	1	1	1	3	2	3	4
Aerial Spacer Cable	3	3	2	4	2	2	2	3	2	1	1	1	2	1	4	1
Shielded Aerial Cable	4	4	1	3	1	1	1	1	1	1	1	1	2	1	No	3

1 = best, 2 = better, 3 = good, 4 = worst

A rating of 1/2 means the relative level is between 1 and 2.

Note: These rating numbers represent typical relative values only.

VII. REFERENCES

1. "National Electrical Safety Code" ANSI C2, 1993 Edition.
2. H. B. Slade "Three Phase Measurements of Charging Currents on Spacer Cable Systems Under Simulated Service Conditions" paper 70 CP 62-PWR presented at the IEEE Winter Power Meeting, New York, Jan. 25-30, 1970.
3. J. P. Markham and H. B. Slade, "Three Phase Measurements of Charging Currents on Spacer Cable Under Simulated Service Conditions" IEEE Paper 31 pp. 66-361 presented at the IEEE Summer Power Meeting, New Orleans, July 10-15, 1966.
4. R. T. Harrold and T. W. Dakin, "On Predicting the Life of Polyethylene Spacer Cable Eroded by Surface Discharges in Wet Weather" IEEE Trans. on Power Apparatus and Systems, PAS-95, pp. 821-828, May/June 1976.
5. E. K. Duffy, S. Jovanovetch, I. J. Marwick, "Discharge Resistant Characteristics of Polyethylene for Wire & Cable" IEEE Paper #CP 63-413 presented at IEEE Winter General Meeting, New York, January 27-February 1, 1963.
6. R. G. Raymond "Spacer type Aerial for Higher Voltages" Paper #DP 63-851 presented at IEEE Northeastern District Meeting, Portsmouth, New Hampshire, May 20-22, 1963.
7. J. W. McAuliffe "Aerial Spacer Cable Systems, 'An option for reliable overhead distribution service', presented to "Distribution 2000" Brisbane, Australia, June 1991.
8. A. L. Clapp "NESC Handbook", 3rd Edition, Institute of Electrical and Electronics Engineers, New York, 1992.
9. Rodick and P. Musser, "Evaluation of Measures and Costs to Mitigate Magnetic Fields from Transmission and Distribution Lines", Missouri Valley Electric Assoc. Eng. Conf., April 7, 1993, Kansas City, MO.
10. ANSI/ICEA S-70-547-1992, "Weather-Resistant Polyolefin-Covered Wire and Cable".
11. C. C. Landinger, J. W. McAuliffe, J. B. Dagenhart, A. L. Clapp, W. A. Thue "Safety Considerations of Aerial Systems Using Insulated and Covered Wire and Cable" paper _____ presented at IEEE T&D Expo, Los Angeles, September 1996.

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