Technique for Accurate Voltage Measurement of Energized Street Level Objects

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The demand and volume of "stray voltage" testing in urban areas have increased greatly in recent years. Several techniques for detecting energized objects are in use but once detected, confusion can arise between diagnostic and repair groups about the presence and magnitude of the voltage. No standard technique exists for making voltage measurements in the field. Accurate, repeatable voltage measurements are crucial both for reliable reporting and for effective cooperation between testing technicians, diagnostic technicians, repair personnel, and other parties with a stake in effective mitigation of potentially hazardous conditions. The described process eliminates sources of measurement error to ensure parity among measurements made by different individuals. Particular attention is paid to the choice of a ground reference point with no elevated potential and a low impedance path to ground.

Increased attention to shock hazards in urban, public spaces has led to increased demand for contact voltage (often incorrectly called "stray voltage") testing in urban areas. The market has responded with innovation, introducing new detection technologies with increased sensitivity. Several utilities rely on stand-off electric field detection which provides a positive indication, at a distance, of an object at elevated potential. Responding repair crews, on the other hand, have not changed measurement techniques used to evaluate the findings of such sensitive detection methods. Repair crews and follow-up investigators often base decisions on voltage measurements which are not referenced to ground, are unrepeatable due to large measurement errors, and lack valuable information about the underlying root cause(s.) Comparing absolute with relative measurements results in different or even opposing indications and repairs are replaced by confusion and finger pointing. Similar confusion surrounded measurement of neutral to earth voltages (NEV) on dairy farms until the importance of selecting a remote ground reference for all measurements was recognized. Likewise, a standardized measurement process is described here for reliable, accurate, repeatable measurements of energized objects in the urban environment at street level. This technique has been successfully applied to over 50,000 energized objects over the past 5 years. It has yielded repeatable measurements and actionable diagnostic information used in the mitigation of contact voltage.

Background

Failures in underground infrastructure or wiring errors have led to a number of highly publicized shocks to animals and people in urban areas. The media and New York State's utility regulatory agency borrowed the term "stray voltage" to describe the problem of shocks to pedestrians. This stripped stray voltage of its technical definition which describes NEV and potentials resulting from ground current flow on parallel paths between load and source. The shocks are not a result of stray voltage. Rather, they are most often the consequence of uncleared line to ground faults in underground distribution systems. Such conditions are referred to by IEEE and the industry instead as "contact voltage."[1]

Contact voltage and stray voltage differ in many respects. Contact voltage is a result of a fault to a supply conductor or faulty open neutral conductor in the secondary distribution system. It is not a steady state condition; but a function of the fault impedance. Voltage varies with environmental factors and the degree of insulation breakdown present, from a few volts up to full line voltage. It is prevalent in areas with dense buried infrastructure, often urban. It is especially common around unmetered loads (i.e.

streetlights) with small supply conductors, minimal grounding, and no occupant present to report service or reliability problems caused by the fault. Line faults are allowed to remain active for long periods because either fault current is too low to operate protective devices (nearly always fuses, not GFCI or circuit breakers) or no upstream protection is present. Similarly, open neutral conductors feeding unmetered loads also creates dangerous voltages on bonded surfaces with no mechanism to clear faults or alert the system owner/operator or public.

By contrast, stray voltage is sourced by the distribution system's neutral return current. It exists in any 4 wire distribution system, but becomes large enough to cause problems mostly at the end of long circuits, where load-to-source impedance is highest. Voltage fluctuates with circuit loading, but is relatively low (<10V) and steady state in the short term. It is 60Hz AC but typically contains significant harmonic content. It affects equipment which is typically on the load side of a metered facility. NEV will not reach significantly high voltages associated with shock injuries, but can present a significant problem to livestock, as the small but perceptible voltage between watering or feed troughs and the earth discourage drinking and affect animal behavior in other ways.

Several states such as Michigan and Wisconsin regulate stray voltage.[2] Since 2004, utility regulators in several states and in Canada have also begun to mandate testing to eliminate contact voltage.[3,4] These contact voltage regulations borrow language from stray voltage regulations, but are made with the intent of improving pedestrian safety, rather than livestock health.

Successful stray voltage management depends on well documented measurement techniques to arrive at standardized measurements of the voltage and available current. This data can be used to make decisions about mitigation. Standardized measurements emphasize the use of an isolated "true earth" reference at zero potential for all voltage measurements.[5] A similar approach is needed to manage contact voltage. Selection of a ground reference for a repeatable, accurate contact voltage measurement must consider the measurement circuit's sources of measurement error: (see Figure 1)

1) Ground reference points must be outside the voltage gradient created by the energized object.
2) Ground reference must have low impedance to ground in order to deduce the stiffness of the current source.
3) Contact impedances must be minimized.

With these issues resolved, the engineer or program manager can make decisions about mitigation based on the type and severity of the hazard.

To focus resources on contact voltage, an ideal measurement technique will also characterize the voltage source as either a fault condition or neutral return. This allows prioritization of repair efforts on contact voltage sourced by system faults which may present a shock hazard or become hazardous in the future over stray voltage, which poses little or no shock hazard. The latter can be prioritized further by touch or step potential thresholds and the potential for chronic exposure to animals. It is appropriate to consider the maximum source potential and the potential for a person or animal to be exposed to line voltage should the fault condition worsen. The ability to distinguish between contact voltage and NEV is crucial to prudent safety decisions at the technical and managerial level.

Measurement Process

Many electrical workers will be accustomed to clipping a lead to a neutral and testing the target area, possibly scratching the surface with the test probe to make contact. This activity may work on bare copper bus bars and silver plated terminals, but much more care is needed to measure voltage reliably in the field because contact impedances are high and a bare neutral is not always present and, even if it is, could be at an elevated voltage itself in the presence of an uncleared fault. The process is as follows:

1. Select possible ground references
2. Prepare measurement surfaces
3. Check for energized ground reference
4. Make no-load voltage measurement
5. Eliminate false positives using shunt-load
6. Verify shunt-load voltage measurement
7. Characterize voltage source
8. Documentation

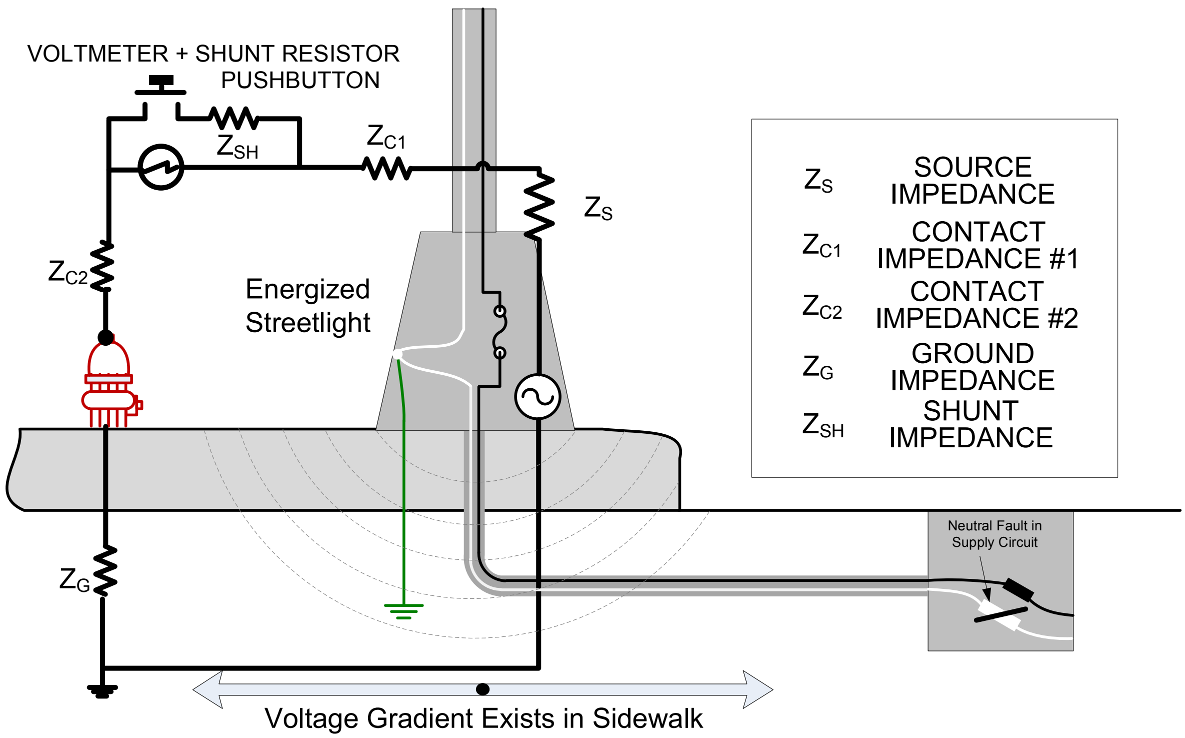

Figure 1 Measurement circuit of an energized streetlight, using hydrant as field ground. In this example, cause of contact voltage is open neutral in supply conductors.

Select possible ground references

Measurement of energized objects in the field differs from most electrical work because there is no easily accessible, well grounded common terminal. At street level, there are typically some good ground references in sight. Long ground leads (50-100ft) are recommended. Ideal references are fire hydrants, water pipes, driven bare metal fence posts or street signs, or guy wires, though none should be trusted implicitly.

Prepare measurement surfaces

Measurement accuracy and repeatability depends on good references and clean connections. Reducing contact impedance to a practical minimum is key to making an accurate measurement in the field. Metal surfaces at both the measurement point and reference must be prepared with a wire brush or file to remove corrosion and paint. Even bare metal surfaces like manhole covers have a resistive patina which must be removed from the test site to get repeatable measurements. Scratching with test lead tips will not penetrate this layer. Strong clamps ensure solid contact is made and maintained throughout the process. For non-metallic surfaces, the key to making good electrical contact is surface area. Utility regulations in dairy states and the guide published by NEETRAC suggest a copper plate with a weight applied to maximize electrode contact surface area. This works well in a wet, electrolytic environment like a muddy feedlot, but not on a hard textured surface like a sidewalk. On sidewalks, a temporary metal rod driven between the cracks or a weighted, flexible metallic pad of foil or steel wool which can conform to the surface texture makes a more solid contact. Making electrical contact for a measurement on a dry day is difficult, but the same surface becomes fairly conductive after rain or snow. Extra attention to making good contact is especially important when following up on reports of electric shock which occurred in earlier, wetter conditions.

Check for energized ground reference

Current from an uncleared fault will use all parallel paths to return to the source, which can cause unexpected voltage on nearby “grounded” objects. A symptom an energized ground reference is that everything measured against it appears to be energized at the same voltage. Using a voltmeter, take an initial measurement from a reference to the energized object. Take another measurement from a different reference. They should be the same. If not, there could be an energized reference. Choose the reference yielding the higher voltage measurement and repeat with a third reference. Using long ground leads to reach references at a reasonable distance from the measured object usually avoids this problem. The surest way to verify something is not energized is through the use of a calibrated electric field detector. A ground reference point at zero potential will emit no electric field.

Pen testers are not suitable tools for verifying ground reference points are not energized for several reasons. First, they provide only positive indications, with no way to show a tested surface is *not* energized. Pen testers depend on the user's body as a reference point and if the user is standing on energized ground, he or she is "a bird on a wire." Also, pen tester performance is greatly affected by the user. The tester must be gripped firmly, with the whole hand, without gloves. These criteria are difficult to reliably duplicate in the field among a large number of users. Finally, many devices have adjustable controls which prevent consistent detection over time among multiple users.

Make no-load voltage measurement

Measure voltage from the energized object to the selected ground reference. This is the no-load voltage to ground of the target object.

Eliminate false positives using shunt-load

Ungrounded surfaces can have significant voltage due to capacitive coupling with a nearby high voltage object like a lighting ballast, unshielded power cord, or overhead power lines. Placement of a small, known load, or shunt, in parallel between the test leads of a digital voltmeter will eliminate false positive voltages due to capacitive coupling.

$$V_{SHUNT} = V_{OC}\left(\frac{Z_{SHUNT}}{Z_{SOURCE} + Z_{SHUNT}}\right)$$

Equation 1 V_{SHUNT} collapses to 0 in cases where voltage is sourced via capacitive coupling as $Z_{SOURCE} >> Z_{SHUNT}$.

This capacitively coupled voltage is measurable on a digital voltmeter but cannot drive current through a load and is not a hazardous condition. From Eq 1, we can see that for a capacitively coupled voltage, which has very high source impedance, Z_{SOURCE} >> Z_{SHUNT} and the change in voltage with shunt applied will be ~100% of the open circuit voltage. Placing the shunt load causes voltage to "collapse" to zero because no current can flow. As of this writing, digital voltmeters are available with a built-in switchable shunt resistor designed with this test in mind.

Verify shunt load voltage measurement

When performing this test, it is prudent to retest a collapsed voltage against an additional ground reference just to verify the result was not a result of very high ground impedance and not capacitive coupling. If the voltage collapses against a second reference, the condition is not hazardous and no further testing should be performed.

For verified voltages with a current source, measurement errors can also be minimized by a verification step using the shunt resistor. Errors due to contact and ground impedance cause disagreement between testing, repair, and management personnel and the small extra effort to record repeatable voltage measurements is worthwhile. The shunt resistance must be small enough to collapse the voltage from a capacitively coupled source, but large enough not to result in variability from user to user as a result of the error.

$$V_{SHUNT} = V_{OC} \bullet \left(\frac{Z_{SHUNT}}{Z_{SOURCE} + Z_{SHUNT}}\right) \bullet \varepsilon$$

$$\varepsilon = \frac{Z_{SHUNT} + Z_{SOURCE}}{Z_{SHUNT} + Z_{SOURCE} + Z_{CONTACT} + Z_{GROUND}}$$

$$MeasurementError(\%) = (1 - \varepsilon) \bullet 100$$

Equation 1 Measurement error of shunt voltage is a function of the ground and contact impedances in the measurement circuit

Ideally, the variability in measurements as a result of typical error values in the field should be <10%. Table 1 shows shunt voltage variability for a 20Ω source impedance, low total (ground and contact) impedances (50Ω) and more realistic value (250Ω), using 500Ω and 3000Ω shunt resistors. Those impedances will vary from technician to technician and it is easy to see how a lower shunt impedance results in large measurement variability which can cause confusion and miscommunication between multiple diagnostic or repair crews.

Z_{SHUNT}	500Ω	3000Ω	500Ω	3000Ω
Z_S	20 Ω	20 Ω	20 Ω	20 Ω
Z_G+Z_C	50 Ω	50Ω	250 Ω	250 Ω
V_{SHUNT}	0.88•V_{OC}	0.98•V_{OC}	0.65•V_{OC}	0.92•V_{OC}
Error (ε)	9%	2%	32%	8%

Table 1 Measurement error (ε) in shunt voltage is large for 500Ω shunt resistor because shunt resistance is close to typical values of contact and ground impedances

Examining the result, we see that measurement error when using a 500Ω shunt is only low when ground and contact impedances are remarkably low. When more realistic values of ground and contact resistance are considered, it is apparent that measurement error increases rapidly.

The best way to implement shunt measurements in the field is through the use of a shunt resistor applied to the input terminals of the voltmeter via a switch which can be engaged and disengaged by the operator quickly without moving the test leads. The technician can then reduce measurement error through repeated application of the shunt resistor to observe the reduction in voltage drop as contact impedances are improved through tighter connections or the choice of a better ground reference. This positive feedback for the technician is an important practical consideration and is crucial to getting top performance from field personnel.

Characterize the source

Utility workers use words like “kaboom” to describe a fault, and describe faults in terms amps or kiloamps, not volts. A high impedance fault on a secondary cable, however, is not so dramatic. Insulation failure may result in leakage current through accumulated salts and moisture in a conduit or the earth with relatively low levels of current. Over time, the fault may grow more severe and eventually result in a “boom,” but otherwise current will flow from the fault proportional to the impedance of different paths to ground, per Ohm’s Law. This type of condition may remain hidden for long periods of time and may not be much more noticeable than an elevated neutral voltage until conditions are right for a shock to occur.

Recent work at EPRI and by utilities in New York have demonstrated the use of spectrum analysis for differentiating NEV from a buried fault, even at identical voltage levels. [6] The application of spectrum analysis in cases of energized objects in public spaces is a very effective way of separating small, normally occurring voltages from small voltages which could develop into shock hazards. Repair crews also gain a troubleshooting advantage, knowing in advance whether to look for a fault in supply conductors in the immediate vicinity of the energized object or degraded neutral conductors and splices upstream on the circuit. A voltmeter with the capability of measuring harmonic distortion allows the technician to characterize the source of the voltage because voltage from a phase conductor has a different waveform than neutral return. IEEE Standard 519 recommends no more than 5% voltage THD on a distribution line and no more than 3% of any individual harmonic e.g 3rd harmonic. Utilities are normally required to operate below the recommended limit, and published surveys of harmonic voltage distortion measured on distribution systems have shown that they do.[7,8] Neutral return current has harmonic distortion impressed upon it by non-linear loads which make up a large part of modern customers’ energy consumption. They can and do have THD well above 5%. Published neutral current surveys observed 30% or greater THD on rural distribution and an average of 45.8% THD at a national sample of 146 urban and suburban computer centers.[9,10] In an urban setting, a voltage with less than 5% THD is nearly certain to be sourced from distribution, and not from NEV. Such an energized object is a case of contact voltage, a potential shock hazard, and should be investigated to discover and repair its source.

Documentation

A technician must document voltage found, reference(s) used, and voltage source characteristics. Even the most rigorous procedures are for naught if another colleague following up the job does not have this information. It is the single most important step to follow.

Best Practices For Implementation

The described measurement procedure is more rigorous than any typically used by electrical workers. It is designed to yield accurate measurement and characterization of even low voltages sourced from high impedance faults. These are more difficult and variable measurements than those typical of utility work, which usually focuses on line voltages from very low impedance sources. Measurement error is a much larger concern . After making tens of thousands of contact voltage measurements in the field, the authors have developed some guidelines for accuracy and repeatability.

Use a 3000Ω shunt resistor

The shunt resistor's purpose is eliminating capacitively coupled voltages from the contact voltage data and to aid in deducing the source impedance of the fault. Sources of error in the source impedance calculation are contact and ground impedance which can be minimized by the technician but never eliminated. Field surfaces are dirty and textured. Ground references do not meet any industry standards and may add hundreds of ohms to the measurement circuit, leading to inaccurate and unrepeatable voltage measurements when a 500Ω resistor is used. To achieve less than 10% error, a common measurement engineering standard, a larger 3000Ω shunt resistance is needed.

Choose lowest impedance ground reference

One of the largest sources of error in measurement is Z_G, ground impedance. It is not reasonable to assume a field reference is grounded without verification; even fire hydrants may be connected to a section of non-metallic pipe or isolated from ground by to heavily corroded fittings. Short, temporary ground rods are also used in the field, but care must be taken to locate them far enough away from the object being tested to keep them out of any voltage gradient created by a buried fault. The most reliable way to choose a low impedance ground reference is to compare several. Measure voltage of a possibly energized object with the shunt resistor and multiple reference points. Assuming Z_S is constant for a given source and steps are taken to minimize contact impedances, the reference yielding the lowest voltage drop with the shunt applied has the lowest impedance to ground.

Conclusions

Sensitive detection of energized objects in a street level urban environment can find underground faults. To follow up with repairs, line workers must pay careful attention to eliminating sources of error in the measurement process so that they can identify the root cause and act on it. To these ends, a measurement technique is proposed based on selection of the best available ground references, and characterization of the source using harmonic analysis. These steps are possible using equipment readily available to utility field forces. Goals of both regulators tasked with control of contact voltages and the field workers and engineers tasked with mitigation are served through careful application of consistent measurement protocols. The method described here has had successful use in the real world settings for the past five years, reducing confusion between test and repair groups of several large US utilities.

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