Ghost Voltages on LA Metro Traction Power Cable Jackets

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ABSTRACT

The Los Angeles County Metropolitan Transportation Authority (METRO) discovered apparent voltages on the jacket surface of their 750 VDC traction power feeder cables, sometimes measuring as high as 500 VDC. Through a series of site investigations, field tests and laboratory tests, these voltages were determined to be Ghost Voltages (or Phantom Voltages).

Ghost voltages appear naturally on the surface of any unshielded power cable and are a function of cable construction, installation arrangements and environmental conditions. Ghost voltages are not indicative of any equipment malfunction and do not routinely cause any significant safety risk to maintenance personnel at this voltage class.

PROBLEM STATEMENT

The Los Angeles Metropolitan Transportation Authority (METRO) discovered a surface voltage on the outside jacket of DC feeder cables in several traction power substations along their Red Line subway system. METRO was concerned that the presence of this voltage could be indicative of an unsafe condition and/or the result of cable insulation breakdown.

The Red Line traction power system is a nominal 750 volts DC with a high resistance ground. The concerned cables are between 10 and 22 years old and are installed predominantly in non-metallic conduit below grade, except for lengths near the terminal ends in the field and within the substations. METRO staff reported that they had measured voltages as high as 500 volts between feeder cable jackets and ground. Voltages were measured on the exposed outer jacket of DC feeder cables at the four following Red Line Substations: Wilshire/Vermont, Vermont/Beverly, Hollywood/Highland, and Wilshire/ Western.

The project approach involved the following steps:

- Review As-Installed data available from METRO.
- Visit the sites to evaluate the extent of the problem and review measurements initially taken by METRO.
- Determine a test plan and arrange for tests to be performed on cable samples.
- Evaluate all related information and make recommendations to METRO regarding whether the voltages are indicative of an unsafe condition.

Cable Application

METRO traction power substations convert a utility source from a nominal 34.5 kV AC to a 750 VDC for the traction power system. This traction power voltage is supplied to the third rail system via 4,000 amp high-speed circuit breakers and typically six (6) 1,000 kcmil cables in parallel. The voltages in question were present on several of the feeder cables within the noted substations. Not all traction power substations along the Red Line were surveyed but they are all of similar construction.

Cable Theory Overview

It is worthwhile to review some basic cable engineering and construction principles. This review will simplify communication throughout the report and serve as a reminder of the functions that the cable elements perform.

There are five (5) main elements of a modern, extruded dielectric power cable: Conductor, Conductor Shield, Insulation, Insulation Shield and Jacket.

- Conductor: Stranded copper (in this case), intended to carry rated current with minimal losses.
- Conductor Shield: Semiconducting layer provided to minimize the effects of irregularities in the conductor and, in turn, reduce stress on the insulation layer.

- Insulation: A high resistance extruded plastic material intended to limit current flow between the conductor and any exterior surfaces.
- Insulation Shield: Metallic insulation shields are routinely provided above 2 kV. Metallic insulation shields provide a low resistance path for drainage currents, ensure that fault currents are properly disseminated and commonly maintain constant contact with ground. Insulation shields are not typically used for this application and are not present in the subject METRO cables.
- Jacket: Semiconducting layer intended to protect the insulation from damage due to physical abuse, sunlight, flame or chemical attack.

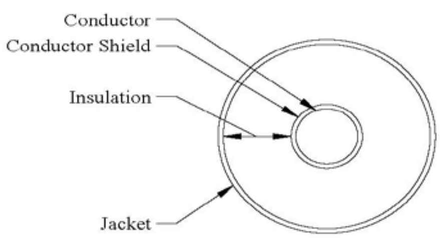

Figure 1: Cable Construction

These cable elements can be seen in Figure 1. The DC feeder cables are unshielded; therefore insulation shields will not be discussed further in detail in this report.

Power cable design and construction creates a voltage divider between the voltage at the conductor and the conductor shield, insulation, insulation jacket and ground. Figure 2 illustrates a simple circuit that, while unintended, occurs normally when a power cable is energized. Cable designers use a high insulation resistance to limit any potential current flow through the unintended conductor-to-ground circuit. Inevitably a potential builds up on the insulation jacket unless a low resistance connection to ground occurs. The strength, or available energy, of this potential build up is limited by the insulation resistance of the cable assembly. While the voltage cannot typically be detected by human touch, this weak voltage can generally be detected by a high impedance voltmeter. Refer to the "*Voltmeter Considerations*" section for additional information.

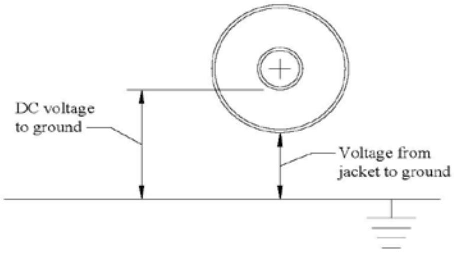

Figure 2: Conductor-to-Ground Voltage-Divider Circuit

Cables are usually thought of as perfect ideal components which contain all of the electrical energy within the insulation. In reality, however, cables behave like a capacitor with one end connected to the positive source voltage and one end usually connected to ground. The two cable elements which impact these capacitive circuits are Insulation Resistance and Surface Resistivity.

- Insulation Resistance limits the transference of any significant amount of energy to the outside. A suitably high insulation resistance ensures that any voltage build up on the cable exterior is current-limited to acceptable levels.
- Surface Resistivity is the ability to conduct electricity along the exterior surface of the cable.

Non-metallic jackets do not conduct electricity sufficiently to drain the voltages discussed. When a cable is laid in grounded metallic conduit and cable tray systems, however, this voltage is discharged continuously along the length of the contact between the cable jacket and the metal. When a cable does not come into contact with a grounded surface, it is to be expected that a voltage develops on the insulation, opposite the conductor, which approaches that of the conductor. This is consistent with Kirchhoff's Second Law (Kirchoff's Voltage Law) for an open circuit. The high (per-unit length) insulation resistance limits any current flow to an undetectable level which cannot be detected by human contact. This capacitive voltage that can build up on the non-metallic jackets of unshielded power conductors is what is referred to in this paper as a Ghost Voltage or Phantom Voltage.

For certain medium-voltage class cables and high-voltage class cables, metallic shields are provided to drain any voltage build up to ground, before it appears on the cable jacket as a ghost voltage. Insulation shields are routinely provided for installations and cable ratings over 2,000 volts are not typically used in DC transit applications.

PROJECT TASKS

Field Investigation and Testing

On September 4, 2012 DC feeder cables in four (4) traction power substations along METRO's Red Line were field-tested in an attempt to assess the danger of, and identify the cause of, the apparent jacket surface voltages. During the field investigations, three (3) different cables were discovered. These cables were discovered at random throughout the system. Some circuit comprised wholly of one type of cable, some circuits were mixed. The types of cables are:

- Amercable 1994 1000kcmil, Class B 2000 V 75 mils EPR / 80 mils XLPO 90Deg C (UL) Marine Shipboard E11461 1.58" (Referred to in this report as 75 Mil Cable.)
- Amercable 1994 1000kcmil, Class B 2000 V 90 mils EPR / 80 mils XLPO 90Deg C (UL) Marine Shipboard E11461 1.58" (Referred to in this report as 90 Mil Cable.)
- Okonite 1000kcmil Cu 120 mils Okoguard EP 65 mils XLPO (UL) RHH or RHW-2 2000 V Sun Res for CT Use 1998 (Referred to in this report as 120 Mil Cable.)

A Fluke Model 289, True-RMS Industrial Logging Multi-Meter was used to measure the apparent voltages on cable sections within the substations. The negative probe was grounded and the positive probe was placed on the cable jacket. The meter registered voltage amplitudes at each cable jacket, ranging from 0 volts to 500 volts. The meter probes were then reversed, the results of which confirmed that the surface voltage was a DC voltage. It was quickly noticed that the Amercables experienced high ghost voltages while the Okonite cable jackets rarely experienced more than 10 volts.

It is important to note that the voltage amplitudes mentioned above were the initial amplitudes seen as soon as the meter was touched to the cables. The amplitudes immediately tended towards zero, indicating a circuit with capacitive characteristics; the speed of the voltage decay being defined by the time constant of the meter circuit.

The multimeter was then used as an ammeter to determine if any significant current could be drawn from the measured voltage. No significant currents were measured (0.1 mA).

For the final field test, a copper braid was wrapped around a DC feeder cable and intentionally grounded. The multimeter was then used to measure the ghost voltage along the jacket at varying distances from the copper braid. As expected, the jacket measured 0 volts near the braid. As the multimeter probe was moved further from the copper braid, the measured voltage amplitude increased. This further supports that the cable insulation and jacket serve as a capacitive dielectric and are constantly being charged by the internal current-carrying conductor.

Laboratory Testing

Samples of each type of cable were cut from the field and sent to Cable Technology Laboratories, Inc. (CTL) of New Brunswick, New Jersey for testing. Each of the three samples was approximately forty inches (40") in length and was removed from the actual in-service cables. Each sample underwent three (3) laboratory tests, in accordance with NEMA, ANSI and UL standards:

<u>Specific Surface Resistivity Test – As-Received</u>: This test measures the resistivity of the semiconductor cable jacket along the cable length. To perform this test, two electrodes are painted unto the surface of the cable with metallic paint, placed six inches (6") apart. The electrodes then supply 500 VDC across the cable jacket, the results of which indicates the resistivity of the cable surface. Minimum result required: 2.0 E5 meg ohms.

Results:

Sample	Measurement	Result
75 Mil	6.4 E3	Fail
90 Mil	4.7 E2	Fail
120 Mil	8.7 E6	Pass

<u>Specific Surface Resistivity Test – Post Immersion</u>: This test is identical to the above test, except that it is performed after the cable samples have been immersed in tap water at room temperature for forty-eight (48) hours. The excess moistures is then blotted off and the cable samples are held in still air for 10 minutes, then tested by the same procedures mentioned above. Minimum result required: 2.0 E5 meg ohms.

Results:

Sample	Measurement	Result
75 Mil	3.2 E6	Pass
90 Mil	6.5 E6	Pass
120 Mil	4.0 E6	Pass

Insulation Resistance: This test measures the resistance of the cable insulation. Unlike the previous tests which measure the resistance along the axis of the cable jacket, this test measures the resistance radially through the insulation and jacket. To perform this test, the conductor is energized to 500 VDC and the cable jacket is grounded. Minimum result required: 1.4 E3 meg ohms.

Results:

Sample	Measurement	Result
75 Mil	1.8 E4	Pass
90 Mil	3.0 E4	Pass
120 Mil	6.0 E4	Pass

RESULTS & DISCUSSION

Cable Properties

Each cable sample was tested for Insulation Resistance and Specific Surface Resistivity.

Insulation Resistance is a property that helps determine the maximum ghost voltage that could build up on the cable jacket. As discussed earlier and illustrated in Figure 2, above, a voltage divider exists between the conductor and ground. When the cable jacket is not physically in contact with ground, the two major parameters of this voltage divider is Insulation Resistance and Air Resistance. When the cable jacket is in constant contact with ground, the Air Resistance is zero, therefore the entire voltage drop occurs across the cable insulation. In METRO's case, however, the cable jackets are not in contact with ground and the air resistance, which varies with the cable's distance to ground, shares a portion of the voltage drop. A goal of cable construction is to maximize the voltage drop across the cable insulation, therefore the Insulation Resistance is kept as high as practically possible for the cable's intended application. Satisfactory insulation levels were observed for all three samples according to the noted standards. It is understood, however, why the cable with the highest Insulation Resistance experienced the lowest ghost voltages.

While a high Insulation Resistance optimizes the voltage drop across the cable insulation, it also promotes the capacitor effect between the conductor and the cable jacket. The Specific Surface Resistivity (SSR) is a property that can help drain this unwanted charge off of the cable jacket. An extremely low SSR (as in a shield) drains charge to ground and does not allow ghost voltages to build up. A jacket with an extremely high SSR is not conducive to current flow along the cable length and will facilitate charge buildup when the cable is not in constant contact with ground. Intermediate SSR levels, however, are not as easily understood.

A jacket with an intermediate SSR exhibits traits of both a conductor and an insulator. The conductive traits further promote the capacitor effect introduced by the cable's Insulation Resistance. This unseen, mildly conductive, layer on the outside of the cable jacket introduces a surface onto which a capacitive charge can build. However an intermediate SSR also acts like an insulator, the resistive traits of which do not allow the surface charge to drain effectively. This phenomenon is key to understanding the ghost voltages on METRO's DC feeder cables.

The SSR was unacceptable for both Amercable samples when tested in as-received condition, but performed adequately after being soaked in water for two days. This suggests that a thin film of conducting materials was present on the cables, the origin and makeup of which could not be determined. It is clear, however, that this film affected the cable performance and altered the SSR significantly enough to allow a ghost voltage to be realized. It is unknown why the film was only present on the Amercable cables and that the Okonite cable appears to be immune.

Cable Standards

The cables discussed herein are, per METRO specification, rated at 2,000 volts and are manufactured in accordance with NEMA WC-70-2009 (also known as ICEA S-96-658-2009) Standard for Non-shielded Cables Rated 2000 volts or less for the Distribution of Electrical Energy. Cable testing is to be performed in accordance with ANSI/ICEA T-27-581(NEMA WC 53-2008), Standard Test Methods for Extruded Dielectric Power, Control, Instrumentation and Portable Cables for Test. All cables under discussion are Underwriter Laboratories (UL) listed for the voltages and currents of the application.

The Amercable cables do not meet the minimum insulation thickness requirements of NEMA standard WC 70-2009. While the Amercable samples are listed for Marine Shipboard application instead of Cable Tray (TC) like the Okonite cable, this difference isn't deemed significant as the Marine listing ensures a cable suitable for application in a harsh environment. It is not know why the Amercable Marine Type cables were used on this project.

Voltmeter Considerations

Traditionally, voltmeters are categorized such that a high quality voltmeter will have very high input impedance; the higher the better. The high input impedance will not affect, or load, the voltage being measured. For this reason, many, if not most, of the quality meters routinely used by maintenance departments have very high input impedance.

Initial voltage measurements were taken using high impedance voltmeters. This is key to this investigation and the corresponding results. If a low-impedance analog voltmeter was used, or if the Fluke 289 was set to low impedance mode, then these ghost voltages would never have been discovered. The reason for this is that the low impedance of the meter circuit would instantly drain the cable's capacitive voltage to ground, without ever registering it.

CONCLUSION

Summary

Ghost voltages are a function of cable construction, environmental conditions and maintenance procedures. This phenomenon can only be measured by low impedance voltmeters, contrary to the high impedance meters usually used by professional maintenance personnel. METRO experienced ghost voltages on their DC feeder cables but through site investigations, field testing and laboratory testing, it was determined that this ghost voltage phenomenon is normal, is not a result of any malfunction of the traction power system and poses no risk to METRO personnel or equipment.

Recommendations

While the potential on the cable jackets is not hazardous, it may trouble METRO personnel working in the substations. The voltage can be minimized within the substations where the cable is exposed, by following either method here:

- Periodically take feeder circuits out of service and wipe down the cables. This approach may require some onsite testing to determine the best approach but a cleaning method which will remove the pollutant seems reasonable.
- Wrap copper braid around the cables in the exposed areas and connect these braids to ground. As noted above, the Amercable cables (as discovered) have an intermediate SSR which allows a noticeable ghost voltage to build up. These braids could provide a low resistance path to drain these charges to ground, thereby mitigating the potential build up.

Note that these remedies are not necessary as the potentials are not harmful.

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