Safety-Related Contact Currents for Humans Touching Medium Voltage Covered Conductors

Hendrix
AERIAL CABLE SYSTEMS

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Introduction

Medium voltage covered conductor has been used throughout North America for almost 70 years, and in countries on all seven continents for decades. Covered conductor falls into two categories: Spacer Cable configurations and Tree Wire. Spacer Cable configurations consist of three heavily covered conductors without a shield, mounted in spacers every thirty feet and attached to a messenger wire. Tree Wire consists of covered conductors installed using polyethylene pin-type insulators mounted on crossarms, in an open configuration similar to bare wire construction.

In both cases, a common concern has been that medium voltage covered conductor is designed to provide high reliability and, as a result, may fall or be knocked to the ground and fail to activate protective devices (fuses, reclosers, relays, etc.). The most frequently asked question has been "If it falls and someone touches it, is it safe?"

The purpose of this paper is to provide some answers to this question. We will compare theoretical current magnitudes from touch contacts to values obtained in the lab, see how those magnitudes change across various operational scenarios (wet, dry, contaminated, etc.) and, finally, compare those numbers to known thresholds for human safety hazards (shock, burn, fibrillation, etc.).

Conductors Under Discussion

As a cautionary note, it is worth saying that not all covered conductors are compliant to the standards and specifications defined in ICEA S-121-733-2016, the *Standard For Tree Wire and Messenger Supported Spacer Cable*. Some cables are manufactured to foreign standards, such as the significantly less rigorous European Standard EN-50397, and still others are manufactured to the now obsolete ICEA S-70-547, the *Standard for Weather-Resistant Polyethylene Covered Conductors*.

Simulation data as well as lab test data discussed herein are for conductors that conform to ICEA S121-733-2016. Hendrix cable designs conformed to this standard over 60 years before it was written, and many would argue that the standard was written based on Hendrix.

Contact Scenarios

Consider a human coming into contact with a covered conductor, with bare hands, whether that conductor is still in the air (Figure 1 below), suspended from a broken structure but not touching the ground, or perhaps having fallen all the way and laying on the ground.

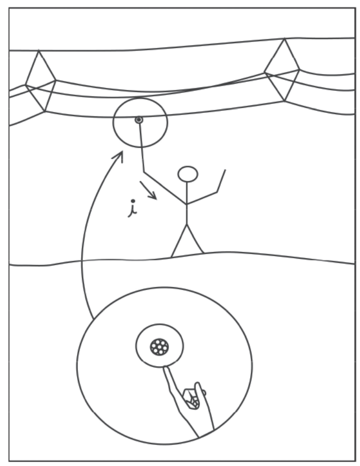

Figure 1: Human touching live conductor

The first exercise is to ascertain what level of current we would reasonably expect the touch scenario to discharge to the human being, from theoretical calculations, assuming the worstcase scenario. This would include assumptions of a solid contact, preferably over a wide surface area, everything being wet, the human standing on ground with zero impedance, and so forth. Since we are most interested in the worst-case scenario, we will not consider additional impedances such as those potentially gained from thick rubber soles or a non-conducting surface, nor will we consider impedances of the human body, which can range from the hundreds to the thousands of ohms, depending on ambient conditions (wet or dry) and contact scenarios (hand to hand or hand to feet). Also not considered will be the geometry of the contact scenario, such as touching with one hand, two hands, etc., etc. We are concerned with worst case scenarios only, and the introduction of impedances will reduce the contact current, which runs counter to the objectives set forth in this paper.

A diagram of a covered conductor in the air is shown in Figure 2, and is intended to be an equivalent circuit of the scenario illustrated in Figure 1. It is essentially a series capacitor circuit, with the capacitance of the cable covering in series with the capacitance of the air. Without anything contacting the cable surface, most of the capacitance is represented by the air, and there is negligible voltage drop across the conductor covering. When a human or other potentially grounded object touches the cable's outer surface (Figure 1), the air capacitance is shunted by the human being (which we are modeling here as a zero impedance branch) and is effectively taken out of the circuit.

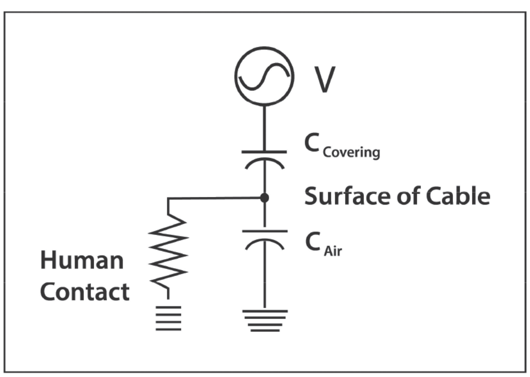

Figure 2: Human Contact on Surface of Covered Conductor

For the purposes of this calculation, we will assume that all impedances are zero (except the cable capacitance), and that there is a concentric neutral on the outer surface of the covered conductor. The concentric neutral would represent the human's hand wrapped around the conductor's entire circumference. This is a highly unlikely scenario, but it facilitates our calculations and is consistent with our exploration of a worst-case scenario.

The formula that gives the current on the surface of the conductor is as follows:

$I = 2(\pi)fCV$

Where:
I = current on surface of conductor
π = pi
f = frequency
C = cable capacitance
V = line voltage

The calculation of cable capacitances is covered elsewhere and will not be repeated herein[1].

Three terms are often used interchangeably. "Charging current" is the current associated with the capacitance of a line, or covered conductor in this case. This current is also what is described as "surface current" since it is available on the surface of the conductor. Should a path to ground become available on the surface of the conductor, this current then becomes what is termed "leakage current." Figure 3 next page gives the surface current, or charging current, as a function of cable size and kV class. These values are available to become leakage current, should the cable come into contact with a grounded, or partially grounded object (or human being).

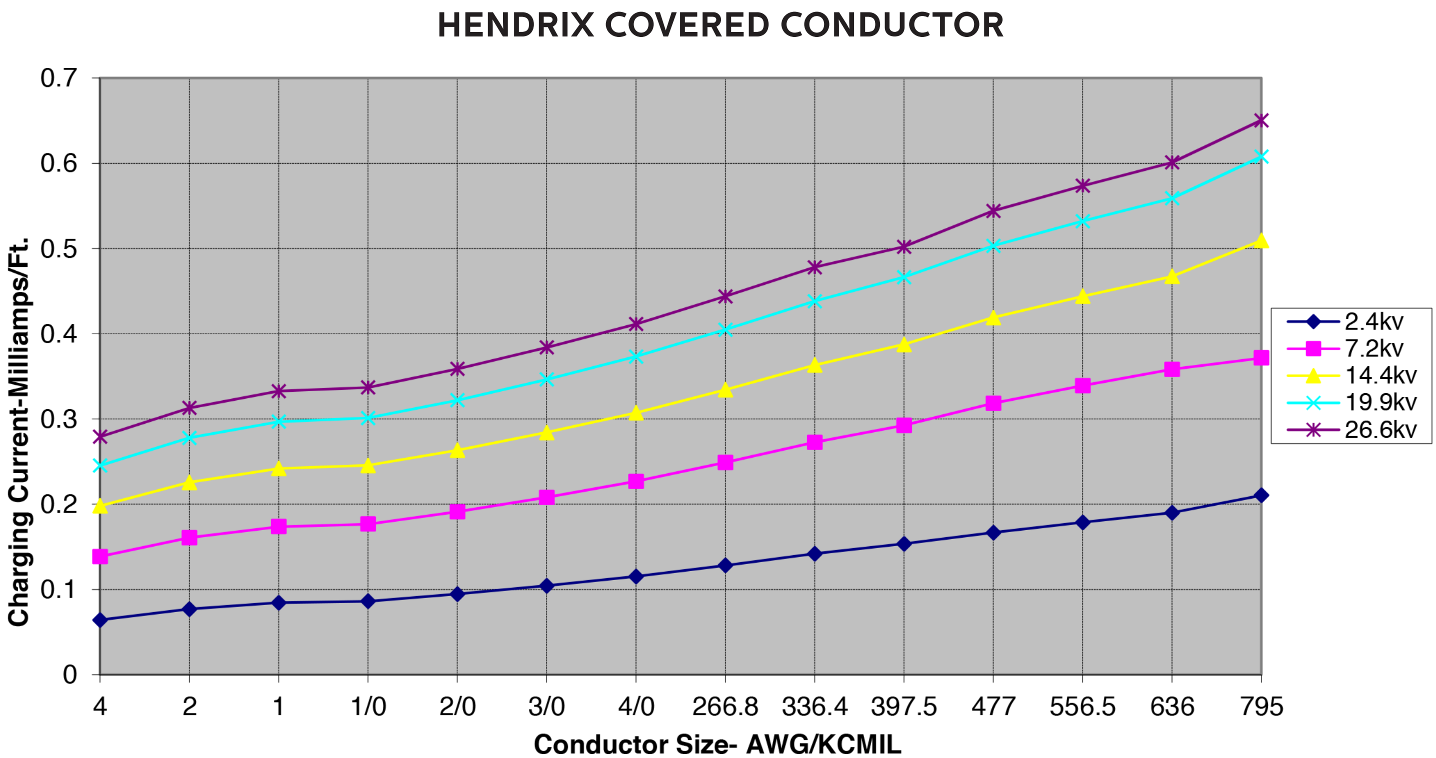

Figure 3: Charging Current as Function of Cable Size and Energization Voltage

Safety Thresholds

It can be seen from the graph above that surface currents can vary over a wide range depending on conductor size and voltage class, but in general remain below 1/3rd mA to ½ mA for the majority of cases. It is instructive now to compare these values to safety thresholds for human beings.

IEEE 80-2000, the IEEE Guide For Safety in Substation Grounding[2], discusses these values in detail, including various current thresholds and their respective physiological reactions by the human body. The guide indicates that lower contact currents will have mild effects on the body. Above the threshold of perception, however, effects can become quite severe, and can include muscle contraction, loss of consciousness, heart fibrillation, breathing problems, and burning[3].

Current Magnitude (mA)	Physiological Effect on Human Body
1	Generally recognized as the threshold of perception, the magnitude at which a human detects a tingling sensation in the hands or fingertips.
1-6	Below level of impairment, and below level at which a person is not able to let go.
9-25	Painful reactions, and much above 9 mA possible inability to let go. Higher currents may result in muscle contractions, breathing difficulty, and worse, depending on whether current is interrupted and duration of exposure time.

Table 2: Physiological Effects of Current on the Human Body

To put this into perspective, let's look at a fairly typical application, say, a 336 kcmil covered conductor at 12.47 kV voltage class on a multi-grounded wye system. Figure 3 above shows that for a completely solid contact, the person touching the cable would receive a current of 0.28 mA. The studies referenced above indicate that this is below the level of perception, yet testimonials of individuals who have contacted the cable at this voltage class describe the feeling as that of being stuck by a pin. Being stuck by a pin is certainly unpleasant, but not fatal. This is not to say that touching a covered conductor is safe, rather, quite the opposite. Energized conductors are, by definition, safety hazards, and should always be treated as such.

NESC 230D refers to this construction and says "Covered Conductors shall be considered bare conductors for all clearance requirements except that clearance between conductors of the same or different circuits……"[4] As such, there is no justification for anyone ever to touch a covered conductor while utilizing live line work procedures codified by the electrical entity employing them.

In practice, the modeling of the human body coming into contact with an energized conductor is more complicated than simply modeling impedances (of the body itself, ground, etc.) as zero. It depends on what type of shoes the person has on (i.e., rubber soled, steel tipped, bare feet, etc.), whether they are standing on dry vs. wet ground, what capacitance the person presents to the contacted conductor, the body's resistance, whether the skin is dry or moist, and more. Furthermore, studies have been conducted which differentiate between male and female thresholds of perception and pain. The IEEE Standard 1048-2003 "IEEE Guide for Protective Grounding of Power Lines" lists current thresholds of perception, pain, and injury which include statistical considerations, since concerns for safety are elevated for those individuals least physically capable of coming into contact with power frequency currents without adverse effects.[5]

IEEE 1048 also includes the industry accepted Dalziel's formula, which calculates the threshold below which 95.5% of the adult population (weighing 154 lbs. or less) will not experience ventricular fibrillation. The formula is shown below:

$I\ (mA) = 157/(t)^{1/2}$

The conclusion is that the shorter the time of contact, the higher the threshold for fibrillation, and since fibrillation is associated with the let-go current, a precursor to pain and injury, this is extremely important. However, regardless of the magnitude of contact current, it is not realistic to expect that one can control the duration of contact.

Since all of these variables are difficult if not impossible to control, we are left with trying to control the available contact current from the covered conductor, and this has been the fundamental design goal since the inception of Hendrix covered conductor systems in 1951.

Laboratory Tests of Charging Currents

In the mid-90's Hendrix undertook vigorous testing of covered conductors, at the request of numerous electric utilities as well as representatives from the National Electric Safety Code. These results were published in a series of two papers,1,6 which are available through the appropriate channels. A subset of the raw data from that study is reproduced here (in different format) to make comparisons to current magnitudes generated from theoretical calculations. Different scenarios were included in the test protocol, among them loop contact, significant area contact, and under dry, wet, and contaminated conditions.

The test specimens were ten foot sections of covered conductor, dried and cleaned prior to testing. The ground was a single strand of #14 copper (Cu) wire. A single loop of this was also used for the test labeled "1 loop wire" in Table 3 below. For the one foot of copper tape ("1 ft. Cu tape"), a 0.5" x 1.5" bare copper tape was wound around the test specimen for a length of one foot, tightly wrapped and secured with electrical tape that did not touch the insulation.

For the Wet Condition, tap water was used, applied with a cloth. For the Wet Contaminated, 100 gms of sodium silicoaluminate (used in ordinary table salt) was dissolved in one liter of tap water prior to application onto the test specimen. For the Dry Contaminated, the initial test specimen was measured after one hour of drying at room temperature (some droplets were still visible on the sample), then measured again after 1.5 hours.

For test measurement, readings were taken upon reaching the desired voltage (within 15 seconds of reaching voltage step). If current fluctuations occurred, the highest stable reading was recorded.

It should be noted that these were the first recorded tests of surface current on covered conductors, and the researchers were trying to get a handle on surface current magnitudes under varying conditions. The single loop of wire was intended to represent a point contact. The one foot of copper tape was intended to represent a contact over a larger surface area, such as perhaps two large hands wrapped around a conductor, or a section of leaves from a tree branch enveloping the conductor. The one foot of cooper tape test measurements were also good to later compare to calculations done with the same assumptions.

Testing with dry and wet conditions, as well as dry contaminated and wet contaminated, was intended to represent real world operating conditions under ideal as well as worst case conditions.

Measurements for these test conditions are shown in Table 3. Data sets shown in the table are for test voltages at or near the line voltage on a multi-grounded wye system, and are intended to replicate what one would reasonably expect to encounter in the field.

Cable (kcmil)	Black or Grey	kV Class	Test Voltage (kV)	1 loop wire	1 ft. Cu tape dry	1 ft. Cu tape wet	1 ft. Cu tape dry contam.	1 ft. Cu tape wet contam.	Calc. Values
336.4	G	15	8.0	0.021	0.282	0.688	0.325	0.448	0.303
336.4	B	15	8.0	0.019	0.299	0.430	0.321	0.440	0.303
336.4	B	25	14.5	0.051	0.422	0.599	0.449	0.507	0.367
795	B	25	14.5	0.070	0.564	1.178	0.566	1.178	0.511
556	G	35	20.0	0.128	0.609	0.672	0.643	0.646	0.536

Table 3: Hendrix Covered Conductor Charging Current - Lab Tests vs. Calculated Values (mA)

A number of conclusions can be drawn from the Table 3.

- Surface current magnitudes, at least those drained to ground through contact, will vary as a function of surface area being contacted. This seems logical at the outset: the greater area contacted, the more surface current one would expect to be available to travel to ground through the contact.
- Looking back to Figures 1 and 2, a hand and finger are shown touching the conductor, essentially a "point contact." From speaking to field people who have come into contact with live covered conductor (either accidentally or intentionally), it is with 100% certainty that I can say that no one would have the ability to wrap their whole hand circumferentially around an energized covered conductor. Their reflexes upon coming into contact with that current would automatically kick in and draw the hand back. Nevertheless, these calculations and measurements are valid inasmuch as a person coming into contact with an energized conductor could conceivably, as a result of a fall or inadvertent body movement, come into contact with a large surface area of exposed conductor.
- For purposes of safety considerations, the column which would most realistically replicate human contact with an energized covered conductor would be the column labeled "1 loop wire". Comparing these magnitudes to the values in Table 2, it can be seen that they are relatively benign (the highest value is 0.128 mA for the 35 kV 556 kcmil).
- The measurements taken with the one foot of copper tape are reassuringly close to the calculations made. When the copper tape became wet, the current values did not appreciably increase, so this is another positive result. When the copper tape became contaminated, there was another small increase in current values, although not into problematic current magnitudes described in Table 2.
- The copper tape measurement for the 25 kV 795 kcmil is higher than anticipated and seems to be an anomaly, but is included for completeness.
- Though not specifically tested, it is anticipated that long term exposure to a solidly grounded (copper tape in this case) contact with a contaminated conductor surface would produce currents in excess of the magnitudes shown in Table 3. These would produce operating conditions both unsafe for human contact and detrimental to the cable system itself. This is one reason why design of covered conductor systems for locations where the environment is inherently contaminated (seaside, industrial, petrochemical) or dry (locations with extended periods of less than one inch of rain per month) should follow guidelines set forth by Hendrix and based on IEC 60815 "Guide for the Selection of Insulators in Respect of Polluted Conditions."

CEATI Testing of Covered Conductors

In 2014 the Centre for Energy Advancement through Technological Innovation (CEATI) published an extensive report of their lab testing to measure leakage current levels available on various covered conductors, the objective of which was to compare them to theoretical calculations and to known thresholds of sensation and danger for humans coming into contact[7].

The report abstract states that "The project investigated safety concerns over leakage current produced by contact between covered conductors and [humans]. According to the literature, including data provided by OSHA, the threshold for slight disturbing shock is 5mA. Therefore, this level was considered as the safety threshold for leakage current in this study."

The CEATI study looked to the OSHA standards for expertise on physiological effects of current on the human body. It is interesting to note that while those physiological effects agreed with other studies, the thresholds in empirical terms varied somewhat. For instance, the CEATI study assumed that 5 mA was a threshold for a "slight disturbing shock," while IEEE 80-2000 uses other numbers, and the IEEE Standard 1048-2003 lists still different numbers. Still other studies used fixed thresholds rather than current ranges, as the OSHA data does. Table 4 below is from a multidiscipline collaborative effort to determine fixed thresholds for physiological effects of current on the human body[8]. A quick review of the numbers in Table 4 shows that they seem to disagree somewhat with the Table 1 (IEEE 80) numbers. The

Current	Estimated Effects of 60 Hz AC Currents
1 mA	Barely Perceptible
16 mA	Max current an average human can grasp and "let go"
20 mA	Paralysis of respiratory muscles
100 mA	Ventricular fibrillation threshold
2 Amps	Cardiac standstill and internal organ damage
15/20 A	Common fuse or breaker opens circuit to let go.

Table 4: NIOSH Estimated Effects of 60 Hz AC Currents

IEEE 80 standard says that the "let go" current is above 1-6 mA, without saying specifically what it is. The NIOSH standard says the maximum "let go" current is 16 mA, while the OSHA standard says the "let go" current is actually a range of 6-16mA. This is a large range. When one considers touch surface area, impedance of the body part in contact, and other extenuating circumstances (proximity of ground planes, etc.), it is clear that one should either avoid touching an energized covered conductor or, barring that, ensure that available touch scenario currents are well below even the lower part of this range -- 6 mA.

Table 5 below shows the charging current values from the tests conducted. The test conditions seemed to closely mirror the test conditions used in the Hendrix testing some years earlier, in that they used small and large area contacts, each under dry, wet, and polluted (contaminated) conditions. The test set-up, however, varied somewhat. For the "hand electrode," CEATI used a grounded wrap, which seemed intended to simulate a human hand, whereas the Hendrix test used a single loop of copper wire. For the "large electrode," CEATI used a flat square grounded plate perhaps 31 inches per side, so that the cable under test had a solid contact with ground, albeit along only a small portion of its circumference.

The polluted electrode used a solution of one liter of water mixed with 40 gr. Kaolin and 10 gr. of salt, although it is unclear how this solution was applied, and if a salt-fog chamber was used, what mechanism was employed to ensure there was no pooling of water on the flat surface.

Tests were run for 15 and 25 kV cables only, and no 35 kV tests were conducted. Another difference is that the Hendrix tests (and calculations) used line-neutral voltages, the objective being to mirror real word conditions, whereas the CEATI tests and simulations (calculations) used full line to line voltages. These would only be relevant if they were testing phase to phase contact, which was not done. Using full line to line voltage, one would anticipate the leakage currents measured (or calculated) to be fully √3 higher than the values one might encounter in the field.

Measurements were taken at 5 kV increments, not specifically at line voltage for a multi-grounded wye system. CEATI conducted exhaustive and rigorous testing, and the numbers shown below are a small subset of their extensive work. It is further noted that the CEATI researchers used Hendrix cables in their tests, so one would expect test value magnitudes somewhat similar to those obtained at the Hendrix labs.

ACC Cable (kcmil)	Results	Test Voltage (kV)	Hand Electrode Dry	Hand Electrode Wet	Hand Electrode Polluted	Large Electrode Dry	Large Electrode Wet	Large Electrode Polluted
1/0 15kV	Test	15	0.17	0.76	2.41	0.48	1.75	3.13
1/0, 15kV	Simul.	15	0.22	0.74	-	0.36	1.36	-
336,25kV	Test	25	0.33	1.37	3.9	1.04	2.37	5.37
336,25kV	Simul.	25	0.43	1.44	-	0.60	2.55	-

Table 5: CEATI Covered Conductor Charging Currents – Lab Tests vs. Calculated Values (mA)

Comments and Conclusions from Table 5:

- Lab test measurements were relatively close to the calculated values, with slight variations above and below. This illustrates the difficult nature of measuring such small currents and arranging a test set up that accurately simulates field conditions.
- Lab test currents for all test scenarios (hand, large, and polluted electrode) all yielded currents that are far below both the "let go" and fibrillation thresholds.

Summary and Conclusions

1. While (properly designed, installed and maintained) covered conductors are never entirely safe, they are not lethal when casual human contact occurs. This is favorable in comparison to bare wire systems, in which human contact poses a severely elevated risk of fatality.
2. Applications assessed to present an elevated risk of humans (or their equipment) coming into contact with power lines would seem to benefit from the use of covered conductor systems. Example applications include restricted right of way commercial or residential alleyways, lines strung over or close to rooftops or buildings, river crossings, boat ramps, etc. One large program in Australia addressed this need with Hendrix spacer cable after a fatality involving a sailboat mast and a bare wire crossing.[9]
3. Tests done at Hendrix laboratories, the CEATI lab test site, and simulations done at both organizations seem to corroborate each other. The test set-ups were somewhat different in terms of geometry, but leakage current measurements were fairly close.
4. What is most significant is that all test values, as well as calculated values, showed leakage or contact current values which, although admittedly not safe, per se, were consistently below danger levels (below "let go" and well below fibrillation thresholds).
5. While the calculated values and test values showed promising results, it should be noted that they were taken with the assumption of the electrode having zero impedance. In reality, the human body, while varying depending on contact point and numerous other factors, presents an impedance of between roughly 500 and 1,000. This impedance would further reduce the leakage current experienced by a human coming into contact with a covered conductor.

References:

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