EPRI

Ignition Scenarios and Solution Options

Technical Brief — *Distribution Systems*

Several types of faults on overhead distribution systems can ignite dry vegetation. These include high-current and low-current (high-impedance) faults. This whitepaper covers some of these scenarios with data and signatures available in the industry. Technologies and approaches to prevent or detect these scenarios are covered.

Ignition Scenarios

High-current faults (low-impedance) happen when energized conductors make contact or insulation flashes over. Here are several examples of high-current faults:

- Tree limb bridging phase-to-phase or phase-to-neutral
- Balloon, animal, or another external object
- Conductor slap
- Equipment failure

These are the most common type of fault on distribution systems, and protection equipment (circuit breakers, fuses, and reclosers) are designed to protect the system when these faults occur. In a high-current fault, the main ignition risk is burning sparks created by a high-current arc. If vegetation or flammable materials such as oil or polymer animal guards are ignited by an arc, these can increase risks of wildfire ignition.

Figure 1. High-current fault

Conductor slap (EPRI 3002014978, 2018; Short, 2014) can happen when the magnetic field from fault current produces forces between conductors all along the circuit from the substation to the initial fault location. These forces can cause conductors to swing. If they swing together, a second fault can occur upstream of the initial fault. The main scenario that causes the most issues is where the initial fault is downstream of a recloser, and a follow-on fault occurs upstream of the recloser and trips the circuit breaker. Wildfire risks are increased because one initial fault turns into two or more additional faults with higher fault currents and longer durations.

Low-current (high-impedance) faults can also cause ignitions. Scenarios include a:

- Tree touching one conductor
- Tree limb bridging phase-to-phase or phase-to-neutral
- Downed conductor on a shrub
- Downed conductor on grass

For a tree in contact with one medium-voltage conductor, the resistance of the tree is high enough to remain a high-impedance connection; it will not draw enough current to operate a fuse or other protective device. (EPRI 1016219, 2007; EPRI 1018463, 2008). Currents in the hundreds of milliamperes can be drawn if the contact point is to a larger-diameter main structural component of the tree. Such a condition may ignite flames (Figure 2). If a branch or trunk of a tree bridges between two conductors (phase to phase or phase to neutral), the fault will start out as a high-impedance fault (Figure 3). A tree branch between two conductors can progress to a low-impedance (nearly bolted) fault. Arcing occurs at each end where the wire is in contact with the branch. At this point in the process, the current is small (the tree branch has high impedance). The arcing burns the branch and creates carbon by oxidizing organic compounds. The carbon provides a good conducting path. Arcing then occurs from the carbon to the unburned portion of the branch. Once the carbon path is established completely across the branch, the fault is a low-impedance path. Now, the current is high—it is effectively a bolted fault. It is also a permanent fault. The likelihood of a low-impedance fault depends on the voltage gradient along the branch. Smaller diameter branches can burn clear before the burning transitions to a low-impedance fault. That is still an ignition risk because the burning branch can fall into other vegetation.

Energized, downed conductors are a significant ignition source. Arcing normally happens at multiple locations where a conductor contacts the earth (Figure 4). A conductor can remain energized on the ground because the current is often much lower than needed to operate a relay or a fuse. Fault currents range from 0 to 100 A (EPRI DRC-1, 2022; EPRI 3002012882, 2018). Ignition can happen quickly (Marxen Consulting report, 2014).

Figure 2. One phase conductor contacting a tree

Figure 3. Tree-limb phase to phase

Figure 4. Downed conductor on grass

Downed conductors happen because of failure of overhead hardware. Several stresses can cause these failures, including mechanical forces from falling trees, vehicle impacts, or other sources. Equipment such as splices can fail due to deterioration and due to misapplication. Arcs from faults can also damage conductors and line hardware and cause burndowns. Arcing damage is a function of fault current and duration (EPRI DRC-2, 2022; EPRI 1017839, 2009).

High-current, low-impedance faults occur at a rate ranging from 50 to 350 faults per 100 circuit miles per year on overhead lines in North America (Short, 2014). Weather plays a major role in fault rates. Industry information on the frequency of high-impedance faults is more limited. Most utilities responding to an IEEE survey reported that high-impedance faults made up less than 2% of faults while a sizeable number (15% of those surveyed) suggested that between 2 and 5% of distribution faults were not detectable (IEEE Working Group on Distribution Protection, 1995). In a sample of 3605 events, PP&L found that broken conductors accounted for 11% of faults (IEEE, 1989). Downed conductors remained energized for about one third of events or 3.4% of all faults.

Signatures and Data

Many scenarios with wildfire risks have characteristic signatures or patterns. Others are less apparent. See the appendix for example signatures. High-current faults often look similar. The current instantly jumps to a near-bolted fault. The fault current is based on the system impedance to the fault location. The arc itself has voltage, and that signature can reveal information about the type of the fault. Arc length and arc voltage are closely related (Short, 2014), and this can be used to differentiate between some fault types.

Faults can recur at a location because of damage or clearance issues. For example, a fault might cause repeated temporary faults in a location where trees push conductors together. It may only happen with certain wind speeds and direction. Flashover across insulation can also recur based on weather conditions. These recurring patterns can be identified by tracking patterns of phasing and fault currents.

Some faults and ignition risks have precursors to failure. These are referred to as *incipient* events. As an example, arcing at a splice can damage the splice, and when the splice fails, that can lead to a low-current fault and/or an energized, downed conductor. The series arcing can be used to identify this incipient event.

High-impedance faults can have unique characteristics. The currents from these are high in harmonics, and the current varies with time as the arcs flicker in and out. Energized, downed conductors often involve a broken conductor, and the broken conductor affects currents and downstream voltages.

Table 1 shows several scenarios along with data sources that EPRI has collected as part of several projects.

Table 1. EPRI data available by scenario

Scenario	Source
High-current faults	PQM, relays
Incipient events	DFA, EFD*
High-impedance faults	
Tree touching one conductor	Tests
Tree limb bridging conductors	Relays, PQM
Downed conductor on a tree	Relays, DFA
Downed conductor on grass	Relays, DFA
Special situations	
Burndowns	Tests
Conductor slap	Relays

DFA = distribution fault anticipator
PQM = power quality monitor
Relays = digital relays or recloser controls
Tests = results from tests
*Ongoing research

Technology Solutions

Several technologies are available to identify faults and scenarios with ignition risk.

Protection Changes

Changes to relay settings and other protection practices can help reduce ignition risks (EPRI 3002018773).

- ***Fast relaying***—Clearing faults more quickly reduces ignition risks from sparks. This practice also reduces downed conductors because conductor burndowns are less likely. Damage at splices is also reduced. Failures inside equipment are less likely to breach the enclosure and create an ignition risk. Faster relaying will also help limit movement of faults and flashovers on other phases and other circuits.
- ***Block reclosing***—Reclosing is normally used to restore service quickly after a temporary fault. Reclosing raises ignition risks. It is common for a downed, broken conductor to start as a high-current electrical fault, either because the mechanical changes caused conductors to contact or because a fault caused a conductor to burn apart. The system protection will normally clear this fault before the broken conductor hits the earth. Reclosing will then energize the downed conductor. So, blocking reclosing is an effective way to reduce ignition risks. The circuit can be patrolled prior to a directed reclose.

Both of these practices sacrifice day-to-day reliability for customers. So, some efforts are being considered to balance coordination and impacts on wildfire risks. Fast communication between reclosers can allow fast tripping while still coordinating between devices. This can be done with fiber optics or low-latency wireless approaches.

Fault Location

Impedance-based techniques to identify fault locations can help utilities manage ignition risks. These approaches can estimate the location of high-current faults (EPRI 1012438, 2006; Short, 2014). This capability is available using most digital relays and recloser controllers. In near real-time, a utility can use this capability to direct firefighting resources to predicted locations to catch ignitions as early as possible. For recurring temporary faults, using location estimates can help a utility find and fix problems.

Arc voltage can also be estimated as part of fault locating (EPRI 1012438, 2006; Short, 2014). This can help improve the accuracy of fault locations and provide insight into the type of fault. Hydro Quebec has successfully used arc voltages from a monitoring system to determine fault type. The monitors were developed to locate faults to improve maintenance; these monitors are toward the ends of circuits. Tremblay et al. (2007) and EPRI 1021999 (2011) show examples of faults that were categorized based on arc voltage. Faults with higher arc voltages correspond to longer arcs, and this information was used several times in conjunction with fault location estimates to identify weak spots and to identify corrective action. Such maintenance included insulator replacement, cutout replacement, and targeted vegetation management. Faults with very low arc voltages are direct conductor-to-conductor contacts.

Current-Limiting Fuses

Current-limiting fuses are fast and unlike most protective devices, they can limit the current let through. That reduces the likelihood of ignition. Current-limiting fuses can be applied on taps on medium-voltage circuits. Fuses that are electronically triggered can also be used to protect an entire feeder (G&W CLiP, 2022). A CliP can be enabled or disabled remotely, so a utility can change operating modes based on wildfire threats. Disadvantages include cost and necessity for a field visit to replace devices. Overcurrent coordination is not generally possible.

PulseCloser

The S&C PulseCloser (2022) technology has the ability to use fast, "pulse" closes. This is a low-energy approach to reclosing. The pulses test whether the integrity of the insulation is sufficient. If so, a solid close follows. Each pulse is less than a half cycle and has low current magnitude. That reduces ignition risks when reclosing. A disadvantage is that the pulse cannot detect some high-risk scenarios. That includes high-impedance faults like downed conductors or some tree branches between conductors.

REFCL

Rapid Earth Fault Current Limiter (REFCL) technology is a tuned Peterson-coil grounding system that uses a dynamically-variable neutral impedance which will respond to faults to choke off any remaining ground fault current. REFCL technologies have been trialed and rolled out by AusNet (report, 2018) and Powercor (report, 2018) 22-kV grids since 2017. They have estimated that the technology has reduced fires due to powerline faults by 50%. Field deployments are shown that this impedance tuning effect completes within approximately 5 cycles of fault initiation and can reduce ground fault current from the order of amps to tens of amps at time of fault initiation down to below 0.5 A once tuning completes. A key advantage of the REFCL is that it is unique in its ability to limit fault current from downed conductors. A disadvantage is that it is not possible to locate faults, and the system will de-energize the whole bus section. This system is applicable to three-wire systems. It cannot be applied on four-wire distribution systems.

Relay-Based High-Impedance Fault Detection

Several commercially relays and recloser controls have algorithms available to detect high-impedance faults (EPRI DRC-3, 2022). These look for signatures of arcing. That may include measures of fluctuations, interharmonics, and harmonics in currents.

Many of these detection algorithms are used only in alarm mode. That is changing. Pepco (Depew et al., 2006) and PPL (Kistler, 2021) have reported successes tripping circuit breakers and reclosers when high-impedance faults are detected. Both utilities only trip for scenarios where there is a low-impedance fault followed by a high-impedance signature. This is common scenario for a downed conductor: an electrical fault happens at the same time as the mechanical or electrical damage, and then the system reclose energizes a downed conductor.

A prediction of location is not available with these systems. That can make these difficult to find. If there is a low-impedance fault along with the high-impedance fault, that signature can be used to locate the event. A key disadvantage of these systems for fire ignitions is the time it takes. An energized, downed conductor can ignite vegetation very quickly, and a relay-based arcing fault detector is not fast enough to prevent this. Therefore, it is best used to identify high-risk scenarios and dispatch resources to that location.

SCADA and AMI-Based Broken-Conductor Detection

Broken conductors can be identified by loss of voltage or by undervoltage on distribution systems. Reclosers and other intelligent devices can detect these scenarios. This can work by alarming on loss of voltage and comparing that with the status of upstream devices. Another approach is comparing to the status of a device with the prediction of an Outage Management System (OMS). A "false outage prediction" may be caused by a broken conductor. Visualization of outages in an OMS can show this pattern (EPRI 3002019790, 2020).

Pinging AMI meters is another way to identify and locate broken conductors (EPRI 3002012882, 2018; EPRI 3002019883, 2020). Utilities can use this approach to identify broken conductors even on laterals. Whenever the OMS predicts a fault on a fuse, it pings meters on the first transformer past the device. A response indicates a possible broken conductor past that transformer. Further pinging can identify a more precise location for the break.

These systems are slow. It can take 15 minutes for the system to identify the issue and for an operator to locate it and trip an upstream device. A utility can still use this technology to identify possible high-risk events and to dispatch resources to that location. Because AMI systems have such wide coverage, location is generally accurate.

Falling-Conductor Detection

A system to detect falling conductors uses voltage measurements and fast communications to trip an upstream device if a broken conductor is detected. Pilots by SDG&E have demonstrated the effectiveness of this system (O'Brien et al., 2016). Tripping operates in less than one second using synchrophasor measurement units (PMUs) and a fast communication system. The system can operate before a falling, energized conductor strikes the earth. Systems by Schweitzer (SEL link, 2022) and General Electric (GE link, 2022) are commercially available.

This technology does not work as well in cases where there is a high-current fault along with the conductor break (a common scenario). The system has to add a delay for this scenario. This technology works best for scenarios that do not have an initial fault, like a failure of a splice where the energized conductor drops directly to the earth.

Online Monitoring

Monitoring capabilities are emerging to assess system condition and identify emerging issues. For an overview of approaches, see EPRI 3002021657 (2021). The Distribution Fault Anticipator (DFA - site) is a monitoring system that can identify several classes of emerging issues that could trigger wildfires. The DFA can identify emerging issues such as failing connectors and splices, issues with insulators, and issues with capacitors. It can also identify several types of recurring issues. Events with high current can be located, but low-current events can be difficult to locate in the field.

The Early Fault Detection (EFD - site) system by IND Technology uses non-contact sensors to detect partial discharges on a system. Sensors are deployed periodically along a line. Discharges are detected and located by triangulating time of arrival of signals on adjacent sensors. See EFD report (2019) for results from applications in Australia. A key advantage of this system is an accurate location prediction.

Acknowledgements

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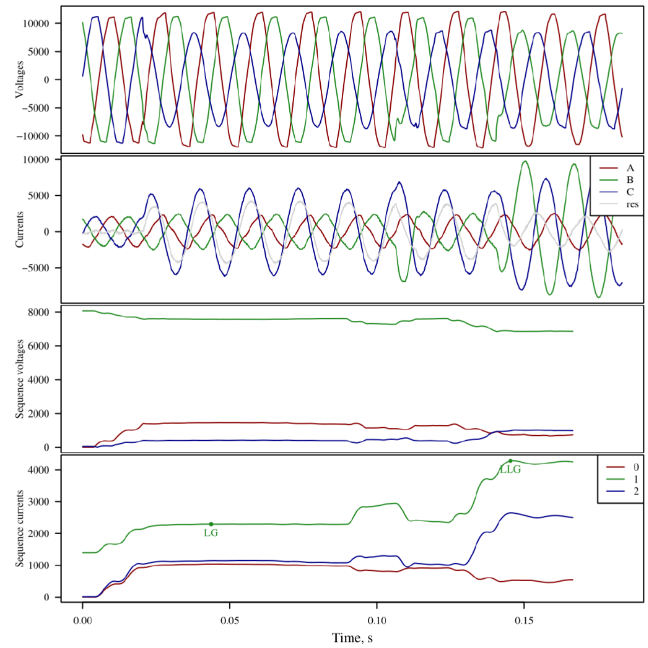
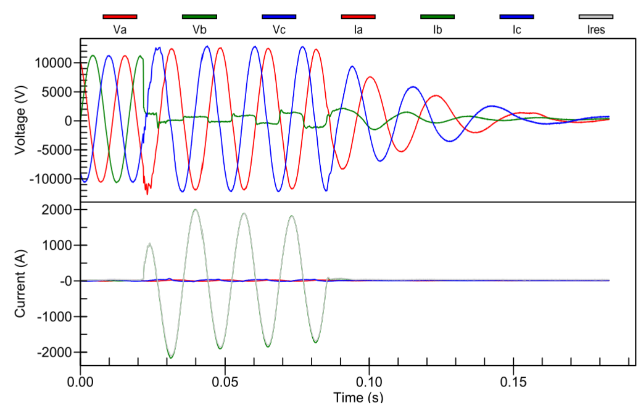
Appendix: Example Signatures

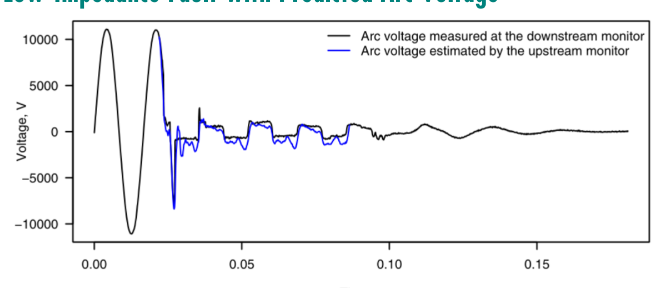
Low-Impedance, Evolving Fault



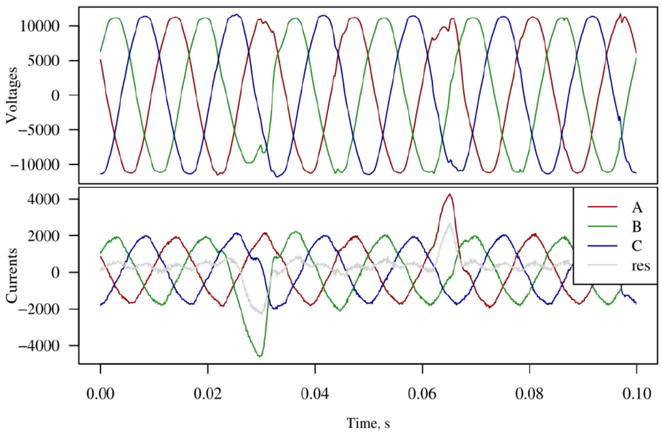
Low-Impedance Fault with Arc Voltage



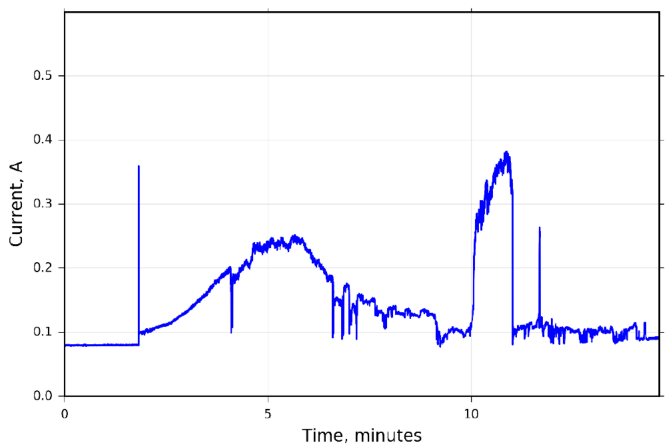
Low-Impedance Fault with Predicted Arc Voltage

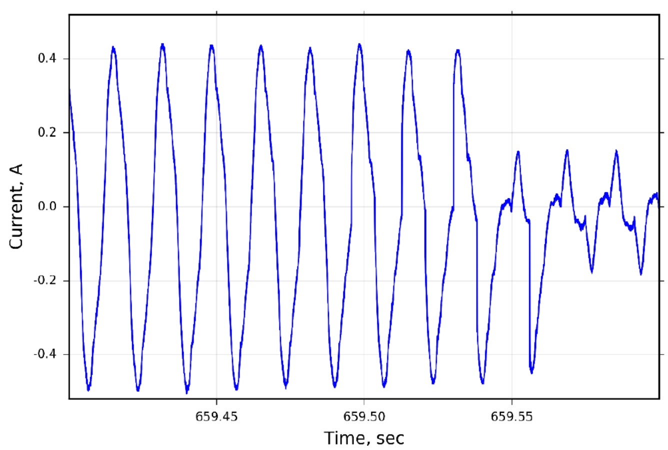


Incipient Signature

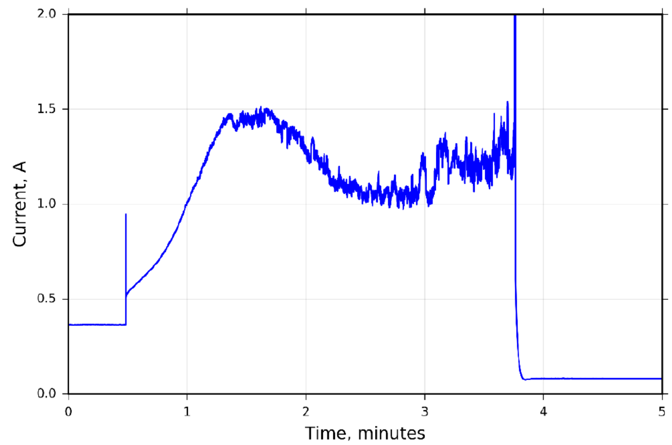


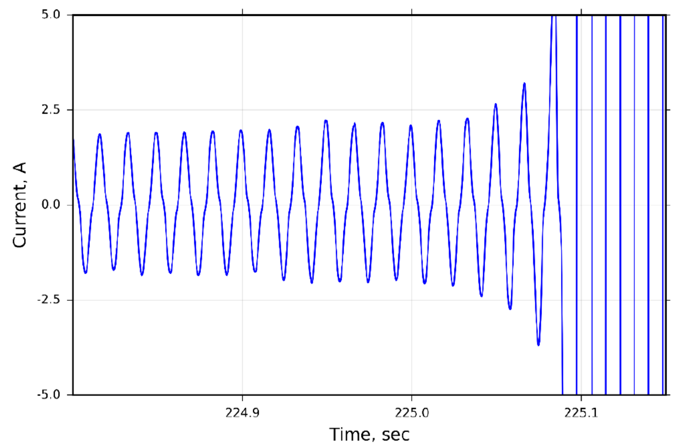
Tree Branch, Phase-to-Neutral



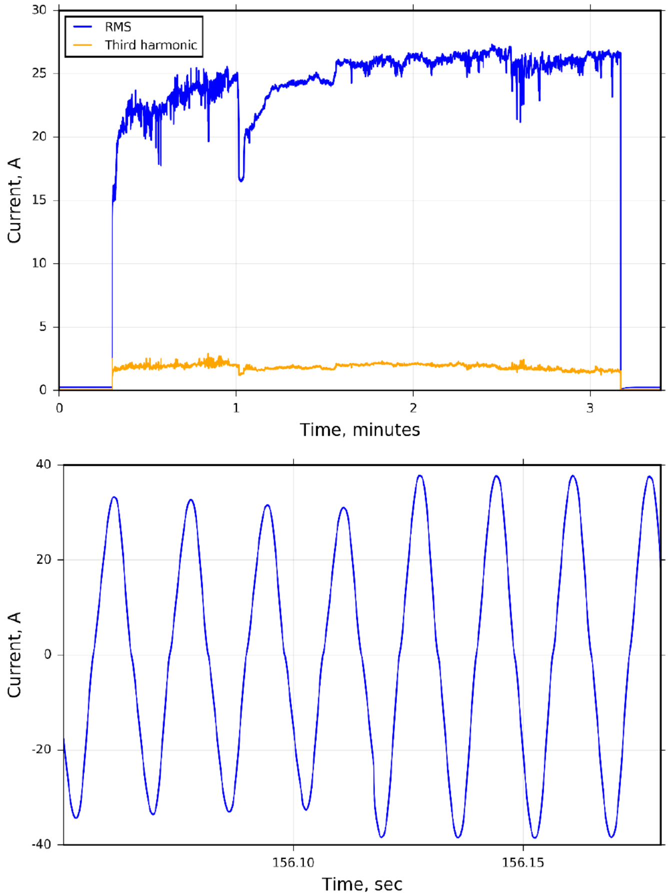


Thicker Tree Branch, Phase-to-Neutral

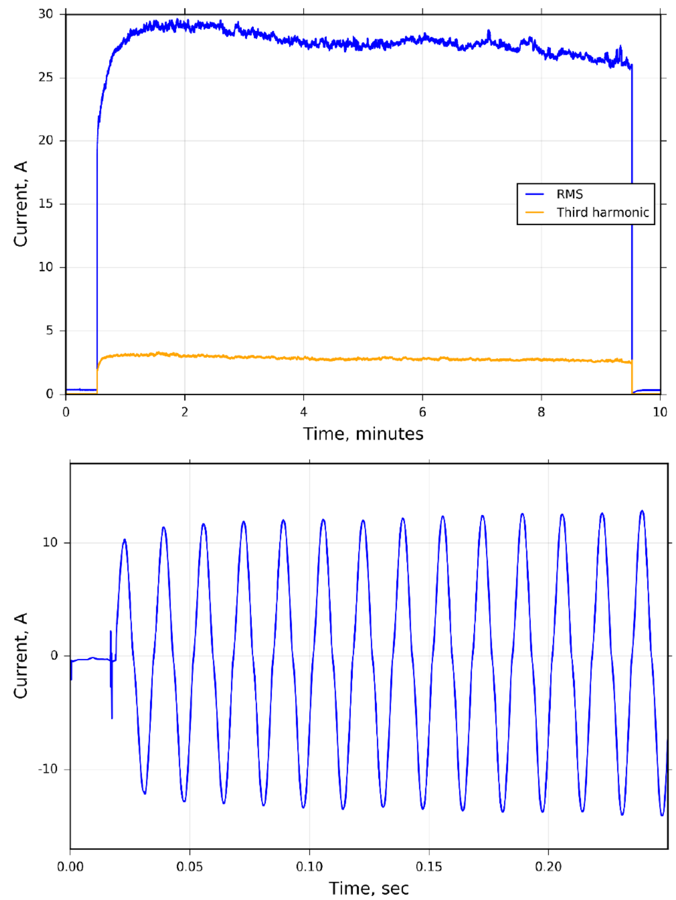




Energized, Downed Conductor, Highly Variable



Energized, Downed Conductor, Low Variability



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Contact Information

For more information contact the EPRI Customer Assistance Center at 800.313.3774 (askepri@epri.com).

EPRI Resources

Tom Short, *Senior Technical Executive*
tshort@epri.com

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com