Distribution Conductor Burndown Test Results

Small Bare and Large Covered Conductor

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Technical Update, December 2009

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PRODUCT DESCRIPTION

On overhead distribution circuits, conductor burndown is a well-documented phenomenon. Two systems are especially vulnerable to burndown: covered conductors (also known as *tree wires* or *coated conductors*) and small bare wires. In a burndown scenario, a power-follow arc develops on the system, with at least one end of the arc attached to a conductor. The arc heats the conductor, which causes the strands to anneal and lose tensile strength. The burndown event results in the strands breaking and the conductor separating at the burndown site.

Results and Findings

Conductor burndowns are problematic for several reasons. First, when the conductor breaks, it can turn an otherwise short interruption into one that requires a line crew to splice the conductor back together before service can be restored. Second, conductor burndowns are a significant cause of high-impedance faults. The conductor usually falls to the ground when it breaks, and if the conductor does not contact the system ground as it falls, the circuit is completed by the high-impedance path provided by the contact surface and the earth. If the conductor breaking is what cleared the original fault (rather than circuit protection), the energized conductor lies on the ground and might not draw enough current to operate circuit protection. Even if the circuit protection does operate, it might reclose and hold—the high-impedance fault does not draw much fault current and is difficult to detect.

Challenges and Objectives

Although the power generation industry has long been aware that conductor burndown is common, the characteristics of burndown have never been thoroughly documented. There are only a few existing references that detail previous research and results related to conductor burndown characteristics. Most of the existing research on covered conductors was performed before 1965, with little research on large covered conductors. Since 1965, the growth in demand for power has caused a shift toward larger (that is, >336.4-kcmil [169.9-mm^2]) conductors, and the lack of information about burndown characteristics for larger conductors is viewed as a deficiency. In terms of existing research on small bare conductors, most such conductors in modern distribution circuits are located far from the substation, where the availability of fault current is reduced. The existing data on burndown include relatively few data points around lower fault currents (500–2000 amps). The goal of this report is to address and bridge these informational gaps.

Applications, Value, and Use

The primary product of the testing described in this report is enhanced knowledge of burndown properties—at the core of the data are the time-current recordings for several conductor types and sizes. This information will help utility protection engineers limit the likelihood of burndown on their distribution circuits. Among the preventive methods and equipment evaluated in this report for covered conductors are fuse-saving schemes, arc protective devices, fusing taps, tighter fuses, and larger conductors. On bare conductors, the options for limiting burndown include fusing taps and fuse-saving schemes.

EPRI Perspective

Conductor burndowns can increase repair costs and compromise service reliability. Accordingly, the Electric Power Research Institute (EPRI) believes that the research on this important topic must be kept current for the sake of utilities' performance and economics.

Approach

The research that is the subject of this report began with a review of the published literature pertaining to conductor burndown testing. Six major references were identified, all of which were published between 1941 and 1982. Most of the previous conductor burndown tests were performed in the 1950s and 1960s, with only a few papers detailing the results of the tests. Section 2 of this report summarizes the main conclusions from four of the six older reference works. EPRI was unable to procure the remaining two reference works.

Testing was carried out at EPRI's high-voltage test laboratory in Lenox, Massachusetts. The conductor burndown research presented herein made extensive use of the lab's short circuit test facilities. Tests were performed in three different configurations: stationary arc tests, high-current arc tests, and running arc tests. Section 3 includes photographs of the test configurations. Various results were collected and are presented in Section 4, including voltage and current data, high-speed video, and still images.

A total of 84 arc fault tests were conducted to study conductor burndown properties, arc attachment, the effectiveness of arc protective devices, and the impact of line hose and gel wraps in motoring arc scenarios. Tests were conducted from 725 amps to 8700 amps, with fault durations ranging from just a few cycles to more than 300 cycles (at 60 Hz). Four conductor types were used: aluminum conductor, steel-reinforced (ACSR) #4 bare; ACSR #2 bare; 336.4-kcmil (169.9-mm^2) aluminum-covered; and 556.4-kcmil (281.0-mm^2) aluminum-covered. The earlier work and conclusions of other researchers are reviewed in light of EPRI's findings. For example, previous research found that the failure mechanism responsible for conductor burndown events is mechanical breakage, and EPRI's observations of bare conductor failures support this conclusion.

Keywords

Burndown
Conductor
Distribution circuit
Flashover
Power-follow arc

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1
INTRODUCTION

Background

Conductor burndown is a well-documented phenomenon that can occur on both covered and bare conductors on overhead distribution circuits (Short 2004). In a burndown scenario, an arc with power follow develops on the system with at least one end of the arc attached to a conductor. The arc heats the conductor, causing the strands to anneal and lose tensile strength. The burndown event results in the strands breaking and the conductor separating at the burndown site. Conductor burndowns are problematic for several reasons:

- *Long-duration interruption* – The conductor breaks and turns what is typically a short-duration interruption into one that requires a line crew to splice the conductor back together before service can be restored to the affected customers. In addition to negatively impacting service reliability, conductor burndowns also increase repair costs.
- *High-impedance faults* – Conductor burndowns are a significant cause of high-impedance faults. The conductor usually falls to the ground when it breaks (Figure 1-1). If the falling conductor does not contact the system ground as it falls (neutral or other grounded hardware), the circuit is completed by the high impedance path provided by the contact surface and the earth. If the conductor break cleared the original fault (rather than circuit protection), the energized conductor lies on the ground and may not draw enough current to operate circuit protection. Even if the circuit protection did operate, it might still re-close and hold since the high-impedance fault does not draw much fault current and is difficult to detect.

Two particular areas are most susceptible to conductor burndowns on overhead distribution systems:

1. *Covered conductor* – The covering holds the arc stationary, thereby concentrating the heating in one location and causing the conductor to burn down faster than if it were bare.
2. *Small bare conductor on the mains* – small bare wire, less than 2/0 in size, is susceptible to burndown, especially if the circuit laterals are not fused.

Covered conductor, also called “tree wire” or “coated conductor” is widely employed to limit tree-initiated faults. While generally increasing the reliability of service, covered conductor does have an increased risk of suffering burndowns. Several utilities have experienced burndowns of covered conductors when the instantaneous trip was not used, or was improperly employed (Barker and Short 1996; Short and Ammon 1997). The initial flashover may come from a variety of sources including lightning, tree branches, or wildlife, but it is the power follow arc that does the real damage and causes the conductor to break.

The junction where the covering has been stripped back is particularly vulnerable as the arc motors along the on bare section until it reaches the covering. At this point, its movement is impeded and conductor heating is concentrated. Stripped insulation is most often found around insulators and splices. Lightning surges cause pinholes in the covering. Pinholes are also prime candidates for burndown locations and can occur anywhere along the conductor length.

Bare conductors are not immune from burndowns, even thought the arc is free to motor. On bare conductor systems the arc will typically motor along until it reaches an attachment point such as an insulator pin. Once one end of the arc attaches to a fixed position, the conductor heating becomes much more localized, and burndown can result. Smaller conductors, under 3/0 in size, are the most susceptible to this type of failure.

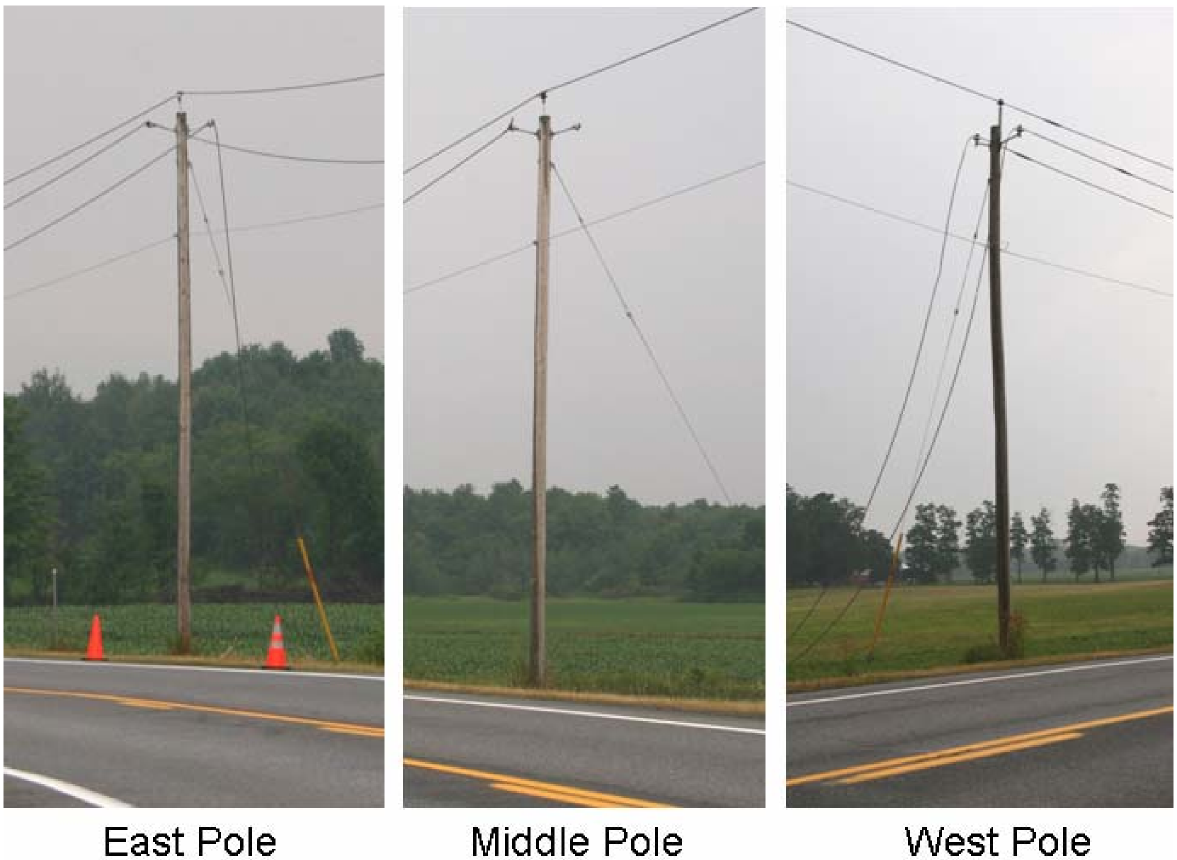

Figure 1-1
A Lightning-Induced Burndown Event on Covered Conductors Affecting the Conductor over Two Pole Spans

Why Is This Research Needed?

Although conductor burndown is a well-documented phenomenon, conductor burndown characteristics are not well documented. There are only a few existing references detailing previous research and results on conductor burndown characteristics. Because there is a limited amount of published research, there are gaps that are left unaddressed in the data. Two of the most prominent data gaps are:

1. *Large covered conductor* – Most of the existing research was completed between 1940 and 1965, and large (>336.4-kcmil [170.5-mm^2]) conductors were not strongly researched. Increasing power demands have caused a shift towards larger conductor sizes, making it desirable to obtain burndown characteristics for 336.4-kcmil (170.5-mm^2) and larger conductors.
2. *Small bare conductor at lower fault currents* – On modern distribution circuits, most of the small bare conductor is located far out from the substation, where fault current availability is reduced. The existing data conductor burndown data tends to have relatively few data points around lower fault currents (500 to 2,000 amps).

This research was designed with these data gaps in mind. The research team set out to provide conductor burndown characteristics specifically targeted to meet these needs by examining:

- #4 and #2 aluminum conductor, steel-reinforced (ACSR) bare conductor at fault currents from 725 to 2,800 amps
- 336.4- and 556.4-kcmil (170.5- and 281.9-mm^2) aluminum-covered conductor at fault currents from 2,800 to 8,700 amps

Options for Limiting Burndowns

The results of this report include time-current burndown characteristics for several conductor types and sizes. That information will help utility protection engineers coordinate protection to limit burndown likelihood. Other suggestions for limiting conductor burndown on covered conductors include:

- *Fuse saving* – Fuse blowing schemes allow longer fault durations, increasing the likelihood of burndowns. With a fuse saving scheme, the instantaneous relay element trips the circuit faster, helping to avoid burndown.
- *Arc protective devices (APD)* – APDs provide sacrificial metal and mass at the junction from the bare conductor to the covering where the covering has been stripped. The arc attaches to the APD instead of the conductor, which greatly reduces the likelihood of conductor damage.
- *Fuse all taps* – If smaller covered conductors are left unprotected, the likelihood of burndown is greatly increased.
- *Tighter fusing* – Faster fuses reduce the likelihood of burndown, especially on taps where the conductor might not be fully protected.
- *Bigger conductors* – Bigger conductors take longer to burn down.

Options for limiting conductor burndown on bare conductors include:

- *Fuse all taps* – Adding protection for tap conductors is the best way to prevent burndown.
- *Fuse saving* – The time delay relay element may not provide adequate protection for smaller tap conductors. Faults cleared by an instantaneous element with fuse saving are unlikely to damage bare conductor. If fuse blowing is used, consider an alternative such as a high-set instantaneous or a delayed instantaneous setting.

2
LITERATURE REVIEW

A search was conducted of the published literature pertaining to conductor burndown testing and data. Six primary references were identified, all of which are dated between 1941 and 1982. It seems that most previous conductor burndown testing was performed in the 1950s and 1960s, with only a few papers detailing test results arising from the work. A summary of these papers is included at the end of this section.

A review of the literature revealed some several common themes:

- Lightning and tree contacts are the two primary initiators leading to conductor burndown events with covered conductor (Lee and Fritz 1981; Lee, Fritz et al. 1982).
- Burndown events result in mechanical failure of the conductor due to loss of tensile strength. The arc causes extreme localized heating, thereby annealing the conductor and causing the strands (under tension) to elongate and sever (Lasseter 1956; Lee and Fritz 1981; Lee, Fritz et al. 1982).
- Arcing protective devices will prevent conductor damage and burndown, but they must be properly installed (Lee and Fritz 1981; Lee, Fritz et al. 1982).
- Variability in burndown times from laboratory testing is often the result of arc movement influenced by the wind, arc gap distance, and circuit configuration (Matthews 1941; Lasseter 1956).
- A common arc initiation method for laboratory tests is to bridge the arc gap with a very thin conductor. The conductor vaporizes in well under a ½ cycle and results in an arc across the gap (Matthews 1941; Lasseter 1956; Goode and Gaertner 1965; Hazan 1970).

Review of Previous Testing

Although the paper could not be procured, it is inferred from other related literature that R. M. Havourd's "Burndown of Overhead Conductors" deals with certain copper and covered aluminum conductors (Havourd 1955). Another reference that could not be located is D. H. Sandell's "Burndown Characteristics and Thermal Limits of ACSR and Stranded Aluminum Conductors" (Sandell 1958).

The following sections summarize the work of several important contributors to the subject of conductor burndown.

J. A. Lasseter/Florida Power & Light (1956)

J. A. Lasseter, "Burndown Test on Bare Conductor," *Electric Light and Power*. pp. 94–100, December 1956.

The Lasseter work considered five different bare conductors:

- #6 hard drawn copper, tensioned to 320 pounds
- #4 hard drawn copper, tensioned to 500 pounds
- #4 ACSR, tensioned to 450 pounds
- #2 ACSR, tensioned to 650 pounds
- #4 all-aluminum-alloy conductor (AAAC), tensioned to 450 pounds

All tests were performed at a nominal 8,000 volts line-to-ground, with current varying from 500 to 3,750 amps, depending on the test. The test line consisted of three wood poles with wooden crossarms approximately 6 ft (1.83 m) above ground level. Each pole span was approximately 100 ft (30.48 m). Each crossarm held four steel pins for mounting insulators and test conductors. There was also a pole-top pin on each pole. A 1/0 copper neutral was installed 34 in (0.86 m) below the crossarm and grounded at each pole location with a 10-ohm ground resistance. All insulator pins were bonded to the neutral at each pole location.

Arcs were ignited at the center pole such that there was 100 ft (30.48 m) of conductor in each direction from the arc location. Arc ignition was accomplished by stringing a very fine wire between the test conductor and a grounded insulator pin. Once the test conductor was prepped, an oil circuit breaker was closed in to energize the circuit and ignite the arc. For burndown tests, the operator manually opened the circuit breaker once conductor failure was observed. This approach to circuit clearing is very important for interpreting the resulting test data. Lasseter addresses the issue as follows:

> "One error in this procedure was failure to provide means to determine exact time the conductor parted in cases of burndown. Time recorded for the burndown includes some arcing time after the conductor parted. In cases of burndown, breaker was opened manually as soon as the operator observed conductor failure. Examination of the oscillograms on which the time of conductor failure was evident indicates that in general this error in data did not materially affect the results."

The impact of the test method on the reported data is not clear from this statement. Lasseter seems to indicate that manual breaker tripping time is included in the reported burndown times, but that it does not materially affect the results. Judging by the first hand experience with performing the tests detailed in this report, it is difficult to rationalize how including the time required for an operator to recognize that the conductor had failed and then manually trip the breaker could not appreciably affect the reported burndown times. Many of the reported burndown times are in the range of 1 to 3 seconds. However, even for those longer durations, it is conceivable that the additional tripping time could be 30% or more of the total burndown time. This subject is dealt with in more detail in Section 4, Test Results.

W. B. Goode and G. H. Gaertner/Baltimore Gas & Electric (1965)

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.

Goode and Gaertner looked at nine different conductor types with a mix of neoprene covering and bare conductor:

- Copper bare – #4 and 1/0
- Copper covered – #6, #4, and 1/0
- ACSR bare – #2, 3/0, 4/0, and 336.4 MCM
- ACSR covered – #2 and 3/0 covered ACSR
- All-aluminum conductor (AAC) Bare – 350 MCM and 500 MCM
- Aluminum conductor alloy-reinforced (ACAR) – 4/0 and 336.4 MCM

This work utilized test conductors that were 4 ft (1.22 m) in length tensioned between two supporting walls. Each end of the test conductor was grounded, and power was fed to the arc by a 4/0 copper electrode perpendicular to the center of the conductor. The gap between the electrode and conductor was nominally 9 in. (22.86 cm). This configuration was used to encourage the fault current to split and flow in both directions on the test conductor, thereby minimizing any motoring effect and keeping the arc confined to a small section of the conductor.

The arc was established by bridging the gap between the electrode and the test conductor with #24 copper wire. A microswitch was used to detect conductor failure, which helped determine burndown time. Testing was carried out at 2,500 volts and from 100 to 18,000 amps, varied with reactors.

Each conductor was subjected to four different values of current, and each current level was repeated three times. The largest variations in burndown time for a single current level were obtained for lower current tests on ACSR conductor. The most consistent burndown times came from high current tests on a small conductor. Goode and Gaertner’s general findings are summarized as follows:

- Smaller conductors burn down faster than larger conductors.
- Covered conductors burn down faster than bare conductors.
- Steel reinforcing increases burndown time.
- For large conductors, doubling the current halves the burndown time.
- This testing should represent worst-case (fastest burndown) times since arc motoring was purposely restricted by the configuration of the setup.

G. A. Matthews / The Detroit Edison Company (1941)

G.A. Matthews, "Power Arc-Over on Overhead Distribution Lines and Newly Developed Equipment for Protection Against Conductor Burndown From That Cause," *Transactions of the American Institute of Electrical Engineers.* Volume 60, Issue 6, pp. 596–604, 1941.

Although Matthews considered a variety of ACSR and copperweld conductors, burndown testing was focused solely on covered copper conductor. Testing of ACSR conductors was restricted to bare conductor on which the arc was allowed to motor, sometimes for predetermined durations, in an effort to evaluate the relationship between fault duration and conductor damage. The bare conductor tests were performed on #4 and #2 ACSR conductor, as well as solid copper and copperweld between 80 and 900 amps with varied fault durations. Damage observations are made for each conductor type and fault current pairing. Matthews also provides data concerning the loss of tensile strength for covered #6, #4, and #2 copper conductor exposed to various combinations of fault current and duration.

Tests were made between conductor pairs at various spacing in both horizontal and vertical configurations. Arc initiation was accomplished by bridging the air gap between the conductors with #40 copper magnet wire.

E. Hazan/The Line Material Company

E. Hazan, "Arc-fault characteristics of bare overhead distribution conductors: seven-strand AAAC (6201) and 6/1 ACSR," *IEEE Transactions on Power Apparatus and Systems*. PAS-89, No. 3, pp. 411–420, March 1970.

Hazan presents the results of a series of tests on #4, 1/0, and 4/0 bare seven-strand AAAC (6201) conductor and bare 6/1 ACSR conductor. The goal of this work was to determine conductor degradation as a function of arc-fault intensity rather than assessing time to burndown. Because of this objective, the test methods and data collected by Hazan can aid in defining damage thresholds, but not burndown curves, for the selected conductors.

These tests utilized 40-ft (12.2-m) samples tensioned between a test frame and a pole stub. Arcing was created between the test conductor and an aluminum rod held perpendicular to the test conductor with a 3.5-in. (8.9-cm) gap. To initiate the arc, the gap was bridged with 28-gauge steel wire. This test arrangement permitted very little arc movement.

Tests were conducted over the range of 200 to 45,000 amps for durations of 5, 10, and 15 cycles, with maximum currents per conductor type as follows:

- The #4 conductors were tested up to 4,500 amps.
- The 1/0 conductors were tested up to 10,000 amps.
- The 4/0 conductors were tested up to 45,000 amps.

As a final product, this testing produced a set of plots showing percent remaining conductor strength versus fault current and broken/damage conductor strands versus I^2t (in amp^2-seconds) for 5, 10, and 15 cycle faults.

3
TEST SETUP AND METHODS

Testing was carried out at EPRI's high-voltage test laboratory in Lenox, Massachusetts. The lab is a unique facility located in a rural setting, featuring multiple outdoor test lines. Originally built by the General Electric Company in the late 1950s, the lab's capabilities were expanded in 1974 with the addition of a three-phase balanced 15,000-kV ac source and in 1977 with the installation of a 1500-kV dc source and an ac/dc converter station.

Today, the laboratory offers a wide range of test capabilities for both transmission-level and distribution-level investigations. The conductor burndown research discussed in this report made extensive use of the lab's short circuit test facilities.

The Test Circuit

The test circuit is supplied at 23 kV by the local utility. The circuit is brought by express feeder to a 23-kV to 4,160-V step-down transformer. The output of the transformer is routed through a breaker set to coordinate with upstream 100T fuses at the point of common coupling with the local utility. A variable tap 3870-kVA isolation transformer is connected to the breaker to provide the final voltage transformation and supply the test span.

Fault current is controlled by a combination of adjusting the taps on the isolation transformer and adding air core reactors to the circuit.

Figure 3-1
Major Components of the Test Circuit

1. 23-kV express feeder
2. 23-kV to 4,160-V transformer
3. 4,160-V breaker
4. 3870-kVA variable tap transformer

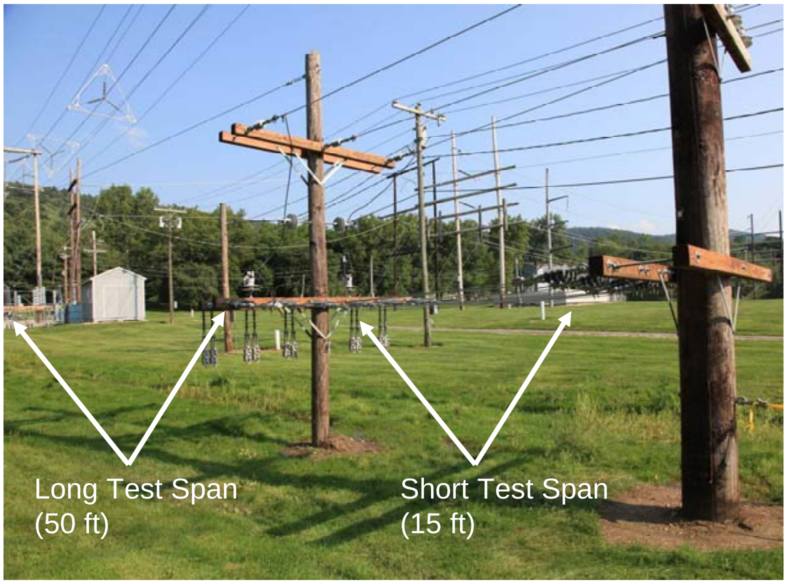

Figure 3-2
The Setup Includes a Short (15-ft) [4.6-m] and a Long (50-ft) [15.2-m] Test Span

Conductor Mounting Configurations

Tests were performed in three different configurations:

1. *Stationary arc tests* – The majority of tests performed were of this variety. The conductor was tied on a pin insulator. The insulator sat atop a copper rod used to mimic the insulator pin. In this configuration, one end of the arc attaches to the conductor while the other end attaches to the insulator pin. Small sacrificial arcing horns were made from copper conductor to limit damage to the insulator pin. The stationary arc configuration is shown in Figure 3-3. These tests were performed on the 15-ft (4.6-m) test span.

   For the covered conductor tests, a small slit was made in the covering with a hacksaw to mimic a pinhole in the insulation. The fuse wire was wrapped into the slit and then down to the insulator pin.
2. *High-current arc tests* – In order to get the highest fault current used in this testing (8,700 amps), it was necessary to use a tap setting at 716 volts on the test transformer. It is quite difficult to maintain an arc at 716 volts, which necessitated a small, stable arc gap. The best way to get reliable arcs at this voltage was to tie two covered conductors together using their insulation as a spacer, to maintain the arc gap. A small gap was cut out of the insulation on each test conductor, as shown in Figure 3-4, and the fuse wire was wrapped around the conductors. This configuration was used only for the covered conductors at 8,700 amps. These tests were performed on a 15-ft (4.6-m) test span.
3. *Running arc tests* – For running arc tests, two parallel conductors were strung on either a 15-ft (4.6-m) short test span or a 50-ft (15.2-m) long test span. Arcs were initiated between the test conductors by wrapping fuse wire around each conductor and across the air gap.

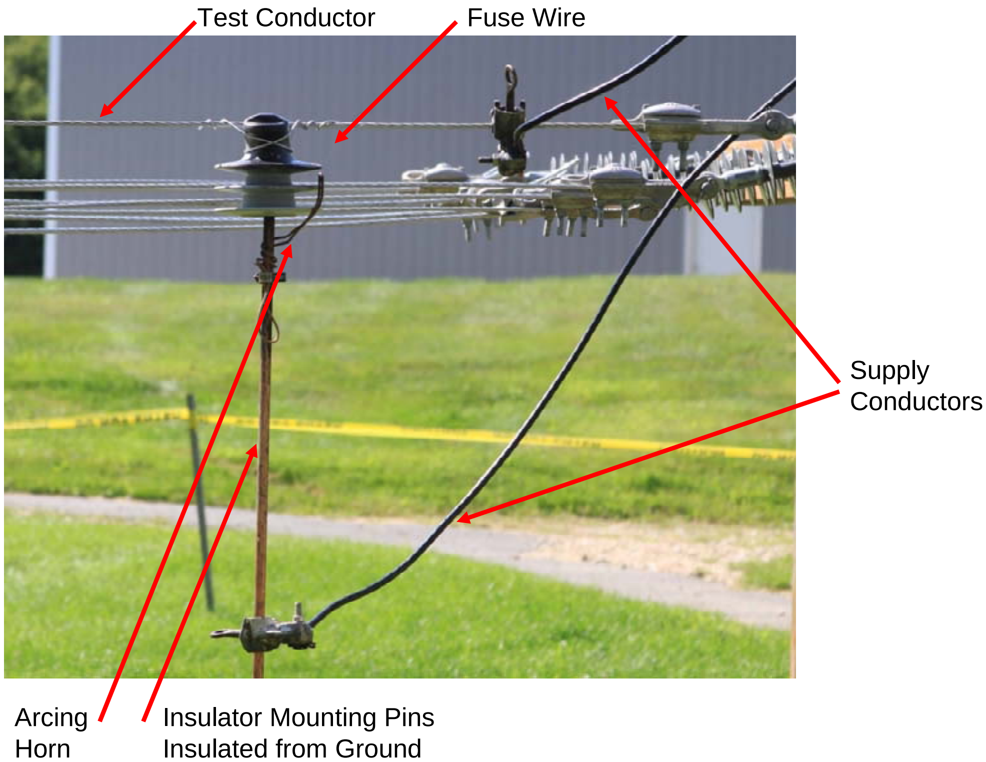

Figure 3-3
Test Configuration for Stationary Arc Tests

Figure 3-4
Test Configuration for Covered Conductors Tested at 8,700 Amps

Arc Initiation

Arcs were initiated by stringing very fine conductor, similar to that shown in Figure 3-5, between the desired arc attachment points. Trials were made with stainless steel and copper wire, and both were found to vaporize in less than a cycle. This method is consistent with previous conductor burndown research (Matthews 1941; Lasseter 1956; Goode and Gaertner 1965; Hazan 1970).

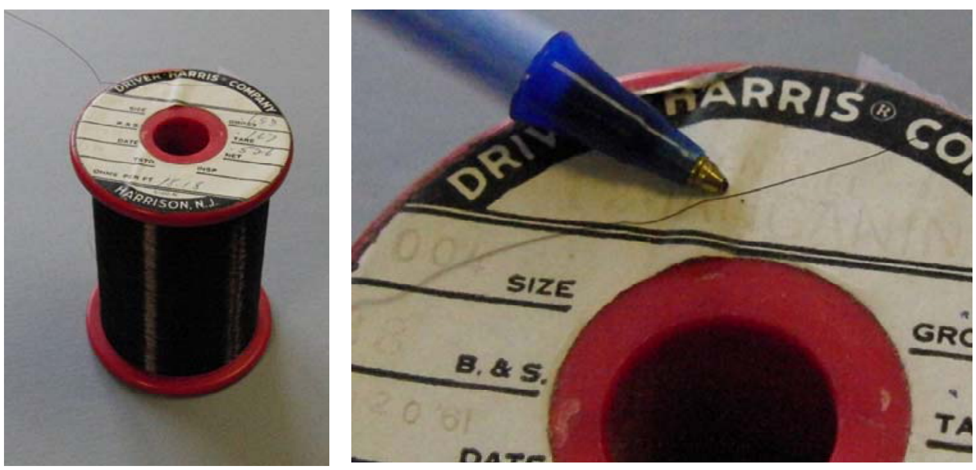

Figure 3-5
Fine Wire Similar to That Used for Arc Initiation

Data Collection

A variety of data was collected for this work, including voltage and current data, still images, and high-speed video:

- *Voltage and current data* – Voltage and current data (waveshapes and root mean square [RMS]) were recorded with a Dranetz-BMI PowerXplorer PX5 power monitoring instrument.
- *Still images* – Two digital SLR cameras were used for recording digital still images during this testing, including during burndown events. In this case, the frame rate of the camera and the ability for a high shutter speed were the two most important factors. The cameras used in this work had frame rates of 5 and 6.3 frames per second, and the project team felt it would have been beneficial to have still faster frame rates.
- *High-speed video* – High-speed digital video was recorded for each event with Casio EX-F1 cameras. Videos were recorded in 300 and 600 frames per second and often from two or three different camera angles. The high-speed video provided highly accurate information to determine the precise moment of conductor failure during each test. The moment of failure can be determined visually. The timing is found by counting video frames from when the fuse wire vaporizes. At 300 frames per second, the camera is recording 5 frames per cycle.

One challenge to this type of filming is that the arc creates an intense cloud of bright light that is beyond the recording capability of most cameras (Figure 3-6). To overcome this challenge, an infrared (IR) filter was used to “see” into the flash and isolate the arc channel. The IR filter blocks most visible light while transmitting infrared wavelengths. This effectively filters out the bright blast cloud, while allowing the camera to see the hot arc channel as shown in Figure 3-7. The only drawback to the IR filter is that it can be difficult to decipher where the arc is attaching because it is hard to see the conductor (it is visible only when it is reflecting IR from the arc or when the arc passes behind the conductor and it created a shadow). To remedy this, a regular visible light reference image is taken prior to the test and then overlaid on the IR filtered image to create a complete picture, as shown in Figure 3-8.

Figure 3-6
Typical View of an Arc Flash Event Using a Camera Recording Visible Light (1/1600 @ f/11, ISO 100)

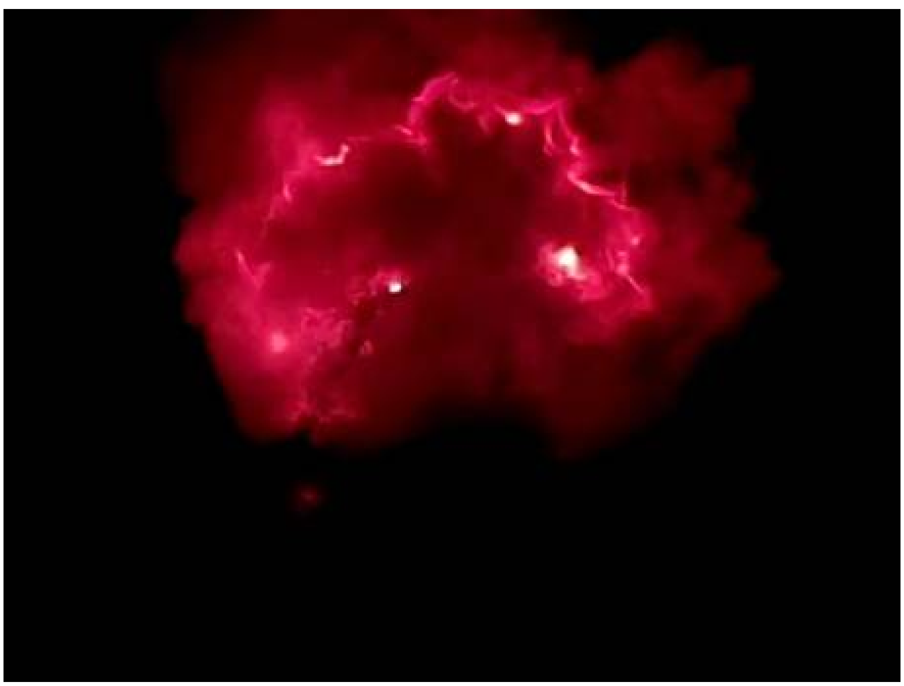

Figure 3-7
One Frame from a 300-Frame-Per-Second Movie of a Burndown Event Taken with an IR Filter

Figure 3-8
Overlaid Composite Image Made from an IR-Filtered Image and a Visible Light Reference Image

4

TEST RESULTS

A total of 84 arc fault tests were conducted to study conductor burndown properties, arc attachment, the effectiveness of arc protective devices, and the impact of line hose and gel wraps in motoring arc scenarios. Several different conductor configurations were utilized. Tests were conducted from 725 amps to 8,700 amps with fault durations ranging from just a few cycles to more than 300 cycles (at 60 Hz).

Test Samples

Four different conductors were examined during this testing:

- #4 ACSR bare
- #2 ACSR bare
- 336.4-kcmil (170.5-mm^2) aluminum compact conductor 25-kV tree wire
- 556.5-kcmil (281.9-mm^2) aluminum compact conductor 25-kV tree wire

The conductor in the tree wire is wrapped with a thin layer of semiconducting polyethylene, which is then covered by a layer of low density polyethylene 0.125 in. (0.316 cm) in thickness. The final exterior jacket is a layer of high density polyethylene that is also 0.125 in. (0.316 cm) thick.

Burndown Test Results

Test samples were subjected to arcing faults at various current levels as previously discussed in Section 3, Test Setup and Methods. Three or four current levels were chosen for each conductor and each current level test was repeated at least three times. The current levels were selected at the onset of this research according to gaps identified in existing burndown data. To meet these goals, the small bare ASCR conductors were tested at lower fault currents, while the larger aluminum tree wire was tested at somewhat higher fault currents:

- ACSR – 725, 1000, 1800, and 2800 amps
- Aluminum tree wire – 2800, 3700, and 8700 amps

Burndown Curves

Figures 4-1 through 4-4 show the burndown data collected for each conductor type. The current values reported represent the average RMS current during the burndown event. The burndown times are taken from high-speed video of each fault event and represent the time from when the arc first ignites until the conductor separates.

The bare ACSR conductor tended to show more variation in burndown times at each current level. This is particularly true for the #2 ACSR conductor. A review of the high-speed video for these tests shows that the longer duration burndown times are the result of increased arc movement on the conductor. Conductor failure is due to annealing from localized heating over a span of approximately 6 to 24 in. (15 to 60 cm). Much of the rapid conductor heating comes from the contact impedance between the arc and the conductor. Therefore, when the arc attachment point to the conductor remains relatively stationary, as shown in Figure 4-5, then the conductor heats up faster and failure occurs more rapidly.

Although each test was initiated in a nearly identical manner, some arcs would motor along the conductor until they broke and then re-strike at the insulator and motor again as shown in Figure 4-6. This arc behavior results in longer times to failure since the arc attachment point is moving along the conductor rather than injecting heat at one location. This behavior is influenced by fault current level, wind speed, and direction. Higher fault currents have a stronger motoring action, making those arcs more likely to move around on the conductor. Wind will also push the arc and have the greatest influence when it is pushing the arc in the same direction as the motoring.

The #2 conductor may exhibit more variation than the #4 because it is larger and, therefore, able to withstand equivalent arc currents for longer durations. Longer duration events provide more time for the arc to move around and, thus, more variability. Test results for the covered conductor are less variable since the covering restricts arc movement and creates more consistency from test to test.

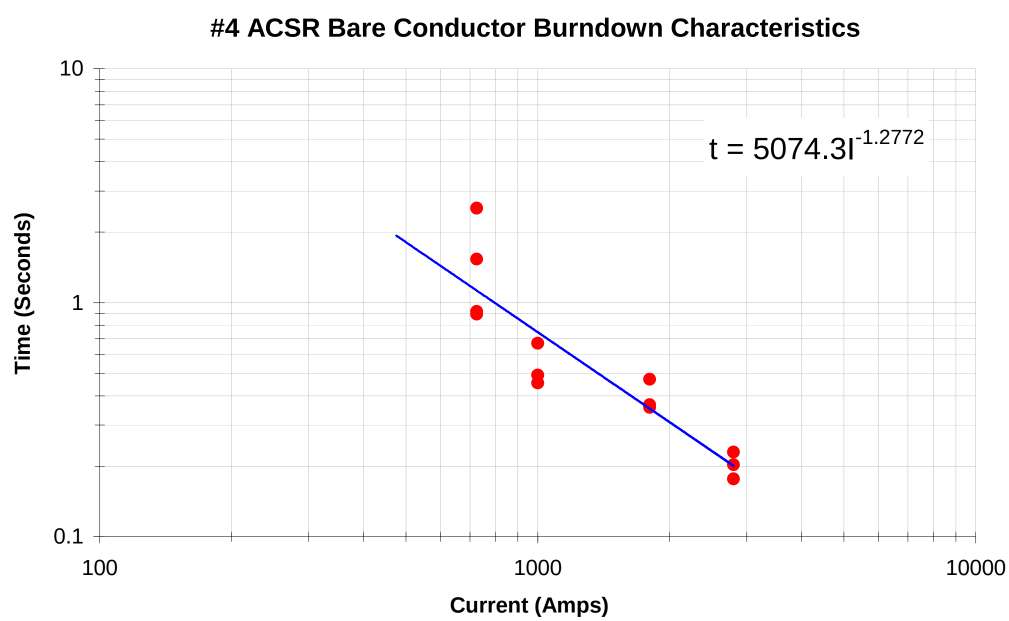

Figure 4-1
Burndown Characteristics of #4 ACSR Conductor

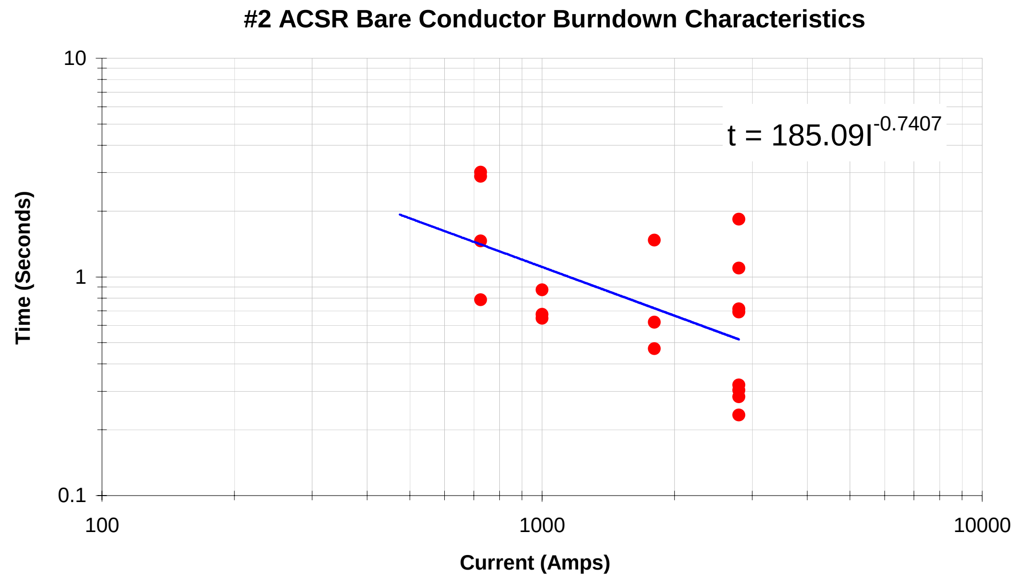

Figure 4-2
Burndown Characteristics of #2 ACSR Conductor

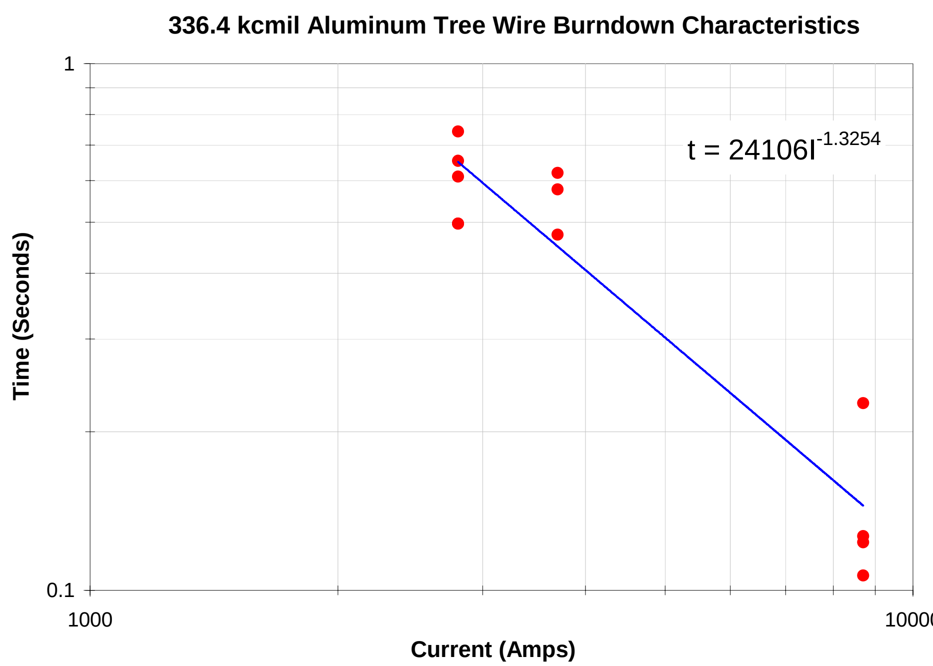

Figure 4-3
Burndown Characteristics of 336.4-kcmil (170.5-mm^2) Aluminum Compact Conductor Tree Wire

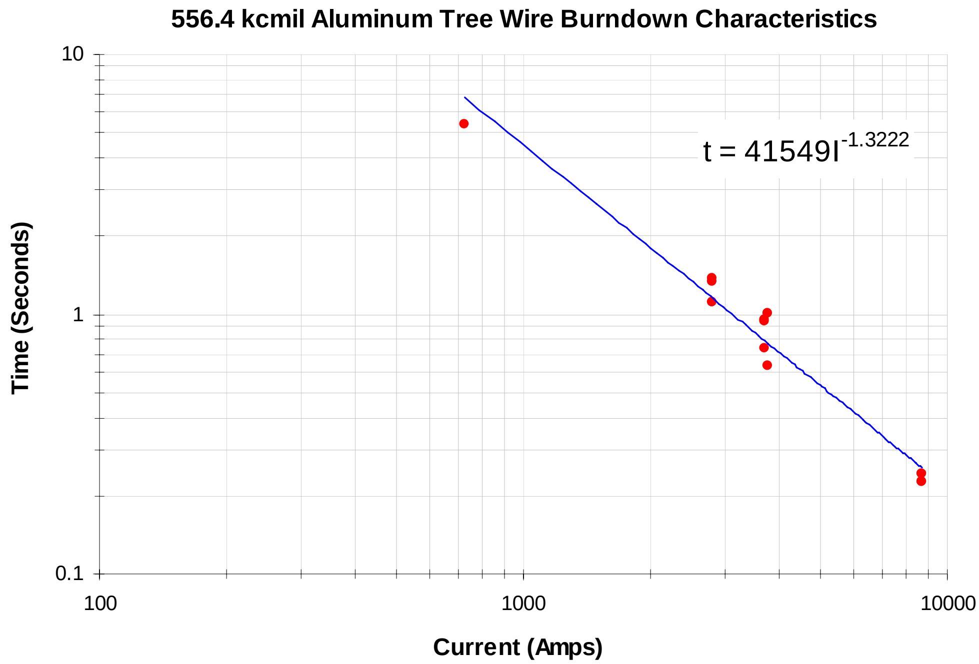

Figure 4-4
Burndown Characteristics of 556.4-kcmil (281.9-mm²) Aluminum Compact Conductor Tree Wire

Figure 4-5
Arcs That Remain Relatively Stationary Result in Faster Burndown Times

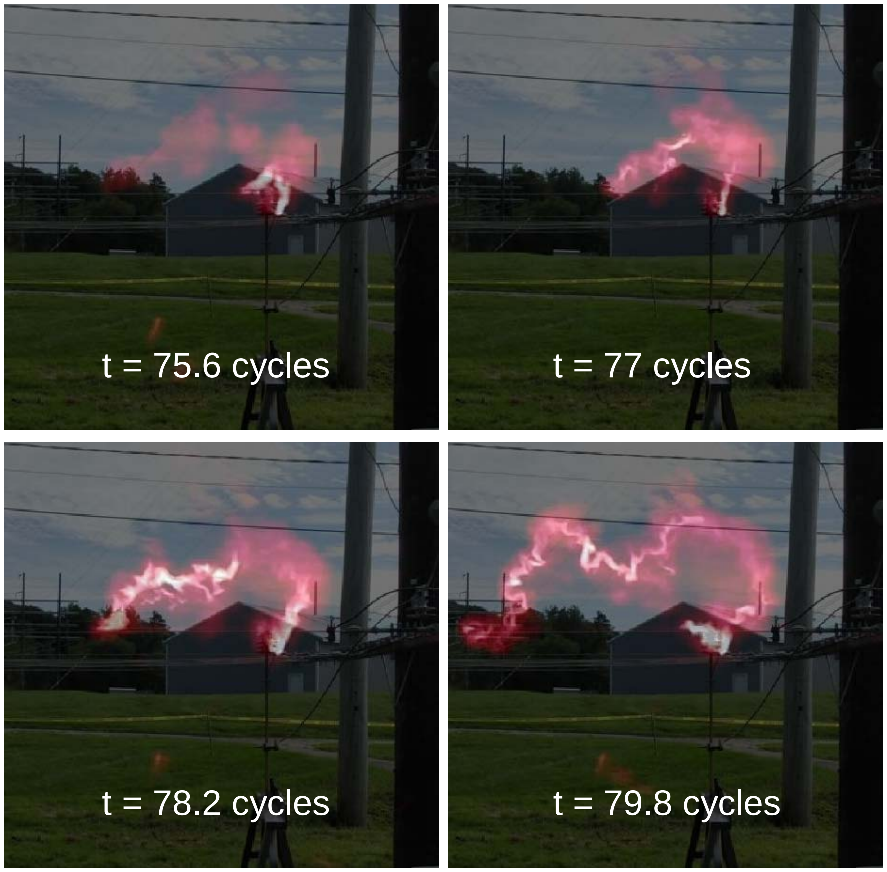

Figure 4-6
Arcs That Repeatedly Motor and Break Result in Slower Burndown Times

Comparison with Protection Curves

The burndown characteristics for the conductors included in this testing generally sit above the time-current curve for many K and T fuse links. The total clearing time for several common K and T fuse links is plotted against the burndown characteristics of the test conductors:

- Figure 4-7 illustrates that small #4 ACSR bare conductor shows the most overlap with 80T and 100T fuse links, while showing very tight coordination with 100K fuse links at 500 amps and above.
- Figure 4-8 illustrates that #2 ACSR bare conductor shows better clearance but does fall under 80T and 100T fuse links under 1,000 amps.
- Figures 4-9 and 4-10 show that the burndown characteristics for the larger covered aluminum conductors can sit above the CO-9 and CO-11 relay curves, but protection is dependent on the pick-up value. Both the CO-9 and CO-11 curves offer good protection at 600 amp pick-up. Increasing the pick-up to 750 amps pushes up against the 336.4-kcmil (170.5-mm^2) conductor's burndown characteristics, but still offers good protection below 5,000 amps. A 900 amp pick-up places the CO-9 curve right up against the 336.4-kcmil (170.5-mm^2)

conductor's burndown characteristics and does not offer adequate protection. The 556.4-kcmil (281.9-mm^2) conductor generally sits under both the CO-9 and CO-11 curve, even with a 900 amp pick-up.

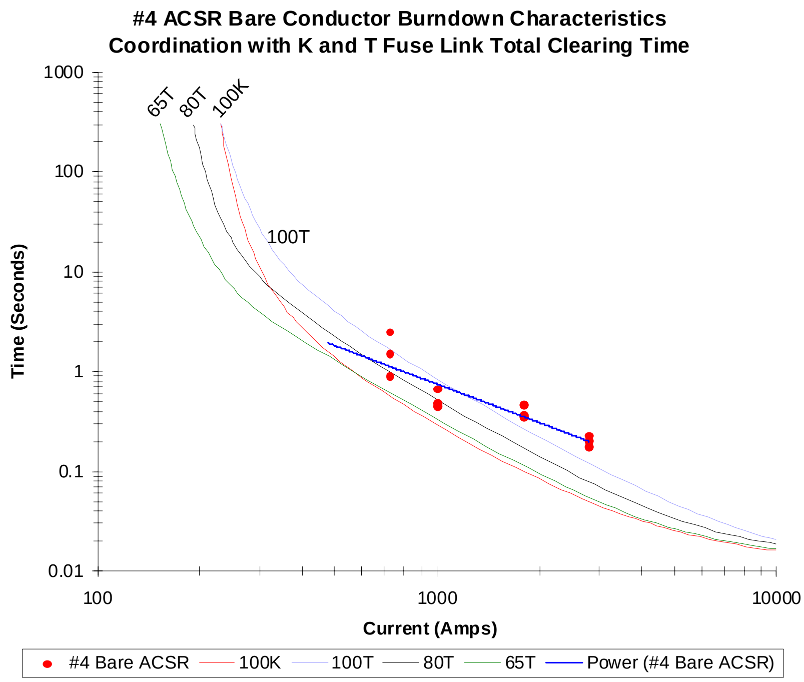

Figure 4-7
Burndown Characteristics of #4 ACSR Bare Conductor Plotted with the Total Clearing Time for K and T Fuse Links

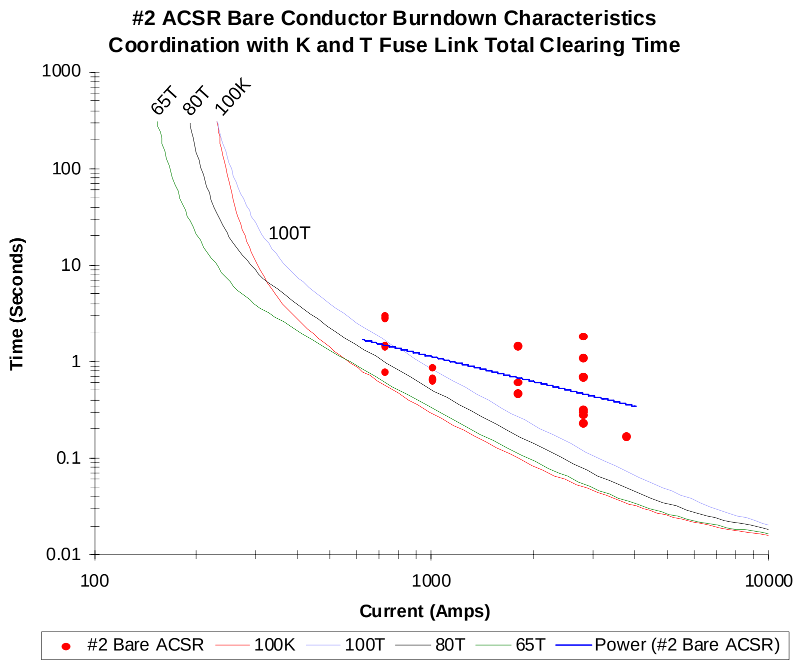

Figure 4-8
Burndown Characteristics of #2 ACSR Bare Conductor Plotted with the Total Clearing Time for K and T Fuse Links

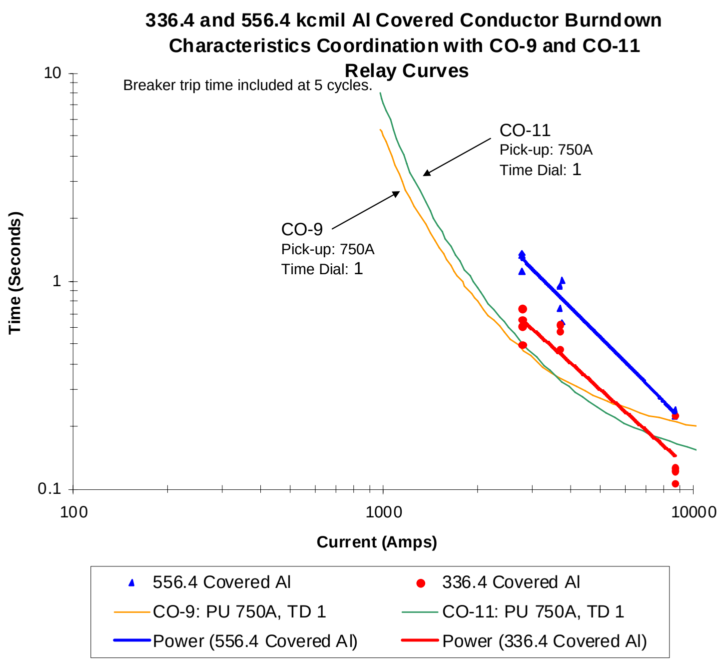

Figure 4-9
Burndown Characteristics of 336.4- and 556.4-kcmil (170.5- and 281.9-mm^2) Aluminum Tree Wire Plotted with the CO-9 and CO-11 Relay Curves

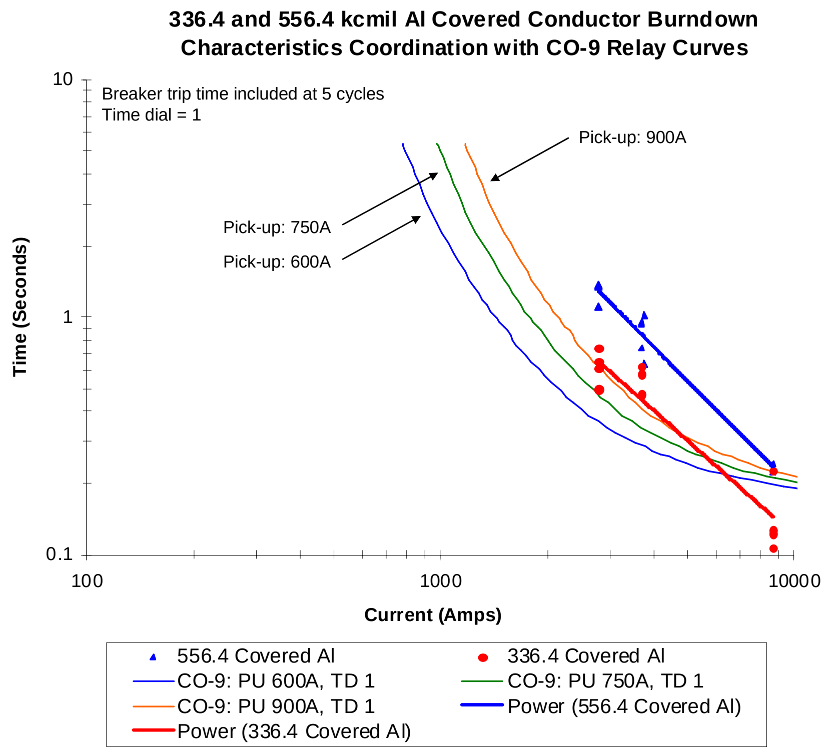

Figure 4-10
Burndown Characteristics of 336.4- and 556.4-kcmil (170.5- and 281.9-mm²) Aluminum Tree Wire Plotted with the CO-9 Relay Curves with Increasing Pick-up Values

Comparison with Previous Work

Figures 4-11 and 4-12 show the conductor burndown data collected during this research plotted along with the trend line data reported by Lasseter (1965) and Goode and Gaertner (1965). Data from Goode's work is shown only on the #2 ACSR graph because that testing did not include the #4 ACSR conductor.

As far as the research team can determine, the Lasseter and Goode papers are the only other references for burndown characteristics of #2 and #4 bare ACSR conductor. It is evident from Figures 4-11 and 4-12that the data taken during this EPRI investigation show these conductors to burn down more quickly than Lasseter reported for all current values tested, but show fairly good correlation to the burndown characteristics found by Goode. The exact reason for this discrepancy cannot be known for sure, but the most likely cause stems from the data recording methods used in the Lasseter work.

During the Lasseter work, the operator manually opened the circuit breaker once conductor failure was observed. This approach to circuit clearing is very important for interpreting the resulting test data. Lasseter addresses the issue as follows:

> "One error in this procedure was failure to provide means to determine exact time the conductor parted in cases of burndown. Time recorded for the burndown includes some arcing time after the conductor parted. In cases of burndown, breaker was opened manually as soon as the operator observed conductor failure.

Examination of the oscillograms on which the time of conductor failure was evident indicates that in general this error in data did not materially affect the results."

The impact of the test method on the reported data is not clear from this statement. Lasseter seems to indicate that manual breaker tripping time is included in the reported burndown times, but that it does not materially affect the results. Judging by the first hand experience performing the tests detailed in this report, it is difficult to rationalize how including the time required for an operator to recognize that the conductor had failed and then manually trip the breaker could not appreciably affect the reported burndown times. Many of the reported burndown times are in the range of 1 to 3 seconds. Even for the longer duration events, it is conceivable that the additional tripping time could be 30% or more of the total burndown time.

It also sounds as if the time of conductor failure was not clearly evident on all of the oscillograms. It can be extremely challenging to determine exactly when the conductor breaks from the waveshape alone. As the conductor separates, the arc continues to burn between the energized end of the conductor and the other electrode (an insulator pin in the Lasseter work). When the conductor breaks, the energized end swings away, drawing out the arc. The fault current will decay and the voltage will rebound as the arc length increases, but full arc current can still flow for several cycles as the conductor pulls away as illustrated in Figure 4-13. The burndown time for this event was accurately determined by reviewing the high-speed video recorded during the test. Figure 4-14 shows several frames from a 300-frame-per-second high-speed video of a burndown test, illustrating how the fault current continues to flow after conductor separation.

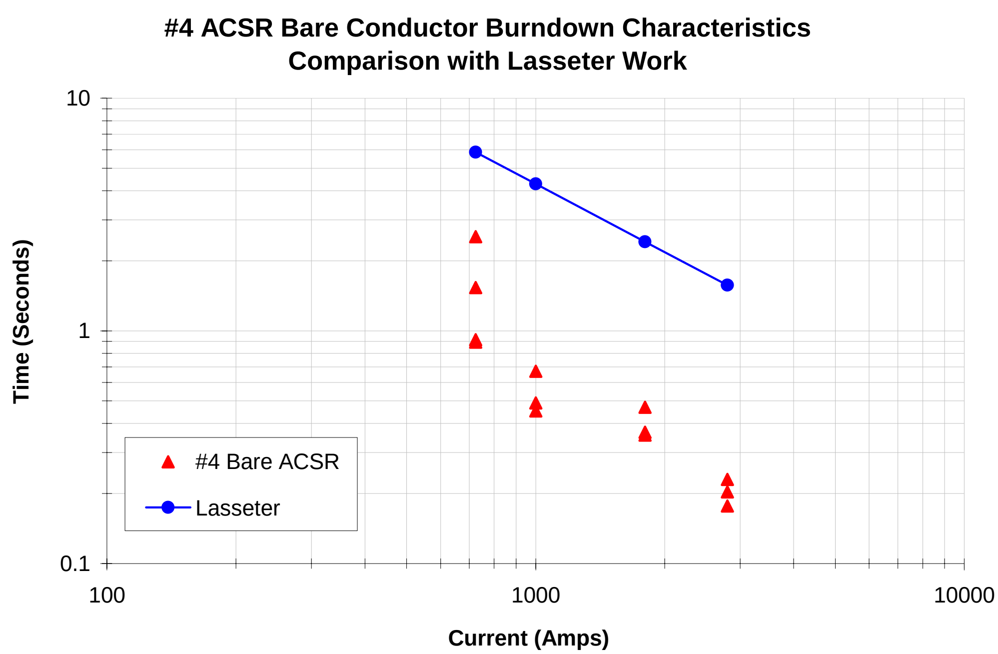

Figure 4-11
Comparison of Recorded Burndown Characteristics with Data Reported from Lasseter Work for #4 ACSR Bare Conductor (Lasseter 1956)

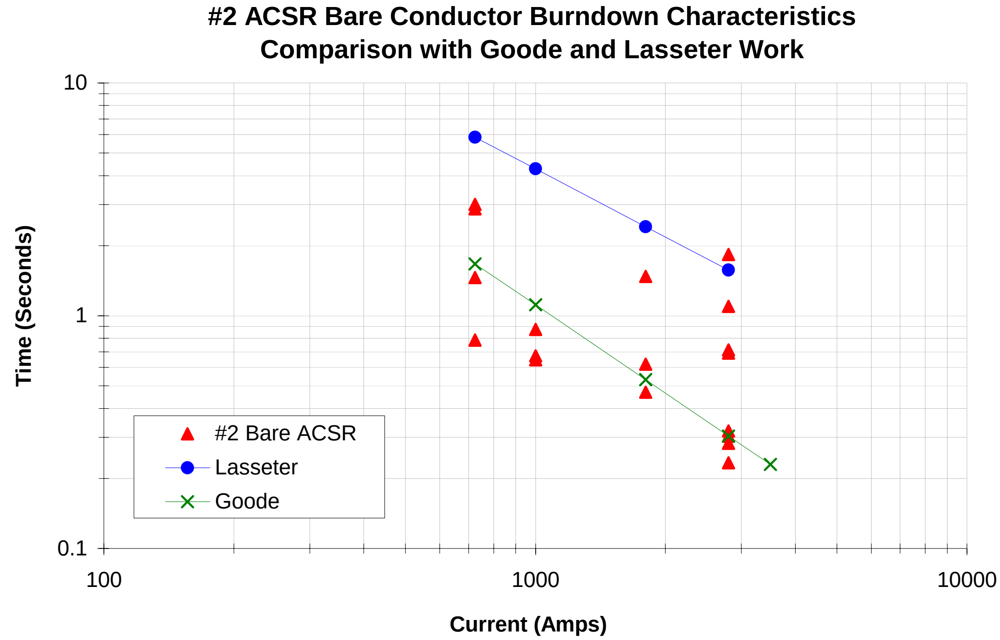

Figure 4-12
Comparison of Recorded Burndown Characteristics with Data Reported from Goode and Lasseter Work for #2 ACSR Bare Conductor (Lasseter 1956; Goode and Gaertner 1965)

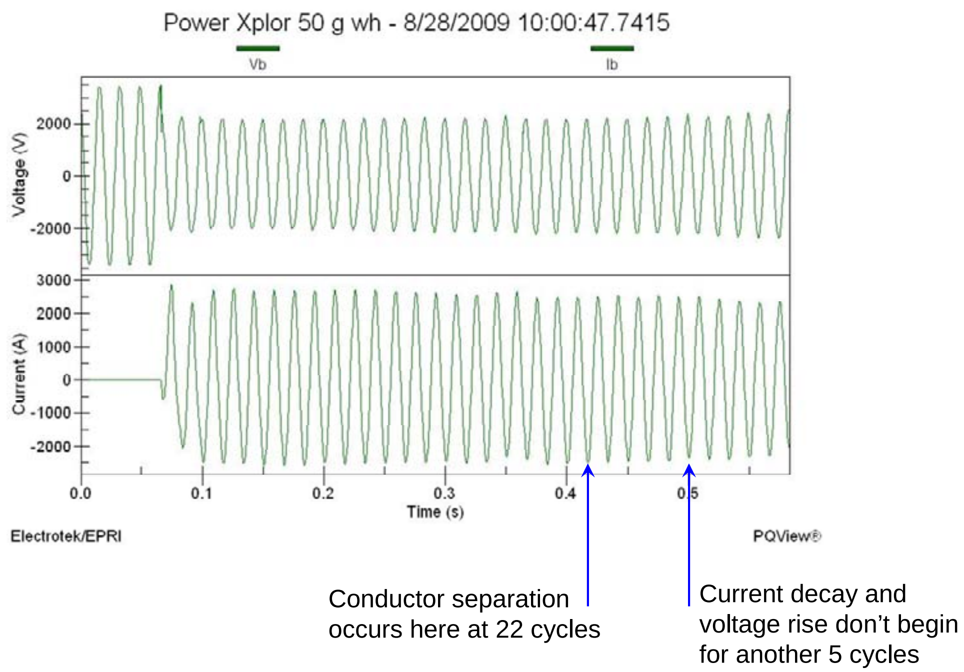

Figure 4-13
Instance Where Exact Timing of Conductor Failure Cannot Be Determined from Waveshapes

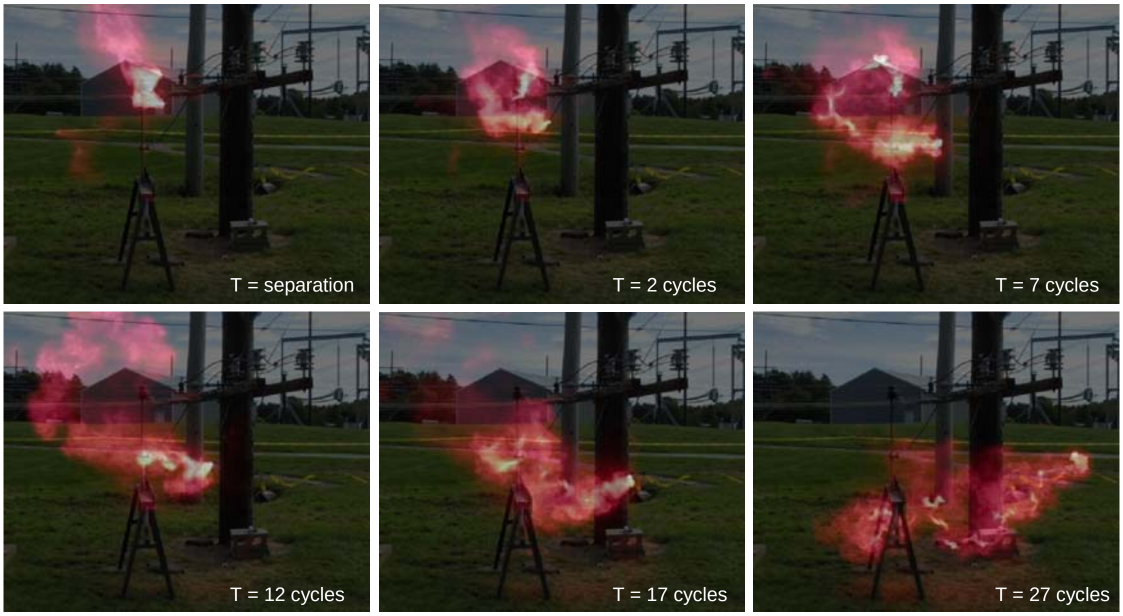

Figure 4-14
Image Series Showing Lead Pull-Away and Arc Draw-Out After Conductor Burndown

A comparison of the burndown characteristics recorded for the 336.4-kcmil (170.5-mm^2) aluminum conductor shows good coordination with the results reported by Goode, as shown in Figure 4-15. There is some discrepancy at the highest current value of 8,700 amps. The data recorded during this testing show two fast burndowns occurring in less than 10 cycles at 8,700 amps. The reason for this discrepancy is not known.

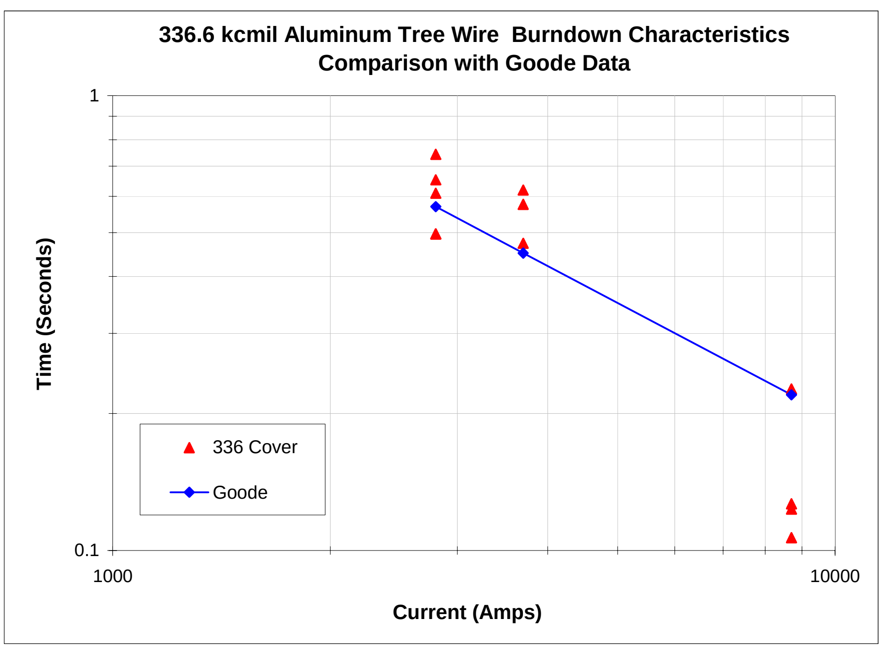

Figure 4-15
Comparison of Recorded Burndown Characteristics with Data Reported from Goode Work for 350-kcmil (177.3-mm^2) Aluminum Conductor (Goode and Gaertner 1965)

Conductor Failure Mode

Previous research has found that the failure mechanism during conductor burndown events is one of mechanical breakage. The contact impedance between the arc and conductor causes heating, which anneals the conductor. As the conductor anneals, it loses tensile strength, leading to strand elongation and eventual mechanical failure (Matthews 1941; Lasseter 1956; Roehmann and Hazan 1963; Goode and Gaertner 1965).

Observations of the bare conductor failures during this work support this conclusion. The end of the conductor that becomes de-energized when the conductor separates shows that the strands are broken at different locations and are, therefore, different lengths (Figure 4-16). The arc remains attached to end of the conductor that stays energized after separation and burns it back to a nub as shown in Figures 4-17 and Figure 4-18.

The covered conductor did not show the same type of broken strands at the de-energized end as the bare conductor. Instead, the covered conductor was expulsed from the covering on both sides of the separation point, resulting in relatively flat surfaces recessed into the covering, as shown in Figure 4-19. It could not be determined if the covered conductor failure was due to loss of tensile strength or section loss due to vaporization of the conductor.

Figure 4-16
The End of the Conductor That Becomes De-Energized After Separation Shows That the Conductor Strands Separate at Different Locations

Figure 4-17
The End of the Conductor That Remains Energized After Separation Continues Arcing, Causing the Broken Strands to Be Vaporized Back to a Nub

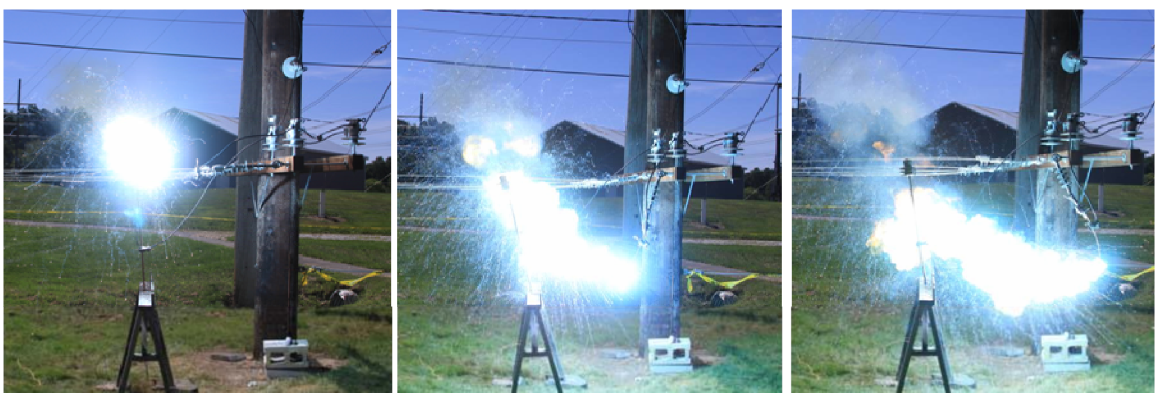

Figure 4-18
When the Conductor Breaks, the Energized End Swings Down, Pulling the Arc Out

Figure 4-19
The Strands of 556.4-kcmil (281.9-mm^2) Aluminum Covered Conductor (Tree Wire) Are Vaporized During a Burndown Event

Arc Attachment

Multiple tests were performed to examine if and how a running arc will attach to the line at various obstacles it may encounter. These tests were performed on pairs of bare #2 ACSR conductors strung on a 50-ft (15.2-m) test line. The conductors were spaced approximately 30 in. (0.76 m) apart. Multiple pieces of hardware were connected to one of the conductors, as shown in Figure 4-20. The arc was ignited between the two conductors with a thin fuse wire on the source end of the line. The arc then motored down the line to the various pieces of hardware. These tests were conducted at 4,160 volts phase-to-phase with a nominal arc current of 2,800 amps.

Figure 4-20
An Example of the Test Configuration Used for Arc Attachment Tests

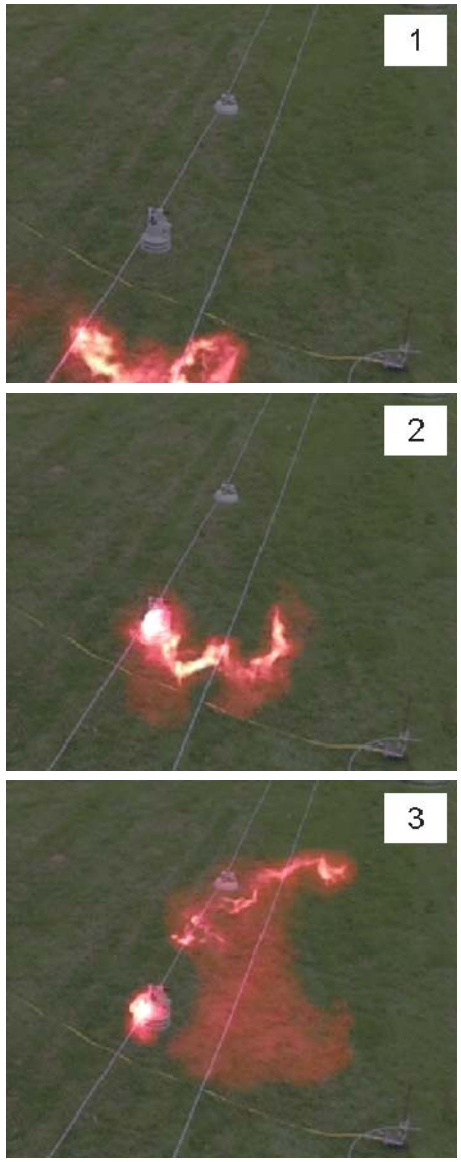

Figure 4-21
Arc Motoring Down the Test Line

Figure 4-21 shows an example of one arc attachment test. The images in Figure 4-21 are taken from a 3000 frame-per-second digital video recording of the test. An IR pass filter is used to isolate the arc channel, as discussed in Section 3, Test Setup and Methods, and then a static background image is overlaid on the video frames to produce these images.

- *Frame 1* – The arc is motoring toward the vice-top polymer insulator.
- *Frame 2* – The arc slows down and lingers at the vice-top, injecting more heat into the conductor at this location than at others where it moves swiftly past.
- *Frame 3* – The arc has motored past the vice-top insulator, but the damage is already done. The conductor begins to separate at the vice-top insulator, creating a second arc.

From the images in Figure 4-21, it appears that the arc is not attached to the conductor on the right side of the images. This is because the static background image is taken before the test begins. Once the arc is ignited, the fault current flowing in the conductors pushes them apart, making the arc to appear to be terminating in the air.

Multiple tests were performed to examine arc attachment at different pieces of hardware:

- *Automatic splice* – The arc motored past the automatic splice in all tests (a total of three). Additional data were also collected while evaluating arc protective clamps, as discussed in the next section. The arc also did not attach to the automatic splices in those tests. The combined test results show that the arc did not attach to an automatic splice in 15 total opportunities (some tests involved splices on both conductors).
- *Hotline clamp* – In several tests the arc was allowed to motor over a hotline clamp and showed no signs of attachment. The clamp was not connected to any other conductor or hardware and was put in place to simulate an errant clamp left on the line.
- *Porcelain pin insulator* – A porcelain insulator was tied to the conductor with an aluminum strand. The insulator rested on a pin that was not grounded. The pin was supported by a wooden frame with approximately 32 in. (0.81 m) of wood between the pin and the ground. This test was repeated twice. The arc did not fully anchor at the insulator location during either test, but its travel down the line did slow considerably at the insulator location. The lingering of the arc at the insulator location was enough to cause some visual pitting and blackening of the conductor strands.
- *Polymer vice-top insulator* – The polymer vice-top insulator was attached to the bare #4 ACSR conductor, with the vice jaws clamped around the line per a typical installation. This test was repeated twice. During the first test, shown in Figure 4-21, the arc did not anchor at the insulator, but its motion down the line did slow considerably. Post-test inspection revealed that the conductor inside the jaws of the vice-top insulator had suffered significant damage (Figure 4-22). The test line was lightly tensioned during this test, and it is believed that the conductor would have fully separated had the line been under tension loading typical of field conditions. The other test conductor also incurred some “bird caging” damage as a result of the arc slowing down (Figure 4-23).

  The tension on the test line was increased for the second running arc test with a vice-top polymer insulator. This time, the conductor was severed at the source side of the insulator.

Figure 4-22
This Damaged Section of #4 ACSR Conductor Was Encapsulated in the Jaws of a Vice-Top Polymer Insulator During a Running Arc Test

- *Bird caging conductor* – The second of the two conductors the arc was motoring on was not immune from damage. When the arc slowed because of an insulator on the other conductor, it caused a prolonged exposure on both feed lines. This often resulted in a small section of *bird caging*—unraveling of conductor strands. Figure 4-23 shows two instances of bird caging, one of which was severe enough to break the conductor strands. It is not known if this would have occurred had the line been tensioned similar to field conditions.

Figure 4-23
Conductor "Bird Caging" Due to a Motoring Arc Lingering at These Locations

Arc Protective Devices

The effectiveness of arc protective devices in preventing conductor damage or burndown was investigated using 336.4-kcmil (170.5-mm^2) aluminum tree wire. The test conductors were configured with automatic splices at the midway point, as shown in Figure 4-24. The insulation was stripped back, such that there was an approximately 2-in. (5-cm) gap between the insulation and the splice. This was felt to be a reasonably accurate representation of a typical field installation. This configuration, with two test conductors approximately 24 in. (31 cm) apart, was used for all of the arc protective device tests. Arcs were ignited by shorting the two conductors together with a thin fuse wire prior to energizing the circuit. The fuse wire was placed on the exposed conductors on the source side of the splices.

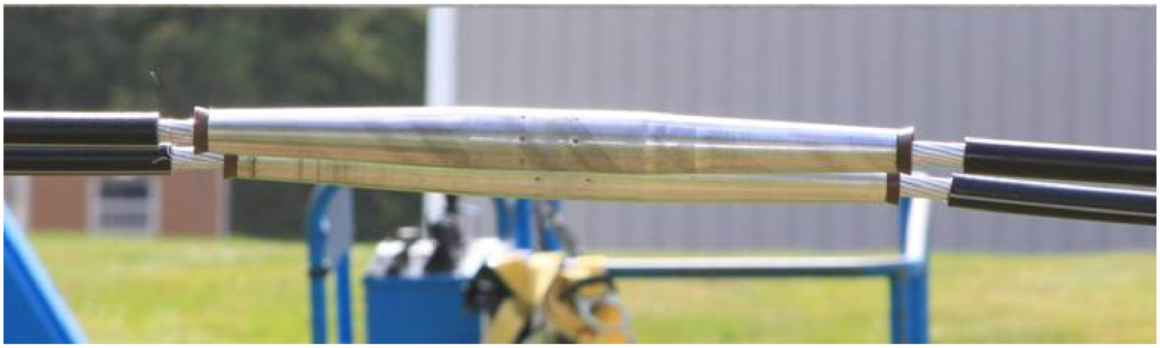

Figure 4-24
Automatic Splices Installed on 336.4 kcmil (170.5 mm^2) Aluminum Tree Wire

Tests Without Arc Protective Devices

Two initial tests were made using this configuration, without arc protective devices installed.

The first test resulted in one of the conductors burning down and the other suffering severe damage. There is a large area on the load side of the splice that did not burn down where the arc anchored and vaporized the splice body (Figure 4-25). The conductor that did not burn down was not sufficiently tensioned during this test. Judging from the severity of the damage and section loss (Figure 4-25), the research team feels that if the second conductor had been under tension, the conductor would have been fully severed.

The second test, shown in Figure 4-26, resulted in burndown of both conductors. The burndown locations are shown in Figure 4-27.

Figure 4-25
The Lower Splice and Conductor Suffered Severe Damage and Probably Would Have Broken Had the Conductor Been Under Tension

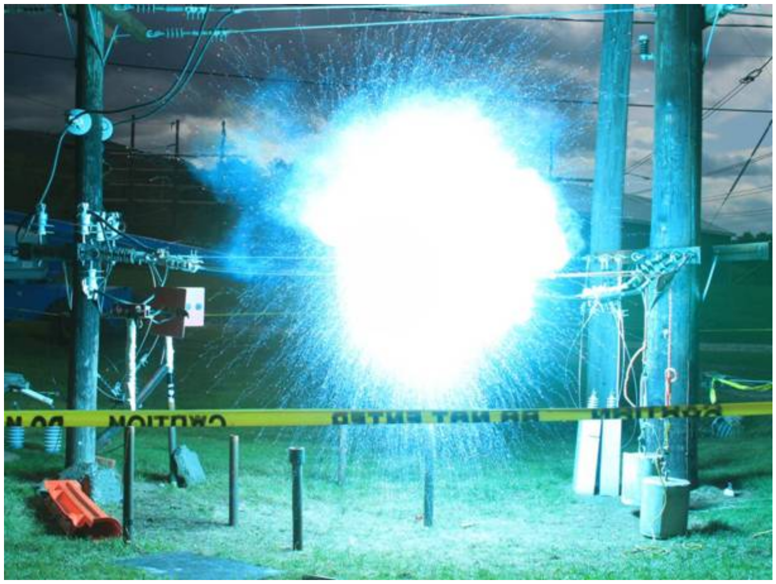

Figure 4-26
Conductor Burndown Test on 336.4-kcmil (170.5-mm^2) Aluminum Tree Wire with Automatic Splices

Figure 4-27
Breakage Occurred on the Load Side of the Automatic Splices

Tests with Arc Protective Devices

The spliced conductor configuration was used again, but this time arc protective devices (APD) were added to the load side of each splice. The clamps were properly installed, with the clamp body bridging the interface between the bare conductor and insulation, as shown in Figure 4-28.

Arc tests were repeated eight times (four tests with two conductors per test) without a single burndown or significant conductor damage. Figure 4-29 shows one of the APDs, still installed on the conductor, after an arcing fault test. Figure 4-30 shows a test in progress. The same APDs were used in the first and second tests. Even with some damage from the first event, the APDs prevented the conductor from being damaged. New APDs were used for the third and fourth tests.

APDs are sometimes referred to as “do nothing clamps” by linemen who feel that the APDs do not protect the conductor from burndown during arcing events. However, this sentiment may be fueled by improper installation of the devices. The APD works by providing sacrificial metal and thermal mass at the arc attachment point. In order to work properly, they should be installed at the load-side junction, where the conductor transitions from stripped to covered. If there is a gap of bare conductor between the APD and the covering, the arc will motor past the clamp and attach to the conductor where the covering begins.

To examine the effect of incorrectly installed arc protective devices, they were placed on the conductor with the APD pushed up against the splice, with a gap between the insulation and the APD. This configuration allows for significant conductor damage during an arcing event, as shown in Figure 4-31.

Figure 4-28
Properly Installed Arc Protective Device

Figure 4-29
This Arc Protective Device Prevented the Conductor from Being Damaged During the Arcing Fault

Figure 4-30
Arc Anchored on Arcing Protective Devices During Testing

Figure 4-31
This Improperly Installed APD Allowed Significant Damage to the Conductor

Line Hose and Gel Wraps

Any insulating covering that restricts arc movement will increase the likelihood of conductor burndown. Line hose and gel wraps both act similarly to conductor covering by preventing the arc from motoring past their location. Several tests were performed to examine what happens when an arc that is motoring on bare conductor encounters a line hose or gel wraps.

Line Hose

Seven total tests were made with line hose installed on #4 ACSR and stripped 336.4-kcmil (170.5-mm^2) and 556.4-kcmil (281.9-mm^2) aluminum conductors. In each case an arc was established between two parallel conductors and allowed to motor to the line hose location. Three tests were made with the line hose on each conductor and parallel to one another. Four tests were made with line hose on only one of the parallel conductors so that the arc was free to move on the other conductor. Some tests were made with the larger connector end of the line hose on the source side, while other tests placed the smaller end of the hose on the source side. All tests on #4 ACSR bare conductor resulted in burndown of the conductor where the arc met the line hose. Tests on the larger conductor resulted in either conductor burndown or severe conductor damage (more than 50% broken strands).

Figure 4-32 shows a burndown event on #4 ACSR bare conductor. Figure 4-33 shows a burndown event on 336.4-kcmil (170.5-mm^2) aluminum conductor. Figure 4-34 shows that same 336.4-kcmil (170.5-mm^2) conductor after the test.

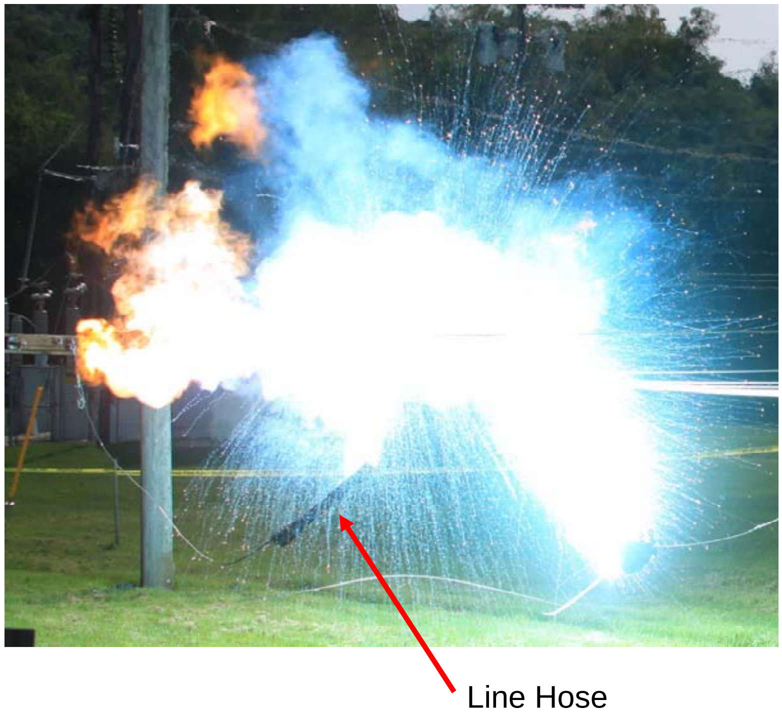

Figure 4-32
Conductor Burndown at a Line Hose on #4 ACSR Bare Conductor

Figure 4-33
Conductor Burndown on 336.4-kcmil (170.5-mm^2) Aluminum Conductor at a Line Hose

Figure 4-34
Section of 336.4-kcmil (170.5-mm^2) Aluminum Conductor After Burndown Event

Note: The insulation was stripped from this conductor prior to testing. The black appearance is due to soot buildup inside the line hose during the test.

Gel Wrap

Gel wraps are primarily used for insulating and sealing spliced-in low voltage (<600 volts) direct buried cables. The wrap is made up of a flexible corrugated thermoplastic housing that is lined with a thick layer of silicone-based gel. It is applied by wrapping around the conductor and closing interlocking tabs on the edges.

Figure 4-35
Gel Wrap Installed on a 336.4-kcmil (170.5-mm^2) Aluminum Conductor Prior to a Burndown Test

Some utilities have begun using gel wraps to cover automatic splices in covered conductors on overhead systems. They are used in this manner to prevent arc initiation at the bare section of line associated with automatic splices. Two tests were made to examine what happens when a motoring arc encounters a gel wrap (no attempt was made to examine the ability of the gel wrap to inhibit arc initiation). In each test an arc was established between two parallel 336.4-kcmil (170.5-mm^2) aluminum conductors. The arc current level was nominally 2,800 amps at 4,160 volts phase-to-phase. The arc motored down the line to the gel wrap. The conductor was fully severed in each burndown test. Figure 4-36 shows the result of one of the burndown tests. Notice how most of the conductor strands have been vaporized back into the wrap. The last strands to break did not have a chance to vaporize and are protruding from the gel wrap.

Figure 4-36
Burndown at Gel Wrap on 336.4-kcmil (170.5-mm^2) Aluminum Conductor

5
SUMMARY

Although conductor burndown is a well-documented phenomenon, conductor burndown characteristics are not well documented. There are only a few existing references detailing previous research and results on conductor burndown characteristics. Because there is a limited amount of published research, there are gaps that are left unaddressed in the data.

The conductor burndown research detailed in this report was designed with these data gaps in mind. The research team set out to provide conductor burndown characteristics specifically targeted to meet these needs by examining:

- #4 and #2 ACSR bare conductor at fault currents from 725 to 2,800 amps
- 336.4- and 556.4-kcmil (170.5- and 281.9-mm^2) aluminum covered conductor at fault currents from 2,800 to 8,700 amps

A total of 84 arc fault tests were conducted to study conductor burndown properties, arc attachment, the effectiveness of arc protective devices, and the impact of line hose and gel wraps in motoring arc scenarios. Several different conductor configurations were utilized. Tests were conducted from 725 amps to 8,700 amps, with fault durations ranging from just a few cycles to more than 300 cycles (at 60 Hz).

Findings

The primary product of this testing is enhanced knowledge of burndown properties for several common conductors. Burndown characteristics for these conductors are summarized in Table 5-1. Data for 3/0 and 4/0 ACSR bare conductor is also included in Table 5-1, but is based on previous work (Goode and Gaertner 1965). The “Typical” characteristics in Table 5-1 represent a curve-fit to the full dataset recorded for each conductor. The “Severe” characteristics were determined by creating a curve-fit approximately based on the fastest 25% of burndowns at each current level.

The effectiveness of arc protective devices (APDs) in limiting damage on covered conductors was investigated. APDs were found to be highly effective if they are installed correctly. It is essential to place the APD at the load-side junction, where the conductor transitions from bare (stripped) to covered. The APD should bridge this junction. If there is a gap of bare conductor between the APD and the covering, the arc will motor past the clamp and attach to the conductor where the covering begins.

Line hose and gel wraps both act similarly to conductor covering by preventing the arc from motoring past their location. Several tests were performed to examine what happens when an arc that is motoring on bare conductor encounters line hose or gel wraps. Seven total tests were made with line hose installed on #4 ACSR and stripped 336.4-kcmil (170.5-mm^2) and 556.4-kcmil (281.9-mm^2) aluminum conductor. All tests on #4 ACSR bare conductor resulted in burndown of the conductor where the arc met the line hose. Tests on the larger conductor resulted in either conductor burndown or severe conductor damage (more than 50% broken strands).

Two tests were made to examine what happens when a motoring arc encounters a gel wrap (no attempt was made to examine the ability of the gel wrap to inhibit arc initiation). In each test, an arc was established between two parallel 336.4-kcmil (170.5-mm^2) aluminum conductors. The arc current level was nominally 2,800 amps at 4,160 volts phase-to-phase. The arc motored down the line to the gel wrap. The conductor was fully severed in each burndown test.

Table 5-1
Typical and Worst-Case Burndown Characteristics for Several Common Conductors

Conductor	Typical Burndown Characteristics	Severe Case Burndown Characteristics
#4 ACSR Bare	$t = 5074.3 \cdot I^{-1.2772}$	$t = 2682 \cdot I^{-1.211}$
#2 ACSR Bare	$t = 185.1 \cdot I^{-0.7407}$	$t = 117.64 \cdot I^{-0.7358}$
3/0 ACSR Bare*	$t = 2870.7 \cdot {}^{-1.0311}$	$t = 1406.1 \cdot I^{-0.9582}$
4/0 ACSR Bare*	$t = 94535 \cdot I^{-1.3552}$	$t = 96613 \cdot I^{-1.3765}$
336.4-kcmil (170.5-mm^2) Aluminum Covered Conductor (Tree Wire)	$t = 24106 \cdot I^{-1.3254}$	$t = 22253 \cdot I^{-1.3335}$
556.4-kcmil (281.9-mm^2) Aluminum Covered Conductor (Tree Wire)	$t = 41549 \cdot I^{-1.3222}$	$t = 26878 \cdot I^{-1.2839}$
* Source: Goode and Gaertner 1965		

Multiple tests were performed to examine if and how a running arc will attach to the line at various obstacles it may encounter. These tests were performed on pairs of bare #2 ACSR conductors strung on a 50-ft (15.2-m) test line. Common distribution hardware was mounted to the test line, and a running arc was established at the source end and allowed to run down the line:

- *Automatic splice* – The arc motored past the automatic splice in all tests (a total of three).
- *Hotline clamp* – In several tests the arc was allowed to motor over a hotline clamp and showed no signs of attachment. The clamp was not connected to any other conductor or hardware and was put in place to simulate an errant clamp left on the line.
- *Porcelain pin insulator* – A porcelain insulator was tied to the conductor with an aluminum strand. The insulator rested on a pin that was not grounded. The arc did not fully anchor at the insulator location during either test (two tests total), but its movement down the line did slow considerably at the insulator location. The lingering of the arc at the insulator location was enough to cause some visual pitting and blackening of the conductor strands.
- *Polymer vice-top insulator* – The polymer vice-top insulator was attached to the bare #4 ACSR conductor, with the vice jaws clamped around the line per a typical installation. This test was repeated twice. During the first test, the arc did not anchor at the insulator, but its motion down the line did slow considerably. Post-test inspection revealed that the conductor inside the jaws of the vice-top insulator had suffered significant damage. The test line was lightly tensioned during this test, and it is believed that the conductor would have fully separated had the line been under tension loading typical of field conditions. The tension on the test line was increased for the second running arc test with a vice-top polymer insulator. This time, the conductor was severed at the source side of the insulator.

Comparison with Previous Work

Goode and Gaertner also tested #4 ACSR and 350-kcmil (177.3-mm^2) aluminum conductors during their work but at higher current levels. The conductor burndown characteristics found during this research for these conductors compares well with the characteristics found by Goode and Gaertner.

Data taken during this EPRI investigation were also compared to #4 and #2 ACSR bare conductor data found by Lasseter. The EPRI characteristics show faster burndown times than those reported by Lasseter for all current values tested. The exact reason for this discrepancy cannot be known for sure, but may come from the data recording methods used in the Lasseter work.

During the Lasseter work, the operator manually opened the circuit breaker once conductor failure was observed. This approach to circuit clearing is very important for interpreting the resulting test data. Lasseter indicates that manual breaker tripping time is included in the reported burndown times, but that it does not materially affect the results. Judging by first hand experience with performing the tests detailed in this report, it is difficult to rationalize how including the time required for an operator to recognize that the conductor had failed and then manually trip the breaker could not appreciably affect the reported burndown times. Many of the reported burndown times are in the range of 1 to 3 seconds. For the longer duration events, it is conceivable that the additional tripping time could be 30% or more of the total burndown time.

A
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