Considerations for Downed-Conductor Mitigation

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⚠ WARNING

This application guide has recommendations for protection engineers focused on risk mitigation for downed energized conductors. The information contained herein is intended only for qualified persons who are knowledgeable in the selection, setting, installation, and operation of overhead electric power distribution equipment along with associated hazards. Downed conductors are one of many factors that protection engineers must consider when designing distribution system protection schemes. Protection and coordination schemes must be developed and approved by qualified persons familiar with the principles of selective coordination and system protection. This application guide is not intended as a substitute for adequate training and experience in safety procedures for the intended equipment. More information on distribution system protection can be found in IEEE Standard C37.230-2020, IEEE Guide for Protective Relay Applications to Distribution Lines.

Over the last decade, many electric utilities have deployed single-phase electronic reclosers on their overhead lateral lines. A limited set of standard settings groups are often used to facilitate simplified deployment of reclosers at this scale, but care should be taken to consider how these settings groups interact with varying wire sizes and may increase the potential for downed conductors (which can be a particular nuisance for smaller wires).

This application guide provides guidance for protection engineers to consider when selecting settings for single-phase electronic reclosers to help mitigate the risk of downed conductors, including an overview of downed-line mechanisms, the types of damage curves used for line protection, categories of faults when considering downed lines, and associated protection considerations.

Before considering protection strategies to reduce instances of downed conductors, it is important to understand how conductors fall to the ground, and the fault types that can occur on these lines. Overhead lines can fall to the ground because of three main mechanisms:

External Force. A tree falling onto the line, or a vehicle striking a utility pole—either breaks the wire or dislodges it from the pole. As the wire falls to the ground it can create a high-current momentary fault on its way down. When the line hits the ground, it can create a high-impedance (Hi-Z) arcing fault. External force is believed to be the primary mechanism causing downed conductors.

Conductor Annealing. Extended fault-current durations may heat the wire beyond its annealing point. When this happens, the conductor expands, experiences a reduction in tensile strength, and the tension on the line is reduced. An annealed conductor may remain in service, but given the reduction in its strength, repeated stresses (such as those caused by wind and weather) may eventually result in that conductor breaking and falling to the ground.[1]

Arcing Faults. An arcing fault may heat a wire enough to melt the wire at the location of the fault. An example is a dislodged tree branch lying across two uncovered conductors.

Overcurrent protective devices (fuses or reclosers) cannot prevent line breakage from external forces. However, with proper consideration of protection settings, conductor annealing and damage from arcing faults can be mitigated through a reduction of fault energy. These considerations will be explained in the "Protection Considerations" section on page 6.

A primary objective of protective devices on power systems is protecting power system components from damage because of prolonged overcurrent events. As a result, damage curves have been developed for conductors, transformers, and capacitor banks that consider their physical characteristics. There are two types of damage curves for conductors described in the following sections. (Melting damage curves are not covered, because annealing damage occurs before melting damage.) For more information regarding damage curves for overhead lines, refer to Section 4.2 of IEEE Standard C37.230-2020, IEEE Guide for Protective Relay Applications to Distribution Lines.

Annealing Damage Curves

Annealing damage curves for overhead conductors have been well-established by conductor manufacturers, and are commonplace in the industry. These curves are widely available in various coordination programs. Qualified protection engineers have the knowledge and experience to set protective devices to protect conductors from annealing damage. Example annealing damage curves for 1/0 A.C.S.R, aluminum, and copper conductors are plotted in Figure 1 below.

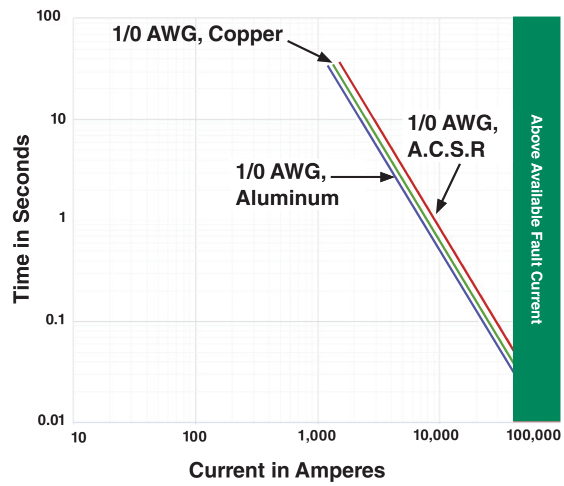

Figure 1. 1/0 AWG damage curves for A.C.S.R, Copper, and Aluminum conductor types.

Arcing Damage Curves

Arcing damage curves for overhead conductors are less frequently used and not as available from conductor manufacturers as annealing damage curves. These curves are available in some power system protection programs and at the Electric Power Distribution Handbook website.[2] Appendix B reviews tests that S&C has performed on overhead conductors to understand the burndown behavior of small overhead wires in a laboratory setting.

The data supports the conclusion that arcing damage generally occurs faster than annealing damage at a given fault current. Therefore, the use of arcing damage curves when configuring single-phase reclosers may reduce the potential for downed conductors.

When considering overcurrent protection schemes that protect against downed conductors, it is important to understand different fault classifications and how these can impact conductor integrity.

High-ampere through-faults. Through-faults that do not involve a broken conductor are unlikely to be a direct cause of downed conductors. These faults are characterized by low-impedance and high magnitude, and protective devices typically operate quickly in response to these faults.

High-ampere arcing faults. For single-phase overcurrent protective devices, high-ampere arcing faults are indistinguishable from high-ampere through faults. Arcing damage curves should be considered when determining protective device settings for these faults.

Medium-ampere arcing faults near the protective device's minimum pickup. These faults—which could result from objects touching the wire while in the air, or when the wire is on the ground—may be picked up by single-phase protective devices, depending on the device's minimum pickup threshold. However, these faults do not maintain a relatively constant fault current and are intermittent in nature. Proper setting of the single-phase protective device reset times can reduce the possibility of the device either a) not tripping in a timely manner, or b) not locking out after the expected number of operations. On distribution feeders, faults not picked up by a single-phase protective device are often picked up by ground protection of upstream three-phase protective devices, which can be set more sensitive than the phase protection of single-phase protective devices.

High-impedance (low-ampere) arcing faults. No single-phase protective device (whether a fuse or recloser) can effectively protect against high-impedance (low-ampere) arcing faults. Some advanced relaying schemes for three-phase reclosers and breakers have attempted to sense the high-impedance signature of these events through complex harmonic analysis, but these schemes are often not applicable to single-phase applications, cost-prohibitive for localized lateral protection, and have a mixed performance record.

There are three protection consideration categories for downed-conductor mitigation: general considerations, fuse-blowing and lateral-reclosing scheme considerations, and fuse-saving scheme considerations.

General Considerations

The following can be considered generally to reduce the potential for downed conductors on overhead lines:

1. **Consider the cumulative heating effect on conductors of multiple reclosing shots.** Traditionally, overcurrent events on conductors are mitigated by coordinating the protecting device with the damage curve of the conductor. This approach is logical for single-shot devices like fuses but does not account for the cumulative heating effects present when a recloser tests the line multiple times. The accumulation of heat energy in the conductors should be accounted for when coordinating reclosing devices.

2. **Increase the TCC Reset Time of the recloser**. Fault current magnitude for high-impedance (Hi-Z) faults when the conductor is on the ground depends on several factors (including impedance of the ground material, system voltage, and available fault current at the location of the fault). Fault current can linger around the **Pickup** value of the TCC (depending on the selected protection curve). A low **TCC Reset Time** value can cause a recloser to fully reset in as little as 100 ms after a TCC timing event disappears. This behavior is different than how fuses respond to intermittent low-magnitude fault currents, where elevated current levels heat the fusible element. This heating is typically retained for several seconds, depending on the speed of the fuse. Therefore, a longer **TCC Reset Time** value can cause the recloser to respond to a downed conductor in a manner that more closely resembles the protection provided by a fuse.

   Another option is to use an electromechanical (E/M) reset characteristic rather than a definite time (D/T) reset characteristic. An E/M reset characteristic will reset its timing slower at higher currents and faster as current levels decrease. This more closely matches the physical nature of fuses cooling over time, as compared to D/T reset characteristics which are based on a fixed time. Regardless of the reset characteristic chosen, reset times should be coordinated with upstream reclosing devices to ensure proper selective coordination. For more information on how fuses accumulate and dissipate heat during reclosing sequences, refer to S&C Technical Paper 200-T76.

3. **Increase the O/C Sequence Time of the recloser**. If the recloser does trip on the downed-conductor fault, but the fault is intermittent and takes time to reappear, a short sequence reset time will cause the recloser to reset back to its initial trip (TCC0), rather than continuing through its sequence to lockout.

Fuse-Blowing and Lateral-Reclosing Considerations

The following can be considered for fuse-blowing and lateral-reclosing schemes to reduce the potential for downed conductors on overhead lines:

1. **Use a faster overcurrent response on the initial time-delayed operation.** For a fuse blowing or lateral reclosing scheme with selective coordination on initial trip, the first shot should only be as slow as necessary to coordinate with downstream devices (to allow faults in the downstream device's zone of protection to be cleared by that device).
2. **Configure subsequent operations after initial trip to operate as fast as is feasible**. After the initial operation, subsequent recloses indicate the fault is likely within the recloser's zone of protection, which means there is no need to coordinate with downstream protective devices (because they do not see fault current). If the single-phase recloser has an inrush restraint function and was coordinated on the initial operation, the only factor to consider for limiting the response time of subsequent operations is hot-load pickup, because cold-load pickup is not applicable in the midst of a recloser's operating sequence. Additionally, TripSaver Reclosers have a second-harmonic inrush restraint feature, to help reduce the likelihood of nuisance trips. With the inrush restraint feature, instantaneous trip operations can be considered to decrease response times.

Fuse-Saving Considerations

The following can be considered for fuse-saving schemes to reduce the potential for downed conductors on overhead lines:

Consider shifting to a single time-delayed (slow) operation and configure fuse-saving operations to trip as fast as is feasible. Because the likelihood of a line dropping due to arcing damage is a function of a fault's energy, it is more likely the line may survive the fast operations, but melt and fall to the ground during the time-delayed operations. Configuring the time-delayed operation at the end of the reclosing sequence and using only one time-delayed operation reduces the likelihood of reclosing into a downed line.

Conclusion

As described in this guide, special care should be given to protection configuration for downed-conductor scenarios on overhead lines. Single-phase electronic reclosers provide many more options for advanced protection schemes compared to fuses or hydraulic reclosers, and traditional reclosing philosophies for larger-conductor applications may need adjustment to suit small-wire protection. Arcing damage curves are faster than their annealing counterparts and using arcing damage curves can help protection engineers select protection settings to reduce the risk of breaking conductors because of arcing damage. A conductor that has fallen to the ground is extremely difficult to detect whether using a fuse, single-phase hydraulic recloser, or single-phase electronic recloser. Through careful consideration, protection engineers can select single-phase recloser settings for small-wire protection where appropriate.

Hot-load pickup. This is defined as the pickup current seen by a protective device immediately following a short-duration outage (less than 30 minutes), such as a momentary outage during a recloser's operating sequence. The hot-load pickup current following a **Close** operation is assumed to be a combination of magnetizing inrush from downstream transformers, plus inrush current associated with the start of motor and lighting equipment.

Cold-load pickup. This is current seen by a protective device following a longer-duration outage (30 minutes or more). Because of the longer outage time, a loss of load diversity occurs. When power is restored, a temporary increase in current occurs from loads with cycling characteristics (such as air conditioning units, electric heaters, and refrigerators) turning on.

Fuse-saving. This is a protection scheme where an upstream recloser is intentionally miscoordinated with a lateral fuse to attempt to restore power automatically for temporary faults in the fuse's zone of protection.

Fuse-blowing. This is a protection scheme where lateral fuses are coordinated with upstream devices, and the lateral fuses operate to clear any fault in their zone of protection, regardless of whether the fault is temporary or permanent.

Time-current characteristic (TCC). This set of curves corresponds to the expected response time of a protective device for various current values.

TCC Reset Time. This is the amount of time it will take to reset a recloser's TCC timing after the loss of fault current before the initiation of a trip command.

Electromechanical (E/M) Reset. This is a type of TCC reset that mimics the electromechanical reset characteristics of induction-disc overcurrent relays. The specified value is the time delay (in seconds) before the curve resets when the **Time Multiplier** setting is "1" and load current is zero amperes. The actual reset time is calculated using the following equation:

$$\frac{\text{Reset time} * \text{Time Multiplier}}{\left(\frac{\text{Load Current}}{\text{Min Trip}}\right)^2 - 1}$$

Definite Time (D/T) Reset. This is a type of TCC reset that operates using a user-configured set time which functions independently of the load current seen by the protective device.

O/C Sequence Time. This is the amount of time it will take to reset a recloser's operating sequence after a **Close** operation where normal current is present. For example, on a recloser programmed with 4 trip operations (three reclose attempts), if a temporary fault occurs, and the recloser successfully closes after the second reclose attempt, the O/C Sequence Time is the time it will take for the recloser to reset to its initial trip setting.

Damage Curve. This is a curve representing the amount of energy which will cause a power system component (such as a conductor, transformer, or capacitor bank) to experience irreversible damage. For conductors, there are three types of damage curves – annealing damage curves, melting damage curves, and arcing damage curves.

Introduction

General concern regarding downed small-gauge overhead conductors has renewed interest in burndown characteristics. Limited investigations of burndown characteristics have been completed and are summarized by T. A. Short in Electric Power Distribution Handbook (Second Edition).[3] S&C reproduced some of the existing data and supplemented it with additional data for conductor types not previously tested. The information collected by S&C (presented below) is used to provide enhanced guidance for customers on settings configuration for TripSaver Recolosers.

Burndown times were recorded for bare 1/0 ACSR, bare #2 ACSR, and bare #2 copper at 1 kA, 2 kA, and 4 kA per the test setup shown in the following section. The test was completed in the High Power Lab at S&C Electric Company in Chicago, IL.

Test Setup

The test used conductors 10-feet (3-meters) long. Like Lasseter,[4] the conductors were tensioned to 650 lbf (2891 N). Like Goode,[5] an arc was initiated along a strike wire connected from an energized electrode to the conductor which was grounded at each end. The electrode was positioned perpendicular to and either 3 inches (76 mm), 6 inches (152 mm), or 9 inches (229 mm) from the center of the conductor. This setup allowed the arc current to split evenly to both ends of the conductor, minimizing motoring. In some tests, the initially-configured energization time is not long enough to burn down the conductor, so a second follow-up shot was conducted in those tests.

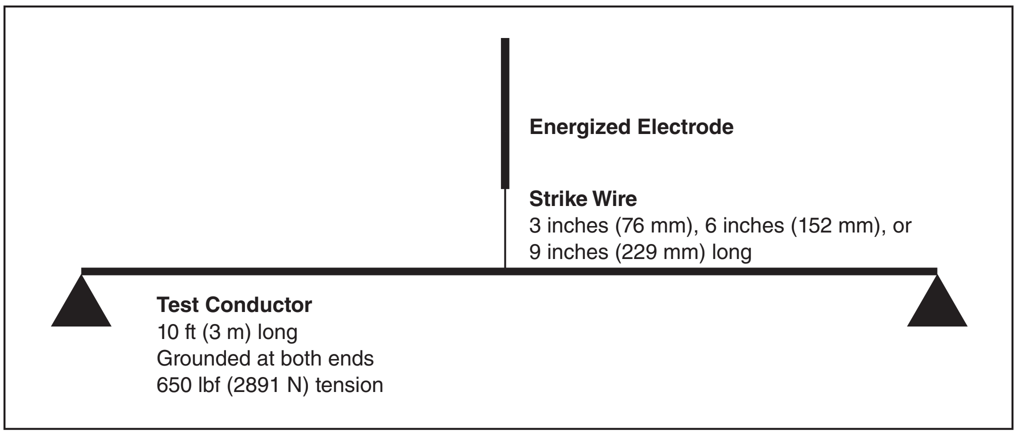

Figure 2.

Results

The data listed in the tables and the individual points shown on the plots represent each burndown time, t_i, that was recorded for this study along with the corresponding arc current, I_i. As was done in the Handbook,[3] a curve fit of the form $t=a/I$ was applied to the data for each conductor type and plotted. The fitting is equivalent to a linear fitting of the form $\log t = \log a - \log I$. The log-normal distribution of t is observed in the experiment data, therefore a sample standard deviation, s was calculated for each conductor type using the following equation:

$$s = \sqrt{\frac{1}{(N-1)} \sum_{i=1}^{N} (\log t_i - (\log a - I_i))}$$

Using s and a z-score $z_{0.01}$ of -2.326, a curve of the form $\log t_{0.01} = \log a - \log I + z_{0.01}s$ was plotted, above which 99% of burndown times should occur. This form is equivalent to $t_{0.01} = a/I * \exp(z_{0.01}s)$. Similarly, $t_{0.1}$ is calculated, above which 90% of burndown times should occur.

Also plotted are curves of the form $t_{(\text{Short},0.1)} = a/I$ provided by Short on his website.[2] Like $t_{0.1}$, they represent a line above which 90% of burndown times should occur. None of these curves are a direct fit of any particular dataset, rather they are the result of a quantile regression of existing data summarized in the Handbook. This allows Short to provide curves for bare 1/0 ACSR and bare #2 copper despite there being no data available for those conductors until now. It is also important to note the curve provided by Short for #2 ACSR is a result of the same analysis and is not a direct fit of any particular dataset despite there being data available for #2 ACSR.

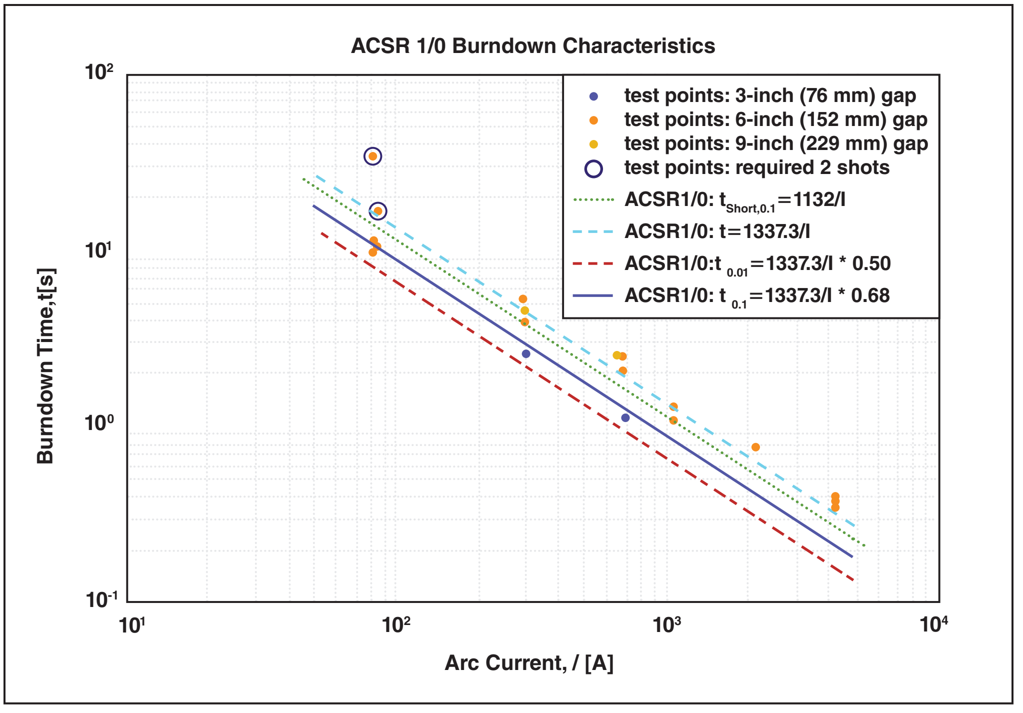

Figure 3. ACSR 1/0 Burndown Characteristics

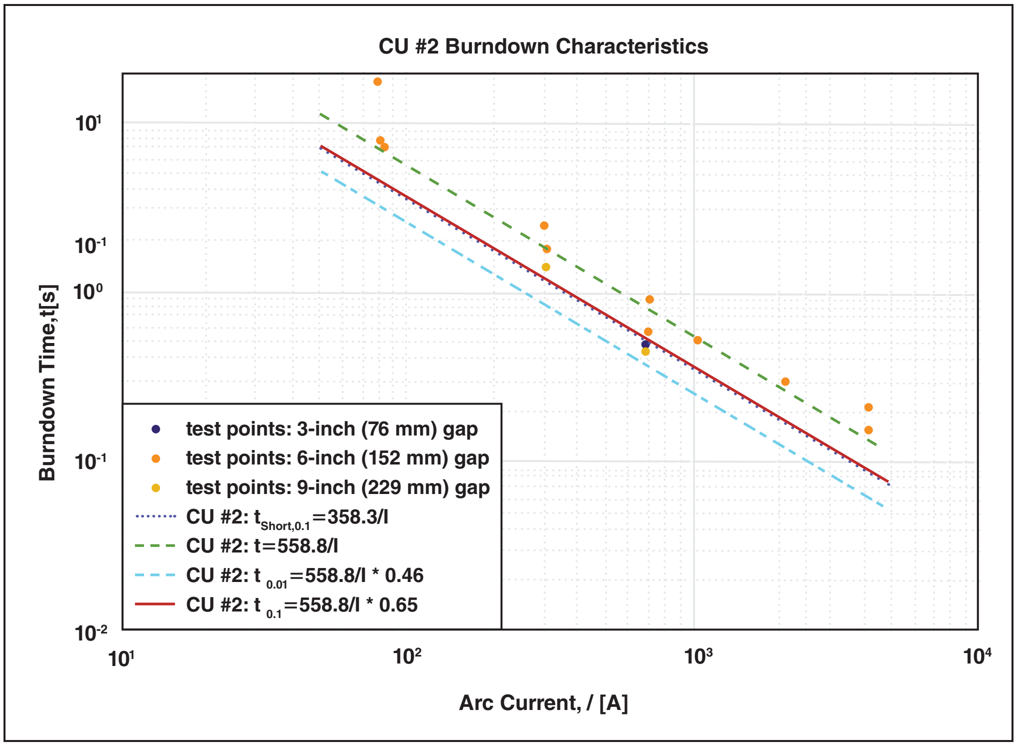

Figure 4. CU #2 Burndown Characteristics

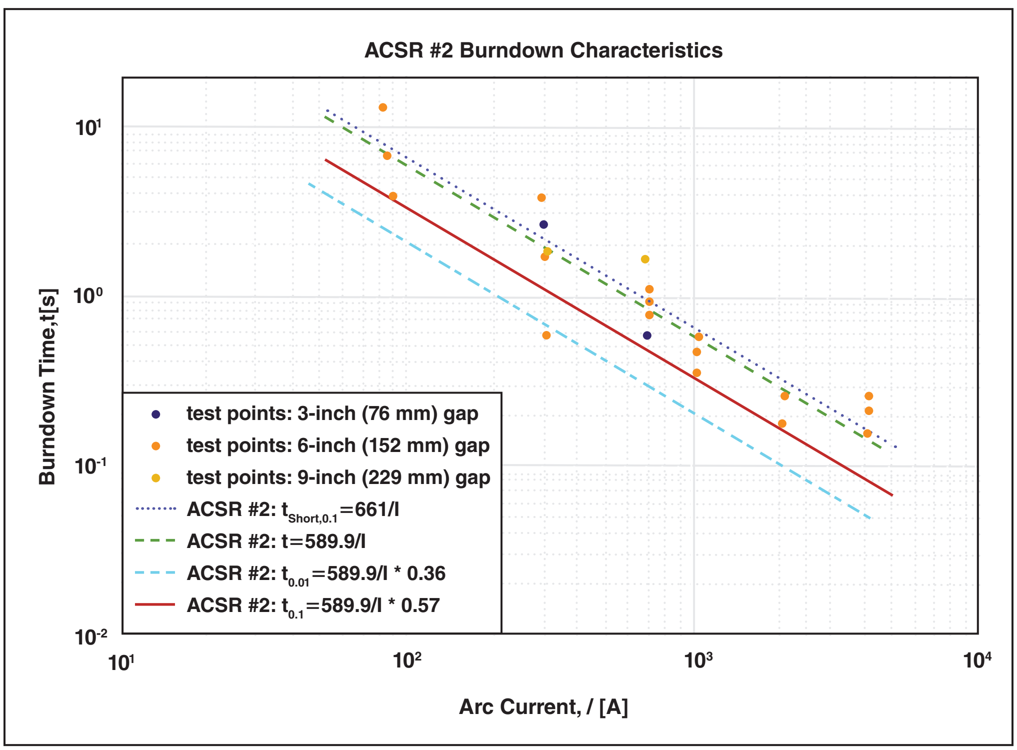

Figure 5. ACSR #2 Burndown Characteristics

In addition to the data collected above, several tests were performed using multiple short intervals of current to burndown the conductor. The numbers labeled next to each point (83 ms, for example) are the duration of each individual shot; however, the points are placed based on the cumulative duration up to that point. By comparing the two different shot sequences for ACSR #2, one notices that even though the conductors were able to cool down between shots, approximately the same amount of cumulative energy was required to burn down the conductors.

Appendix B – Burndown Characteristics of Bare Overhead Distribution Conductors

Table 1.

ACSR 1/0				ACSR #2				CU #2			
Current, A	Burndown Time, s	Gap, inches (mm)	Shots	Current, A	Burndown Time, s	Gap, inches (mm)	Shots	Current, A	Burndown Time, s	Gap, inches (mm)	Shots
81	9.57	6 (152)	1	82	12.92	6 (152)	1	80	17.33	6 (152)	1
81	11.40	6 (152)	1	86	6.63	6 (152)	1	82	7.77	6 (152)	1
81	34.15	6 (152)	2	90	3.87	6 (152)	1	84	7.28	6 (152)	1
84	10.42	6 (152)	1	296	3.76	6 (152)	1	302	2.46	6 (152)	1
84	16.85	6 (152)	2	301	2.69	3 (76)	1	305	1.74	6 (152)	1
291	5.29	6 (152)	1	306	1.75	6 (152)	1	307	1.81	3 (76)	1
294	4.49	6 (152)	1	306	0.60	6 (152)	1	307	1.40	6 (152)	1
297	3.93	6 (152)	1	307	1.83	9 (229)	1	307	1.37	9 (229)	1
297	4.49	9 (226)	1	677	1.64	9 (229)	1	691	0.45	9 (229)	1
304	2.63	3 (76)	1	697	0.60	6 (152)	1	695	0.50	3 (76)	1
649	2.55	9 (229)	1	700	0.95	6 (152)	1	701	0.95	6 (152)	1
680	2.51	6 (152)	1	700	1.11	6 (152)	1	701	0.59	6 (152)	1
687	2.10	6 (152)	1	701	0.78	6 (152)	1	702	0.88	6 (152)	1
690	2.04	6 (152)	1	1032	0.35	6 (152)	1	1034	0.32	6 (152)	1
695	1.12	3 (76)	1	1033	0.47	6 (152)	1	1038	0.51	6 (152)	1
1049	1.11	6 (152)	1	1040	0.58	6 (152)	1	1038	0.53	6 (152)	1
1052	1.30	6 (152)	1	2057	0.18	6 (152)	1	2081	0.28	6 (152)	1
1053	1.30	6 (152)	1	2080	0.27	6 (152)	1	2087	0.28	6 (152)	1
2125	0.77	6 (152)	1	2083	0.26	6 (152)	1	2087	0.29	6 (152)	1
2125	0.78	6 (152)	1	4072	0.15	6 (152)	1	4063	0.15	6 (152)	1
2127	0.79	6 (152)	1	4102	0.21	6 (152)	1	4077	0.16	6 (152)	1
4153	0.41	6 (152)	1	4139	0.26	6 (152)	1	4109	0.21	6 (152)	1
4168	0.38	6 (152)	1								
4174	0.35	6 (152)	1								

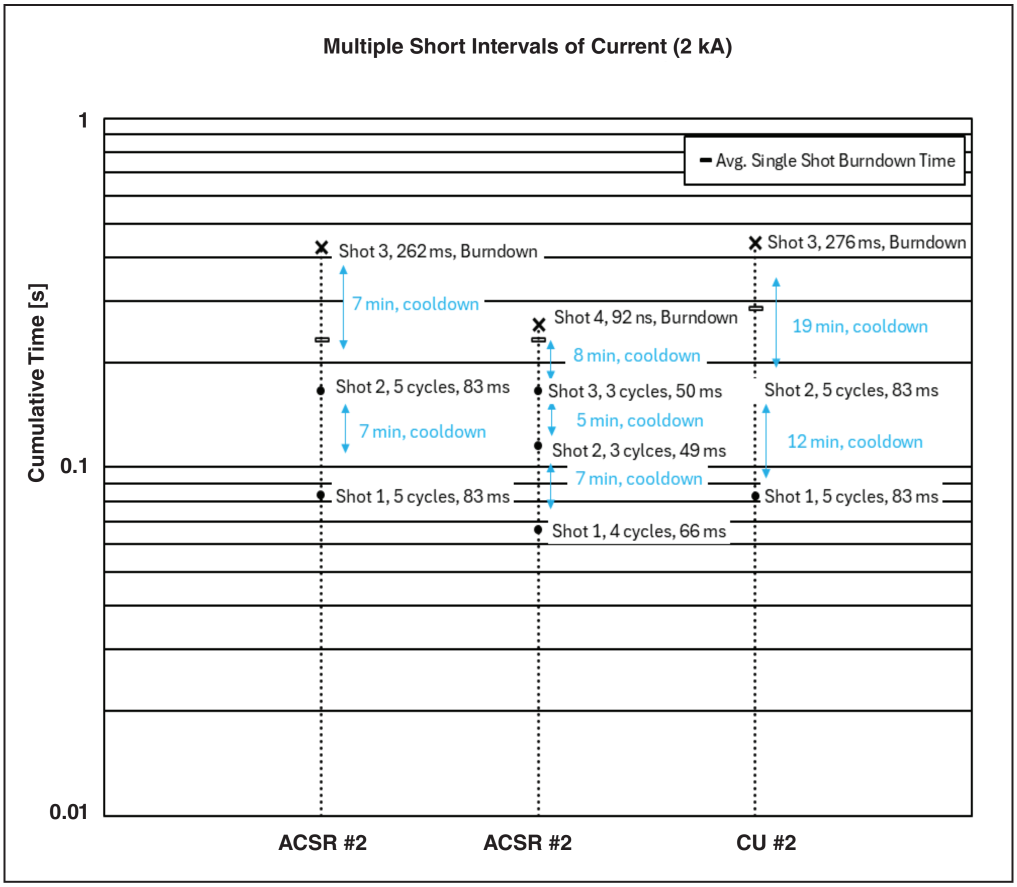

Figure 6. Multiple Short Intervals of Current

References

1. IEEE Standard C37.230-2020, "IEEE Guide for Protective Relay Applications to Distribution Lines."
2. Short, Tom. Coordination of Burndowns on Overhead Conductors. Electric Power Distribution Handbook. https://distributionhandbook.com/calculators/mdpad.html?burndown.md
3. Electric Power Distribution Handbook, 2nd ed., EPRI, Palo Alto, CA, 2014, pp. 76-79.
4. J. A. Lasseter, "Burndown Test on Bare Conductor," Electric Light and Power. pp. 94-100, December 1956.
5. W. B. Goode and G. H. Gaertner, "Burndown Tests and their Effect on Distribution Design," EEI T&D Meeting, Clearwater, Florida, Oct. 14-15, 1965.