Supplemental Information on High Energy Fault Protective Devices (HEFPD)

Appendix A. Background and Overview

1. High Energy Fault Protective Devices (HEFPD) are intended to limit powerline fault-coupled energy to equipment and withstand longer duration ac energy originating from power line faults.

2. In situations where both lightning waveforms and ac power-line fault energy may occur, protection of the signal system against both of these hazards should be provided. However, it is not necessarily expected that HEFPDs will always fulfill both of these roles, and a separate layer of conventional lightning arrestors and equalizers may be required in addition to the HEFPDs. In such cases, the HEFPDs must still withstand exposure to lightning waveforms as modified by any installed lightning arresters, even if the HEFPDs are not expected to mitigate the lightning waveforms.

3. Conventional track circuit SPDs have traditionally been used in groups of three, with an arrester connected from each rail to ground, and an equalizer connected rail-to-rail. HEFPDs may be configured in the same way; as an overlay to or replacing the existing SPDs or they may be configured differently. A single HEFPD device might perform the function of all three as a three-terminal device (two rails and ground) as in existing three element SPDs.

4. Alternatively, two HEFPDs, each connected rail-to-ground, together might perform the necessary functions without a separate rail-to-rail element. If the break-over threshold characteristics of the two are sufficiently close in voltage or if they have, for example, a common trigger circuit so that the devices control both the rail-to-ground and rail-to-rail voltage to acceptable values for power-line fault conditions. The HEFPD devices may function as “crowbar” or “voltage-limiting” type devices, or may provide high-impedance isolation for track-connected signal equipment if the rail-to-ground voltage is also controlled to the limits noted in this manual part for personnel safety. HEFPDs may be designed to work with existing SPDs (lightning arresters), instead of replacing them. It is also conceivable that HEFPDs may be installed in a separate enclosure, external to the signal equipment enclosure.

5. The principal benefit to be derived from using HEFPDs is the protection of track-connected signal equipment. Depending on the details of the exposure and the location of the HEFPDs some benefit may also accrue for power-line fault-induced personnel safety issues. However, additional mitigation methods may be necessary to effectively control personnel-safety hazardous voltages. Those additional mitigation procedures may also help reduce the stress placed on SPDs and HEFPDs by power line fault events.

Appendix B. Definitions

Because this manual part describes the functional requirements of HEFPD devices, which are technology independent, new terms and definitions are sometimes appropriate where the existing terms are technology-specific. Whenever possible, existing terms and definitions have been used.

1. Crowbar Device
   One of two broad types of SPDs. A crowbar device, once triggered, becomes conductive to reduce the potential between its terminals (shown as A1 and A2 in Figure B1 below). Figure B-1 shows the V-I characteristics for a typical crowbar device. A crowbar characteristic is representative of a spark gap or the thyristor class of devices, including DIAC (diode for alternating current), TRIAC (triode for alternating current), or SIDAC (silicon diode for alternating current) devices.

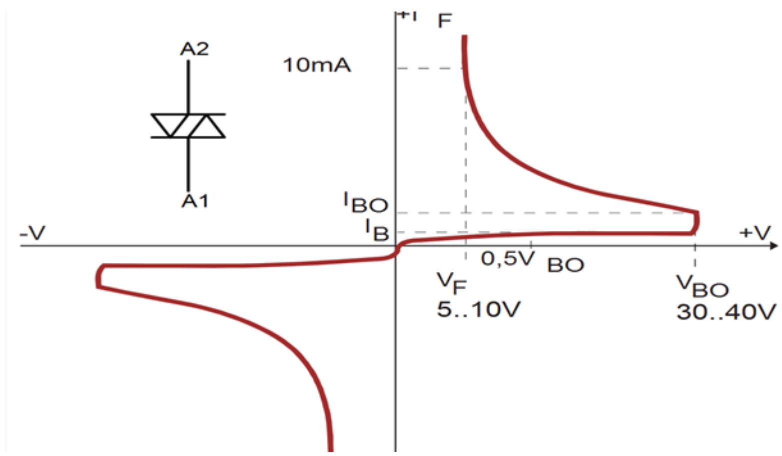


Figure B-1: Voltage Current Characteristic Representative of a Crowbar Device.

2. Clamping Device
   One of two broad types of SPDs. At voltage less than the threshold voltage V_{BO}, the device resistance is high, and the current through the device is low. Above V_{BO}, the device switches to its lower resistance mode and the current increases greatly in response to a small increase in voltage. Figure B-2 shows the V-I characteristics for typical MOV (metal oxide varistor) clamping devices. (Two curves are shown in Figure B-2. One curve indicates a more-constant voltage above the knee of the curve, which is more indicative of a ZnO (Zinc-oxide varistor), whereas the gradually increasing voltage with current above the knee is representative of a SiC (Silicon Carbide) Varistor. The lower slope of the SiC curve results in more heating of the device for voltages both lower and higher than the breakover voltage.

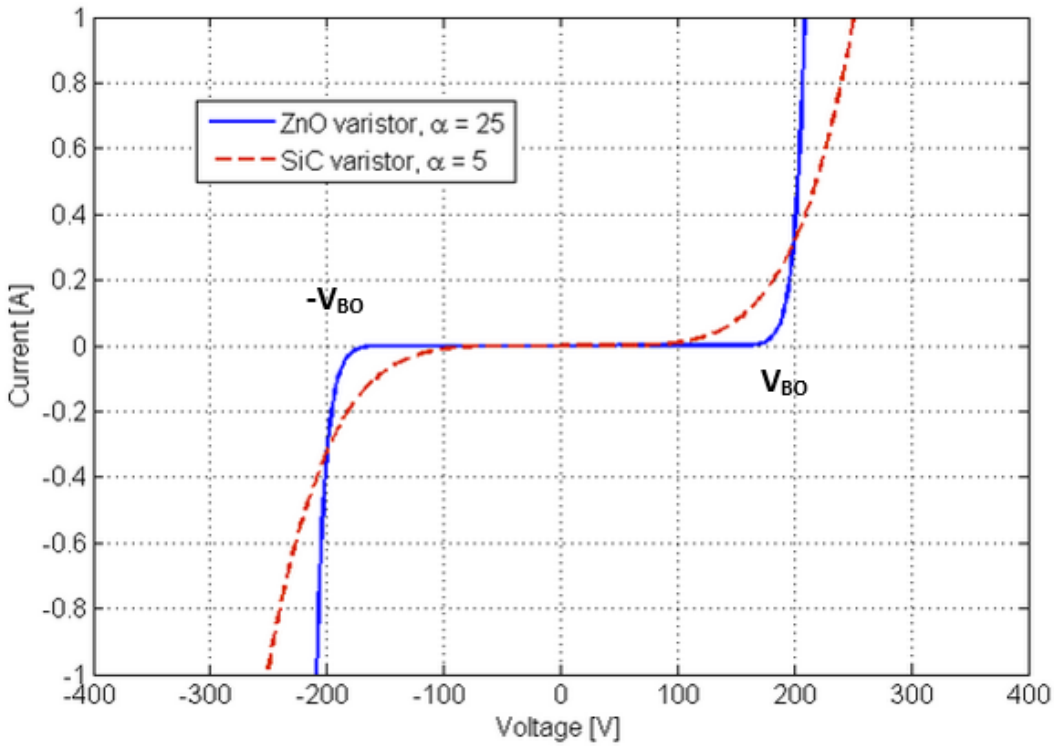


Figure B-2: Voltage Current Characteristic of Clamping Device.

3. Breakover Voltage (V_{BO}) - also known as Voltage Break Point (V_{BP})
   The voltage at which the device changes to a low impedance from its high impedance state (see Figure B- 1 and B-2). In crowbar devices, this is referred to as the breakover voltage (V_{BO}). In clamping devices, the value is commonly referred to as the threshold voltage (V_{TH}). This value is also sometimes referred to as: sparkover voltage, breakdown voltage, firing voltage, flashover voltage, and voltage protection level – although these terms can also be used in different ways. (The transition from low to higher current in the breakover region may be more abrupt than the smooth curve of Figure B-1.)

4. Discharge Current (ID)
   The current that flows through the device in its lower-impedance "on" state.

5. Nominal Discharge Current (In)
   The 60 Hz rms value of the current having a specified duration selected by the manufacturer that can be passed through the HEFPD, where the HEFPD remains functional after "n" surges.

6. Discharge Withstand Current (IDW)
   The maximum magnitude of 60 Hz discharge current (I_D) of a specified wave shape and duration that can be applied to an SPD a specified number of

times without causing unacceptable performance degradation or permanent damage to the SPD or protected devices. For an HEFPD, the wave shape is a 60 Hz ac sine wave, with a duration of a specified number of cycles. Often, the current and duration are related by the energy as an (I squared t) value or (I^2t). The units of I^2t are Joules per ohm.

7. Holding Current (IH)
The minimum current needed to keep an SPD in its lower-impedance state. Transition from the lower impedance to the higher impedance region occurs when the current becomes less than the holding current. This is primarily applicable to crowbar type devices.

8. Lifetime Surge Withstand Capability
A measure of the ability of an HEFPD to withstand multiple surge events without sustaining unacceptable performance degradation or device failure.

9. Maximum Continuous Operating Voltage Rating (MCOV)
The steady-state operating voltage that the device can withstand without overheating or malfunctioning. This is the normal operating voltage in the signal circuit, including any normally induced voltages, with the SPD remaining in the off state.

10. Maximum Let-Through Voltage
The peak transient voltage briefly allowed by the device before it switches to its “on” or low-impedance state.

11. Off State
An SPD in its high-impedance state, with the protected signal equipment operating normally.

12. Off-State Impedance (Z_{OFF})
The impedance of an SPD in its high-impedance state.

13. On State
An SPD in its lower-impedance state. Energy on the protected circuit is conducted through the SPD. Protected signal equipment may not operate normally during the on state.

14. On-State Impedance (Z_{ON})
The impedance of an SPD in its lower-impedance state.

15. Peak Limiting Voltage
See Voltage Protection Level (V_{PL}).

16. Threshold Voltage (V_{TH})
See Voltage Break Point (V_{BP}).

17. Voltage Protection Level (V_{PL})
    The maximum (instantaneous) value of the voltage on the terminals of a surge protective device (see Figures B-1 and B-2). V_{PL} is generally given for a specific lightning or surge test waveform.

18. Voltage Surge
    A sudden and momentary increase in voltage. A voltage surge may be caused, for instance, by lightning, or faults in circuits. If protective measures are not employed, such a surge may bring about a failure or significant damage; also called surge voltage, or transient voltage.

19. Voltage Swell
    This is a short duration increase in voltage values. Voltage swells lasting longer than two minutes are classified as an overvoltage. If swells reach too high a peak, they can damage electrical equipment.

Appendix C. Power Line Fault Background

1. Power Line Fault Waveforms

    a. Power line fault "waveforms" exist somewhere between transient surge waveforms, such as lightning, and what is normally considered steady-state.

    b. A power line fault waveform is essentially a sine wave that lasts for a finite period of time.

    c. On power lines with high-speed relay protection these fault waveforms typically last from 3 to 18 cycles sometimes with subsequent similar fault waveforms after a delay period (perhaps a delay in the range of one-second due to breaker reclosing) if the fault does not clear. At 60 Hz, the fault waveform duration is typically 50 ms to 300 ms.

2. Transmission Lines

    a. Electric power transmission lines typically have devices and systems in place to detect faults and de-energize (a.k.a. trip) the lines. These devices are called relays, and the systems provide what is commonly called relay protection.

    b. Many different relaying methods (a.k.a. relay schemes) are employed in both primary and back-up relaying.

(1) High-speed relaying incorporates relays at different ends of a transmission line (in substations) that are connected by redundant communications channels in order to detect a fault and safely de-energize the line.

(2) For high-speed relaying this process typically takes from 3 to 6 cycles (50 ms to 100 ms).

c. Transmission line relay protection usually includes one or more reclosing attempts. Reclosing involves re-energizing the power line.

(1) If the fault is no longer present, the line is back in service after reclosing of the breakers.

(2) If, however, the fault remains, then upon breaker reclosure, the relay protection will de-energize the line, again, which produces another fault current waveform.

(3) It is common to have multiple reclosing attempts if the fault does not clear.

(4) Often one reclosing is attempted in less than one second, with a second reclosing attempt after a slightly longer interval.

d. For personnel safety purposes, multiple periods of fault exposure within one second are presumed to have a duration equal to the total of the individual durations. Because an HEFPD will not have time to cool between such rapid events, the total time of exposure is used to evaluate them as well.

e. If a relay protection scheme de-energizes the line in 6 cycles (about as slow as they get for modern transmission lines), and has two automatic reclosing attempts, then the total energy delivered within a few seconds would correspond to 18 cycles, or 300 ms.

f. The electric power transmission company can provide the actual fault clearing time and the reclosing scheme for their power lines.

3. Distribution Lines

a. Conventional electrical distribution lines are protected by fuses and “reclosers.”

b. For a variety of reasons, distribution line faults can take much longer to clear (that is, to de-energize) than transmission lines.

(1) On occasion, distribution line faults do not clear, and the fault current continues for an extended time.

(2) This difference should be considered when designing railroad surge protection.

c. It should be noted that distribution line compatibility improvements are beginning to evolve.

(1) Distribution automation and the Smart Grid are changing the way distribution lines operate.

(2) In some cases, fault clearing schemes on distribution lines are beginning to approach the performance of the high-speed relay protection of transmission lines.

4. Power Line Fault Energy Coupling Paths

a. Magnetic Induction

b. Conduction – Ground Potential Rise

c. Electric Field Induction

5. Power Line Fault Energy Magnitude

a. Depends on Short-circuit capacity of terminating substations

b. Depends on distance between substations.

c. Depends on location of fault.

6. HEFPD Damage Mechanisms

a. General – $I^2 t$, total energy without cooling, etc.

b. Direct effect of fault current

c. Fault current with subsequent reclosure currents

7. Personnel Safety Issues

a. The same energy that can damage signal equipment has the potential to injure or kill people if they are directly exposed.

b. The levels of energy needed to produce serious injury or death vary widely depending on the individual and the circumstances of the exposure.

c. The levels that are considered dangerous are a function of frequency, voltage, source impedance, soil resistivity, and duration.

d. Standards or guidelines exist that provide maximum voltage allowed assuming a frequency of 60 Hz and a strong source (i.e. magnetic induction or conduction):

(1) IEC 479-1

(2) IEEE Std. 80

(3) OSHA Standard 1910.333

(4) AAR/IEE Bluebook (out of print)

(5) AAR/AREMA/EPRI: Power System and Railroad Electromagnetic Compatibility Handbook

e. Depending on the specific situation, these standards usually produce maximum allowable touch voltage exposures for 60 Hz transmission lines, with high-speed relay protection, in the range of 400V to 1000V ac rms.

(1) HEFPDs should limit voltage to a protection range that is below the personnel safety level.

(2) The HEFPD should be designed to survive a high energy event so that protection remains for future events.

Appendix D. SPD Background

1. Two broad protective device categories or operating characteristics that are used for SPDs are crowbar devices and clamping devices.

a. A crowbar device is distinct from a clamping device in that, once triggered, it pulls the voltage below the trigger level, usually the resulting voltage is close to ground potential.

b. A clamping device prevents the voltage from exceeding a preset level. These two operating characteristics may be stand-alone or may be incorporated into a single SPD.

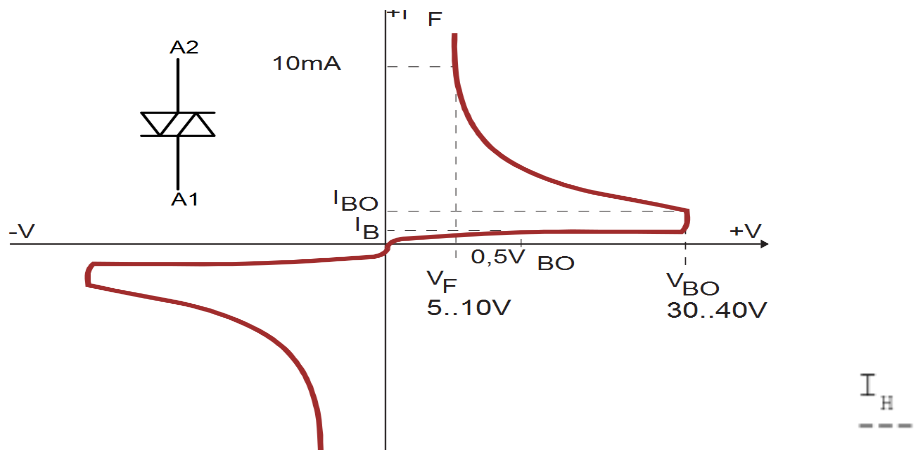


Figure D-1: Voltage Current Characteristic Representative Of A Crowbar Device.

2. Figure D-1 shows the general shape of the V-I characteristic for a crowbar device. Of particular interest is the shape of the curves. A crowbar characteristic is representative of a spark gap or the thyristor class including DIACs (*DIode for Alternating Current*),or TRIAC (*TRIode for Alternating Current*) or SIDAC (SI*licon Diode for Alternating Current)* This class operates by putting a short circuit or low resistance path across the voltage source. Another analogy is a single-pole single-throw switch. For voltage less than V_{BO} (**Breakover Voltage**)the device has a high impedance, the switch is "off." For input voltage greater than V_{BO}, the impedance of the device becomes low, the switch is "on." The transition from low to higher current in the breakover region may be discontinuous rather than the smooth curve of Figure D-1. The current that flows through the device in the low-impedance state is the **Discharge Current.** The **Discharge Withstand Current** is the magnitude and wave shape of a discharge current that can be applied to an SPD a specified number of times without causing damage to it. (IEEE Std 62.62-2000)

3. Transition from the low impedance to high impedance region occurs when the current becomes less than I_H. (the **Holding Current**). To ensure that a crowbar SPD switches "Off" and restores normal system operation after a surge, the holding current of the device must be greater than the maximum system dc short-circuit current of the circuit at the terminals of the crowbar device.

4. An advantage of a crowbar characteristic over a clamping characteristic is that the low holding voltage of the crowbar lets it carry higher fault current

without dissipating as much power as a clamping device at the same location (which could otherwise cause overheating of the SPD).

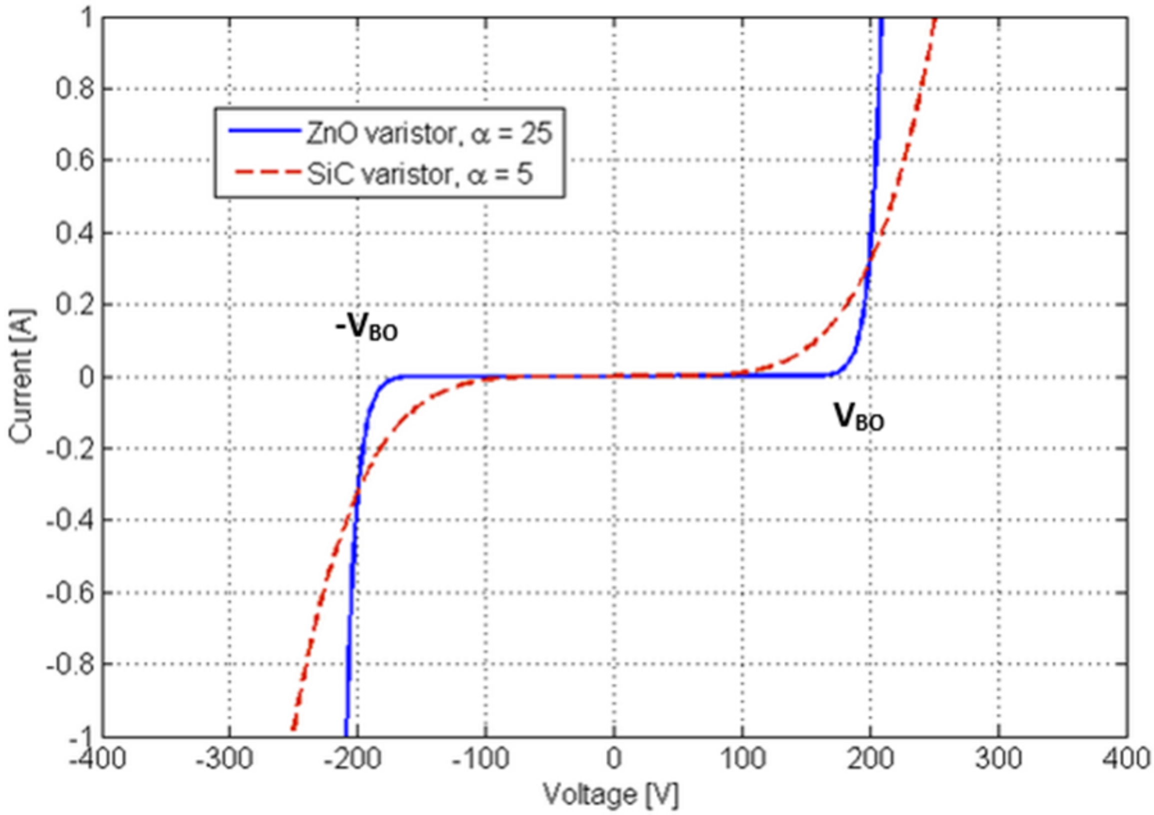


Figure D-2.: Voltage Current Characteristic of Clamping Device

5. Figure D-2 shows the general shape of the V-I characteristic for a clamping device. At voltages less than the **threshold voltage** V_{TH}, the current is low, corresponding to a high resistance. Above V_{TH}, the MOV switches to lower resistance mode and the current increases significantly with only a small increase in voltage. The clamping characteristic is representative of a MOV (*metal oxide varistor*) or SASD (silicone avalanche suppressor diodes). Two curves are shown in Figure D-2. One curve indicates a more constant voltage above the knee of the curve, which is more indicative of a SASD device, whereas the gradually increasing voltage with current above the knee is more indicative of a MOV device.

6. An important value in Figure D-1 and Figure D-2 is the maximum (instantaneous) value of the voltage on the terminals of a surge protective device, which is identified as the **Voltage Protection Level V_{PL}.** This is generally given for a specific lightning or surge test waveform. For surge protective devices designed for protection of IT networks, the voltage protection level has to be adjusted to the immunity of the equipment to be protected (DIN EN 61000-4-5: 2001-12). This same consideration should

apply for track connected signal equipment. A related term is the **Voltage Protection Rating** of SPD's for devices connected to commercial power.

7. For the crowbar characteristic of Figure D-1, the voltage analogous to the voltage protection level (V_{PL}) is identified as the Breakover Voltage (V_{BO}). For any given SPD that maximum voltage on the SPD terminals may depend on the specific characteristics of the "test" waveform, for example the rise time of the lightning waveform. Another related term, particularly with clamping devices used for power line protection is the *Maximum continuous operating voltage rating (MCOV),* which is the maximum steady-state voltage that the device can be used without overheating.

8. IEEE C62.37.1 Guide for Thyristor SPD notes that "to protect the equipment against overvoltages, the – SPD should limit the voltage to a level that does not cause equipment damage. The peak limiting voltage is the main criterion of protector performance under impulse and ac overvoltage conditions." Thus, the term "**peak limiting voltage**" may be a descriptive term that is synonymous with the crowbar "breakover voltage" or the "voltage protection level" for MOV type devices as used above.

Appendix E. HEFPD Firing Potential Considerations

1. Summary & Overview

   a. This appendix reviews personnel safety touch-potential guidelines for power fault waveforms to help identify a range of activation (firing, breakover) voltage that may be suitable for HEFPDs. The power fault personnel safety guideline generally used in the US identifies the safe touch potential to be not only a function of the voltage of an electrified object, but also is dependent on the duration of the overvoltage. This appendix reviews the IEEE safety guideline that might be conservatively applied for track maintenance considerations in a power fault environment, to identify an expression that relates the safe touch potential to a surge voltage and duration.

   b. Since the duration of a power fault event is a factor in assessing the safe touch potential, information is gathered from the technical literature to obtain expected fault durations for both transmission line and distribution line exposures. It should be kept in mind that durations of power line faults for distribution lines can be considerably longer than for power transmission systems.

   c. The review of these voltage and time exposures in this appendix suggests that:

(1) The activation threshold of rail-to-ground HEFPDs should be less than the maximum safe touch potential for the area where they are installed to help provide for personnel safety from power line coupled fault events.

(2) In extreme cases on distribution lines, the fault duration may be 120 cycles (2 seconds) or longer. In such cases, the safe touch voltage approaches the 50 volt limit that is used for steady-state voltages.

2. Rail Touch Potential

a. This Manual Part relies on the guidelines of IEEE Std-80 for evaluating fault-condition shock safety. That standard considers the size (weight) of a person. The IEEE Std-80 safe touch potential guideline is based on the analysis of animal testing data by Dalziel[1] who developed a linear relationship between fibrillation threshold and body weight, and also the square root dependence of the fibrillation current on the shock duration. Dalziel also used a linear regression relationship for the 99.5 percent non-fibrillating current dependence on body weight. The IEEE Std-80, which is based on Dalziel's work, provides values of 99.5 percent non-fibrillating current for two body weights, 50-kg (110-lb) and 70-kg (154-lb) persons, as:

$I_b\sqrt{t} = 0.116$ and $I_b\sqrt{t} = 0.157$ respectively,

where the current is in amperes and the time in seconds. The expression is generally used for a 50-kg person to determine safe (non-fibrillating) current for persons contacting energized rails.

b. The expression used in IEEE Std-80 for touch potential, as a function of body current I_b is,

$$V_t = (R_b + R_f)\, I_b \qquad \text{Eq (1)}$$

where:

R_b is the bulk resistance of the body, for which a conservative estimate is 1000 ohms.

R_f is the two-feet earth contact resistance.

c. The safe touch potential for IEEE-80 depends on the earth contact

[1] Charles F. Dalziel, *Electric Shock Hazard,* IEEE Spectrum, February 1972.

resistance R_f as in Eq 1. When the person stands on two feet, and no shoe or gravel insulating is assumed as a worst case, a value for R_f is given in IEEE STD-80 as,

$$R_f = 1.5\,\rho_e \qquad \text{Eq (2)}$$

where ρ_e is the earth resistivity in ohm·m, and the factor of 1.5 accounts for the equivalent geometry of two feet as two 16-cm diameter conducting disks on ½ meter centers. For a specific region of interest, appropriate representative values for R_f can be used to calculate a safe touch potential using Eq 1 and Eq 2. However, for estimating a safe firing potential for HEFPDs, a conservative approach might be to neglect the R_f term in Eq 1. This conservative assumption is not generally made for development of practical mitigation measures for specific powerline exposures of rail systems, but may be appropriate here for setting guidelines for HEFPD development.

d. Thus, ignoring the feet contact resistance, for a 50-kg (110-lb) person Eq 1 can be expressed as:

$$V_t = 1000\left(\frac{0.116}{\sqrt{t}}\right) \qquad \text{Eq (3)}$$

Ignoring the feet spreading resistance might correspond to very low resistivity soil, or a maintenance worker inside a metal bungalow contacting the bungalow or the ground bus, while also contacting a rail lead wire.

e. Figure E-1 shows how the safe touch potential, as given by Eq. 3 changes with the fault duration. The figure shows that the safe touch potential is less than 250 volts for a fault duration longer than approximately 12 cycles. Thus, for consideration of power transmission lines, which generally can be expected to clear faults in 12-cycles or less, 250 volts rms may be a reasonable firing potential to consider. However, if a single HEFPD guideline is to also to apply for power distribution, consideration of longer duration faults may be appropriate.

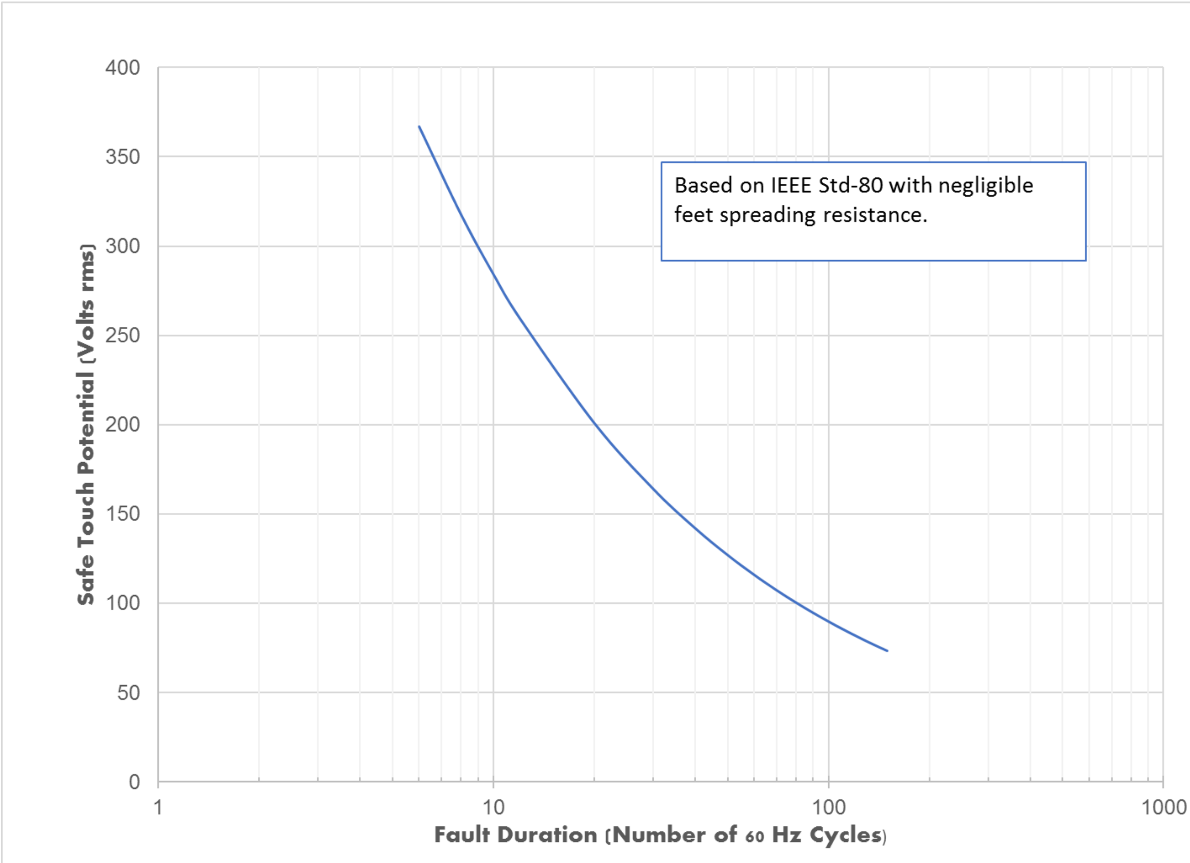


Figure E-1: Safe Touch Potential vs Fault Duration Using Eq. 2.

3. Fault-Current Duration

Figure E-2 shows data obtained by one power utility over a period of 18 months, in which each relay operation was documented to illustrate the clearing time versus the fault current for 34.5 kV sub-transmission.[2] The figure includes data for approximately 1400 relay operations. The red and black lines that are shown on the data in Figure E-2 are attempts by those authors to provide possible trend-lines for the data and illustrates that the data do not present a clear relationship between fault current magnitude and duration. The data in Figure E-2 illustrates that almost all events were cleared in less than 120 cycles (2 seconds), which may not be representative of other utilities as noted in the following.

[2] *ANALYZE RELAY FAULT DATA TO IMPROVE SERVICE RELIABILITY, Roy Moxley*

Schweitzer Engineering Laboratories, Inc. Pullman, WA USA

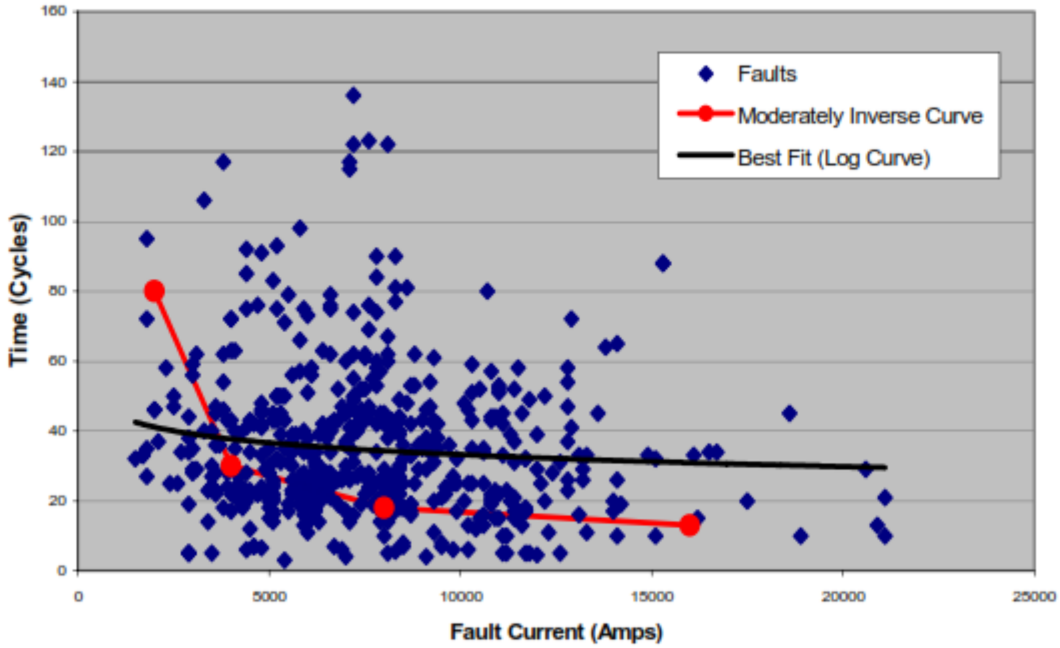


Figure E-2: Distribution Line Fault Current Vs. Duration in 60 Hz Cycles From Reference 2.

4. A survey of numerous power utilities, reported in Reference 3, provides the following summary[3]:

<u>Clearing Times</u> – Only 24% of the respondents have defined protective device clearing time criteria for distribution line protection (considering the last protective device upstream from the end of the distribution line). Of those with a criteria, there was no consensus for a maximum end-of-the-line clearing time. The specific responses were as follows:

Less than or equal to 60 cycles	27%
Between 60+ and 90 cycles	18%
Between 90+ and 120 cycles	9%
Between 120+ and 180 cycles	27%
More than 180 cycles	9%
Other	9%

5. That result suggests that perhaps 45% of those respondents might have maximum clearing times of more than 180 cycles (3-seconds). An interpretation of these citations and Figure E-1 is that if HEFPDs are to be applied in exposures with power distribution:

[3] *IEEE Power System Relaying Committee Report; Distribution Line Protection Practices Industry Survey Results, December 2001.*

a. The activation threshold of rail-to-ground HEFPDs should be less than the maximum safe touch potential for the area where they are installed to help provide for personnel safety from power line coupled fault events

b. In extreme cases on distribution lines, the fault duration may be 120 cycles (2 seconds) or longer. In such cases, the safe touch voltage approaches the 50 volt limit that is used for steady-state voltages

c. However, rail to ground-connected HEFPDs also need to have an activation potential higher than 50 volts ac plus possibly 3 volts dc. Thus, an ac activation potential of 100 volts was selected, which will provide personnel protection for most longer duration distribution fault-induced rail voltage, without compromising the assurance of non-activation for the “steady-state” environment.

d. Depending on the details of the exposure, the power fault induced rail voltage can be much higher than the safe touch values shown in Figure E-1. The firing voltage of HEFPD’s installed in such areas must be low enough to clamp induced fault voltages to below the safe touch potential without damage.

Appendix F. HEFPD Rating Selection

1. Overview

a. This appendix describes the rationale for the range of ratings selected for the High-Energy Fault Protective Devices (HEFPDs) described in Section D of this AREMA Manual Part. These values were not selected at random, but were instead based on the needs of the railroad signaling industry, as identified by the members of the HEFPD working group of AREMA Committee 38-2, and derived from their experiences over the roughly three decades prior to the first drafts of this document, which were written in 2012.

b. The voltages and currents impressed onto railroad rails and signaling circuits during fault events on parallel electric transmission and distribution circuits within a shared-corridor environment are primarily created via magnetic induction affecting the rails or signaling circuits themselves, although earth currents also play a role. The amount of magnetic induction into the rails or signaling circuits is a function of the strength of the overall electromagnetic fields to which these rails or signaling circuits are exposed, as well as other factors. The induced voltages and currents are therefore a function of the:

(1) Degree of proximity and parallelism between the railroad rails/circuits and the electric transmission/distribution line,

(2) Length of the parallel corridor shared by the railroad and electric lines,

(3) Length of each affected track circuit within the parallel corridor,

(4) Presence and location of railroad track circuit devices such as SPDs, Tuned-Joint Couplers, Wideband Couplers, and any other devices that can electrically concatenate multiple track circuits during a fault event,

(5) Magnitude of the fault current on the electric transmission/distribution line,

(6) Type of fault on the transmission/distribution line (e.g. phase-to-ground or phase-to-phase),

(7) Size of the power line's support structure, its spacing, and the grounding resistance to earth at each support structure,

(8) Orientation and spacing of the phase conductors, neutral wires, static wires, messenger wires, etc., and the electrical characteristics of these conductors,

(9) Presence of other above-ground or underground conductive structures along the right-of-way,

(10) Specific location of the railroad rails/circuits within the electromagnetic field surrounding the electric transmission/distribution line,

(11) Railroad track circuit ballast resistance,

(12) Earth resistivity along the shared corridor, and

(13) Various other minor factors

c. Although there are many factors that must be considered in the process of ensuring compatibility between railroad signaling systems and electric power transmission and distribution systems in shared-corridor environments, making sure that the railroad's surge-protection will adequately tolerate the energy that can be induced onto railroad track circuits during a fault event on a parallel electric transmission or distribution line is among the most important, as this directly affects the safety of both railroad personnel and the public, as well as the continued survival and functionality of the signaling equipment. In the broadest possible terms, the adequacy of surge protection can be ensured by:

(1) Increasing the energy-dissipating capacity of the surge limiting equipment protecting railroad signaling circuits,

(2) Reducing the energy absorbed by the surge protection,

(3) Reducing or shielding the exciting field at the railroad tracks by adding overhead wires in the proper location(s), or by installing buried "counterpoise" wires parallel to the railroad tracks,

(4) Replacing, upgrading, or modifying the railroad signaling circuits themselves, in order to provide greater inherent immunity to induced surge voltages and currents, or

(5) Reducing the magnitude of the maximum phase-to-ground fault current on the electric transmission or distribution line by changing how the line is fed (number of substations, etc.), or by adding series inductance or other fault-current limiting devices to the line at the feeding substation.

(6) Reducing the fault current duration.

d. Many situations in which the use of HEFPDs is being considered may require more than one of the above forms of mitigation. The most important key to achieving an efficient engineering solution is to first establish effective communication between the railroad and the electric power transmission/distribution company. Effective communication will allow a comprehensive discussion of all the available mitigation options to be held, and the two parties can thereby determine the most efficient and effective combination of measures to be implemented on one or both systems. This process may also require analysis and modeling of both the railroad and electric power systems to determine the magnitude of induced voltage and current that is to be mitigated and to evaluate the effectiveness of mitigation alternatives.

2. The Lowest Rating

a. The lowest rating for the class of HEFPDs being proposed was intended to be sufficiently robust to limit induced fault voltages that contain more energy than that used in the standard lightning test waveform.

b. The present motivation for the creation of an HEFPD specification in the AREMA standards is that the characteristics of the energy applied to railroad rails and signaling circuits by power-line faults differs significantly in its voltage, current, duration, and frequency, as compared to the energy applied by the lightning events. In general terms, the adverse effects of the energy delivered to railroad systems during a fault on a parallel electric transmission or distribution line can be much greater than that caused by lightning events.

c. The lower HEFPD rating specified is intended to define the parameters of a device that would withstand power line fault surge events that exceed the rating of available track lightning protection. HEFPDs should readily be able to accommodate such fault surge currents and energies multiple times over their lifetimes, with no significant change in their operating characteristics, and without a need for replacement after each such fault/surge.

d. One manufacturer of track arresters that performed well in fault current simulation tests provides ‘rated’ and ‘destruction’ current versus time curves for their product, which is illustrated in Figure F-1. The curves relate to unipolar rectangular current pulses versus duration of the pulse. An expression was deduced for the rated current curve that is shown on the graph.

e. To relate the information in Figure F-1 to power-line faults, assume that ac waveforms of the same rms energy as the manufacturer’s rectangular current pulses would perform in a similar manner. On that basis, the curves of 60 Hz surge rms current versus the duration of the surge, in cycles that is shown in Figure F-2. The HEFPD current rating, as described in Section D.9 of this MP, is the 12-cycle fault surge current that the device will survive and not fail for 10 repetitions of that current application, with cooling time between applications of the surges.

f. It is suggested in the Manual Part main text Section D.9 that a reasonable minimum rating for HEFPDs is 1000 amperes for a 12-cycle fault current. Figure F-2 shows a 12-cycle 1000 ampere surge current as a green dot at the top of the dashed line at 12 cycles.

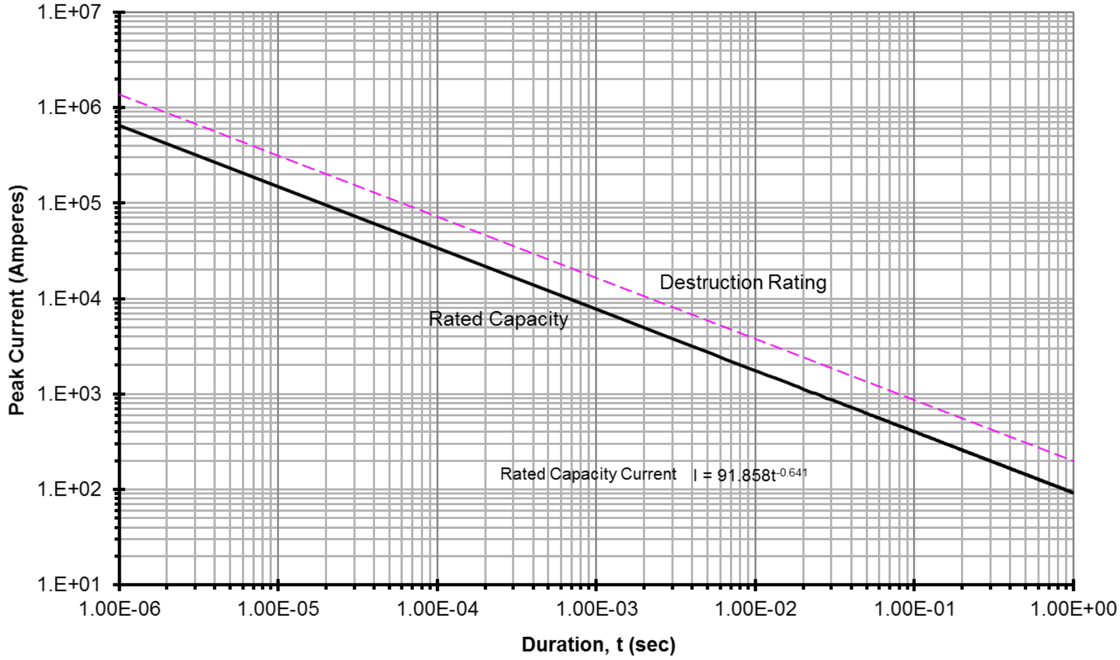


Figure F-1: Published Surge Capacity of Track Arrester

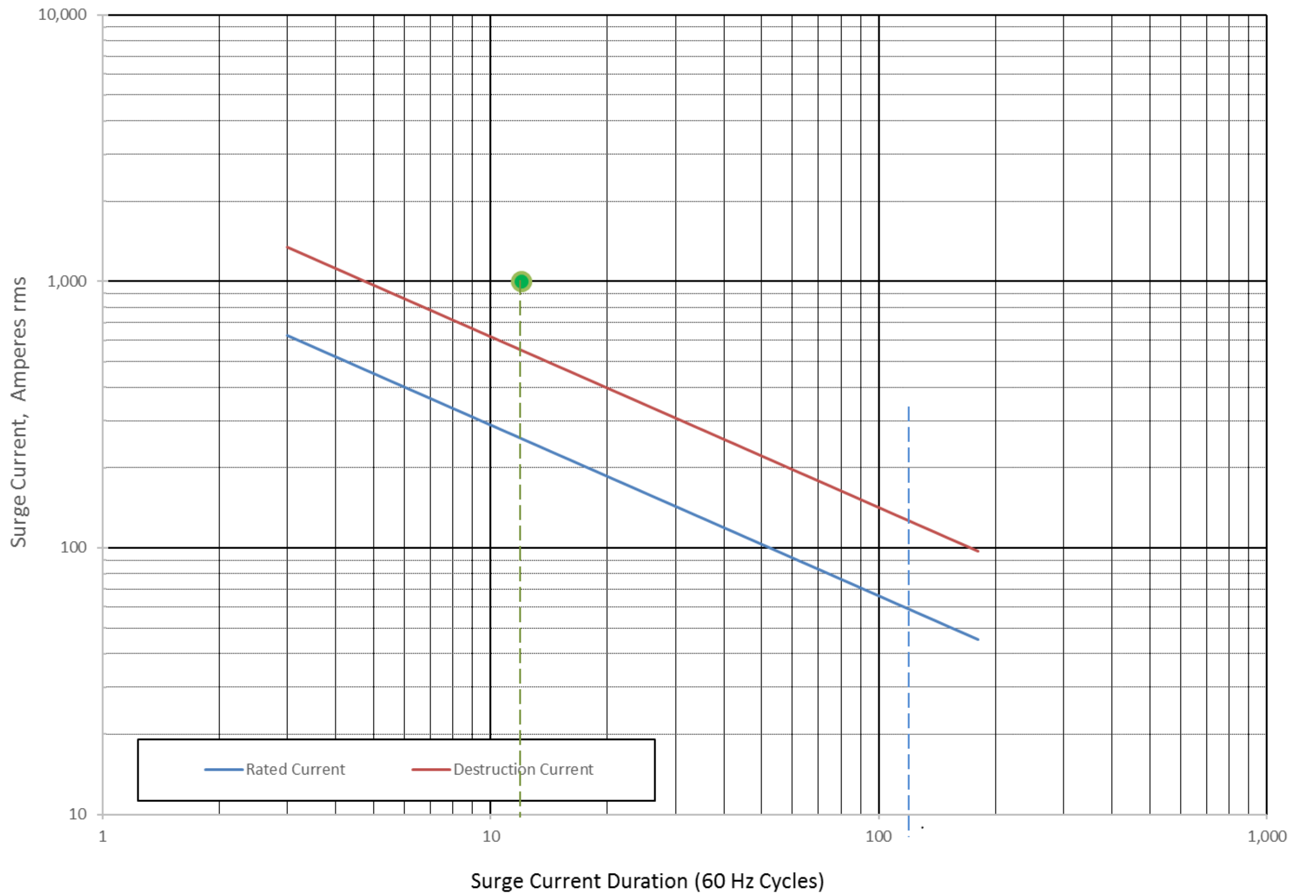


Figure F-2: Estimated 60 Hz Surge-Current versus Duration in Cycles for Arresters of Figure F-1

3. The Highest Rating

a. The highest of the potentially desirable ratings for HEFPDs is derived and reviewed in this appendix from mathematical modeling of several suggested near "worst case" scenarios. Both transmission and distribution scenarios were considered. These two types of electric power lines differ in several important ways:

(1) Electric transmission lines operate at higher voltages than electric distribution lines, and per the National Electric Safety Code (NESC), these higher-voltage lines must be suspended at a greater height above the ground. This effectively increases the average distance between the phase conductors of the transmission line and the rails or wires of a

railroad signal circuit, which reduces the degree of coupling between the two systems.

(2) The maximum fault current for transmission lines (assumed to be 40,000 Amperes, based on experience) is greater than the typical maximum fault current for distribution lines (10,000 Amperes, again based on experience).

(3) Due to differences in the protection schemes used on electric transmission and distribution lines, the fault current duration for transmission lines is typically 6 to 18 cycles (0.100 to 0.300 seconds), which is much shorter than the assumed typical maximum fault current duration for distribution lines, which are mostly less than 2-seconds, based on the data of Figure E-2, but can be much longer.

(4) Transmission lines will normally have one or more static wires mounted above the phase conductors, but no neutral wires. In contrast, distribution lines will normally have no static wire(s), and may or may not have a neutral wire. The physical location of the neutral wires on distribution poles is also highly variable. The net effect of these differences is to cause the currents induced in railroad rails/circuits paralleling a <u>distribution</u> line during a distribution fault to diminish much more rapidly as a function of distance along the railroad, as compared to the induced rail currents resulting from a transmission line fault.

b. The worst-case scenarios of electric transmission and distribution lines were both modeled, and the results of the two models compared to determine which situation represented the more severe worst-case scenario. Although transmission lines might seem to be the obvious choice, fault induced voltages from distribution lines might more likely exceed safe touch potential than transmission lines due to smaller average distances between distribution lines and railroad tracks sharing a common corridor, as well as other factors such as commonly greater maximum fault clearing times of distribution lines.

4. Electric Distribution Line - Modeling of Two Candidate Worst-Case Scenarios

a. Computer modeling of a near “worst-case” distribution line fault scenario used the following parameters:

(1) 12.45kV power distribution line, parallel to railroad tracks for approximately 10 mi.

(2) 10 kA fault capacity at source substation bus

(3) Radial distribution line from source substation. That is, fault current is sourced only from a single substation.

(4) Distribution line centerline is 30 ft (horizontally) from track centerline.

(5) Phase conductor: 336kcm ACSR, on a horizontal cross arm 4.5 ft. from the pole center towards the track, mean height = 22 ft. (see cross section sketch)

(6) Neutral, two sub-cases analyzed:

(7) With a neutral 3/0 ACSR, 4.5 ft. from pole center away from track, mean height= 22 ft (see Figure 4 sketch). (The assumed fault is from phase to neutral.),

(8) Without a neutral. For this case the fault is modeled as being a connection from the faulted phase wire into a 5-ohm ground resistance.

(9) Distributed effective power structure ground resistance is 4 ohms per quarter-mile.

(10) Track ballast resistivity is 2 ohm·kft. (This low ballast resistance results in higher rail current.)

(11) Earth resistivity is 100 ohm·m. (Higher earth resistivity results in a higher induced rail voltage and current. Lower resistivity results in lower induced rail voltage and current.)

(12) Phase-to-Neutral fault calculations were made at least once every ½-mile along the exposure.

b. The profile and cross-section geometry used for the modeling are shown below in Figure F-3 and Figure F-4.

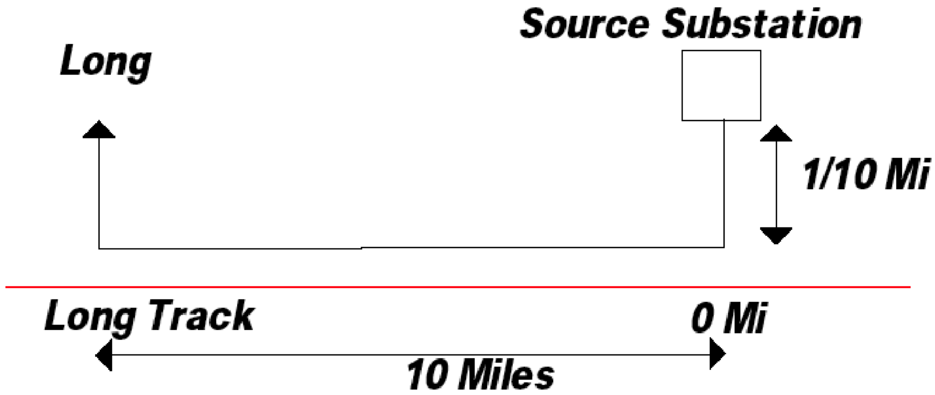


Figure F-3: Profile Distribution Model Geometry

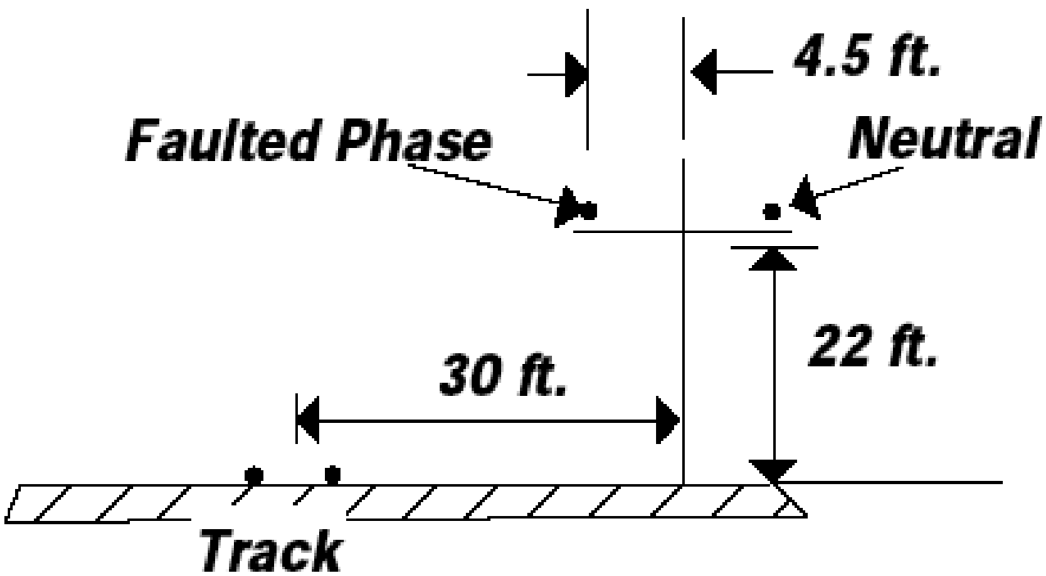


Figure F-4: Cross-Section Distribution Model Geometry

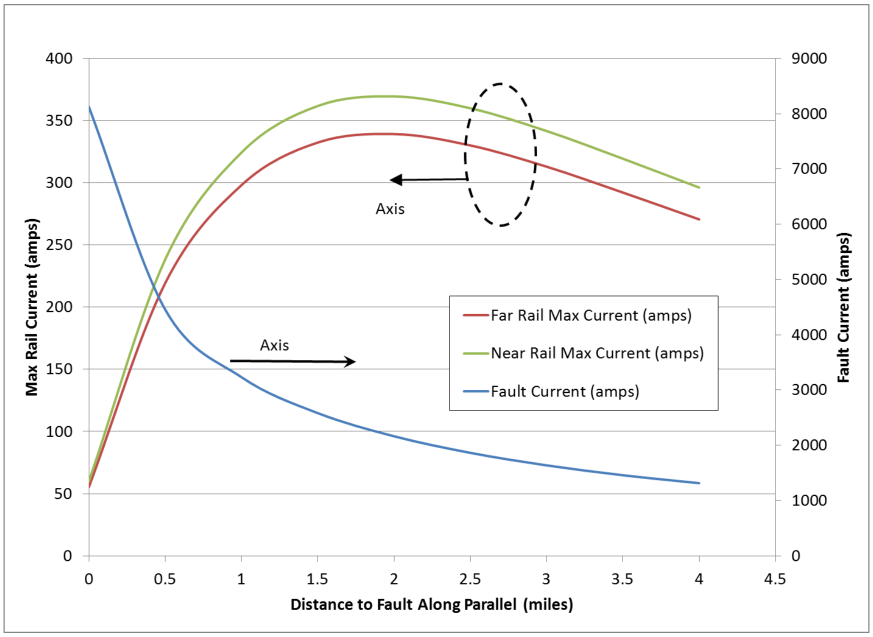


Figure F-5: Fault Current and Induced Rail Current for Various Fault Locations for a 12 kV Distribution Line <u>With a Neutral Wire</u>

c. The parameters listed and shown above for a worst-case phase-to-ground fault on a distribution line <u>equipped with a neutral</u> yielded the results shown in Figure F-5:

(Note: the lassos and arrows indicate the appropriate vertical axis for each curve)

d. The maximum induced rail current in this scenario was approximately 370 Amperes. However, it should be noted that the rail-to-ground voltage at the point of maximum rail current may still be insufficient to fire the lightning arrestors at this location. Also, it is the maximum calculated rail current *at any point along the rails* that is plotted with respect to the location of the fault. The maximum rail current typically occurs at a point that is near the mid-point of the track segment excited by the magnetic field of the faulted power line.

e. This same analysis of a distribution system fault was then repeated for a distribution line with <u>no neutral wire</u>. Although the lack of a neutral wire reduces the “shielding” effect that such wires have, it also increases the return impedance seen by the fault, and thereby reduces the fault current on the distribution line. The maximum fault-induced rail current in this case (as shown in Figure F-6, below) was approximately 312 Amperes, or roughly 80% of that seen in the distribution case with a neutral.

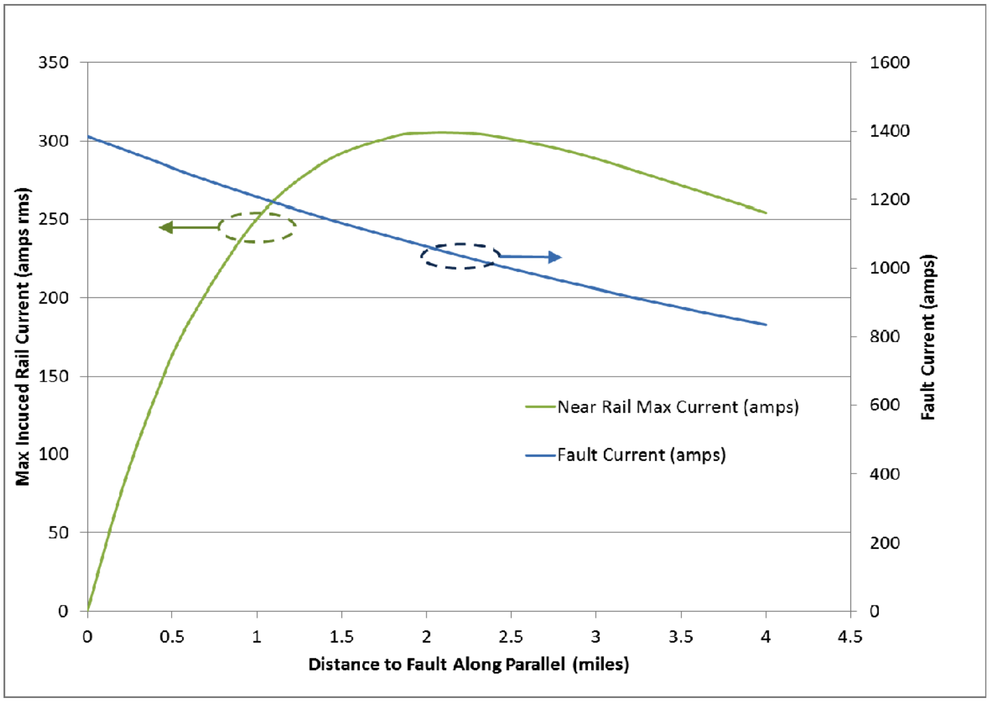


Figure F-6: Fault Current and Induced Rail Current for Various Fault Locations for a Distribution Line Without a Neutral Wire

(Note: the lasso-arrows in Figure F-6 indicate the appropriate vertical scale for each curve.)

f. Although the fault currents and rail currents in the two slightly different modeled distribution-line scenarios (i.e. with and without a neutral wire) seem to approach similar values as the distance to the fault increases, there are practical considerations that focus our attention on the shorter distances. This is because the maximum induced rail current for railroad tracks paralleling a distribution line occurs when the fault is approximately 1.5 to 2.5 miles from the substation, and a typical maximum track circuit length is normally somewhere around 2.0 miles in length. Even if the track arresters (SPDs) fire in a “cascading” fashion, the longer “track circuit” or “induction block” created by the firing arrestors will still not result in a greater maximum rail current.

g. So, for a near worst-case distribution fault location, the scenario with the lower-resistance path for the fault current on the distribution line, i.e. the distribution line equipped with a neutral wire, represents the worst case (i.e. the maximum induced rail current) for distribution. Figure F-5 shows that the maximum current expected for that scenario is approximately 370 amperes.

h. The duration of the fault is also an important factor in sizing an HEFPD for a distribution-line fault. Figure E-2 of Appendix E shows fault current and duration data obtained for one 34 kV sub-transmission system for which only a few fault events had a duration longer than 120 cycles, (2 seconds). However, a survey of power companies presented in Appendix E showed that approximately 20% of those respondents might have maximum clearing times of more than 180 cycles (3-seconds).

5. Electric Transmission Line - Modeling of the Worst-Case Scenario

a. The purpose of this section of the appendix is to identify a reasonable upper limit rating for HEFPDs that could be expected to survive the track-coupled fault environment of a representative power transmission line. The transmission line scenario modeled for this appendix was intended to represent a "reasonable" worst-case scenario, i.e. one that contained several aspects that had been specifically selected for their adverse effect on magnetic induction, but was still realistic, and could in fact already exist somewhere in the real world. Computer modeling of the induced track currents and voltages for a near "worst-case" transmission-line fault scenario was performed by a consultantr using the following parameters:

(1) 138kV power transmission line, parallel to track for approximately 10 mi. The same exposure geometry as is shown in Figure F-3.

(2) Conductor Physical Spacing: Vertical Array, with phase conductors hanging on the "track" side of the transmission line on 9-foot-long arms, at a mean phase conductor height of 50 feet. See Figure F-7.

(3) Transmission-line centerline is 30 ft. (horizontally) from track centerline.

(4) Radial distance between nearest rail and the faulted phase conductor is approximately $(18.7^2 + 50^2)^{1/2} = 53.4$ feet.

(5) Bottom phase conductor is faulted to ground (as in an insulator failure).

(6) 40 kA fault capacity at one (source) substation 138kV bus, i.e.

a radial line.

(7) The source substation was assumed to be approximately 1/10 mile (laterally) from the region of power line parallelism with the track. A more remote sourcing substation with the same fault current capacity would result in less exciting current in the parallel exposure and lower induced track voltage and current.

(8) Primary Fault Clearing Time: Up to 6 cycles (0.100 seconds). This might need to be doubled to 12 cycles (0.200 seconds) to account for backup conditions or the coordinating time interval for faults at the far end of a line.

(9) Radial transmission line from source substation: Fault current is sourced only from a single substation, and the second substation connected to the transmission line is the load.

(10) Phase conductor: 1590AAC, 9 ft. from the transmission line centerline towards the track, mean height = 50 ft. (see cross section sketch below).

(11) Overhead Shield Wire is 7/16 EHS, on-centerline, mean height = 130 ft.

(12) Distributed effective power structure ground resistance is 5 ohms per structure.

(13) Track ballast resistivity is 2 ohm·kft. (This low ballast resistance results in higher rail current.)

(14) Earth resistivity is 100 ohm·m. (Higher earth resistivity results in a higher induced rail voltage and current. Lower resistivity results in lower induced rail voltage and current.)

(15) Phase-to-Pole fault calculations were made each mile along the exposure.

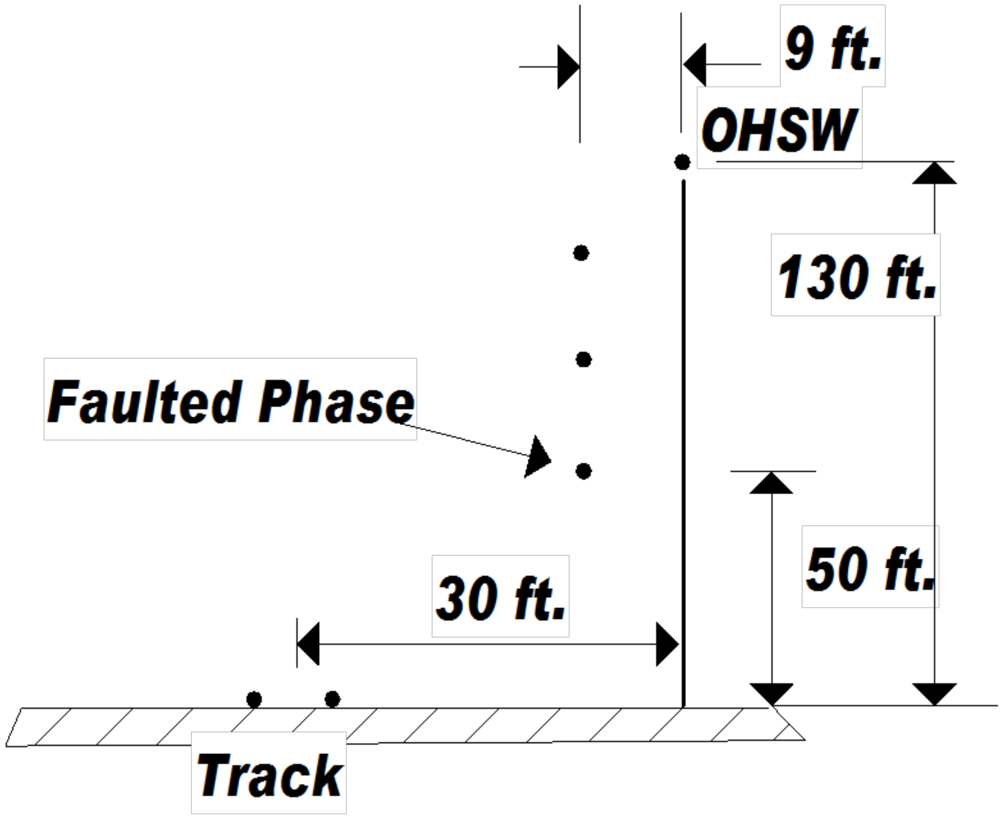


Figure F-7: Cross-Sectional Geometry of Transmission Line

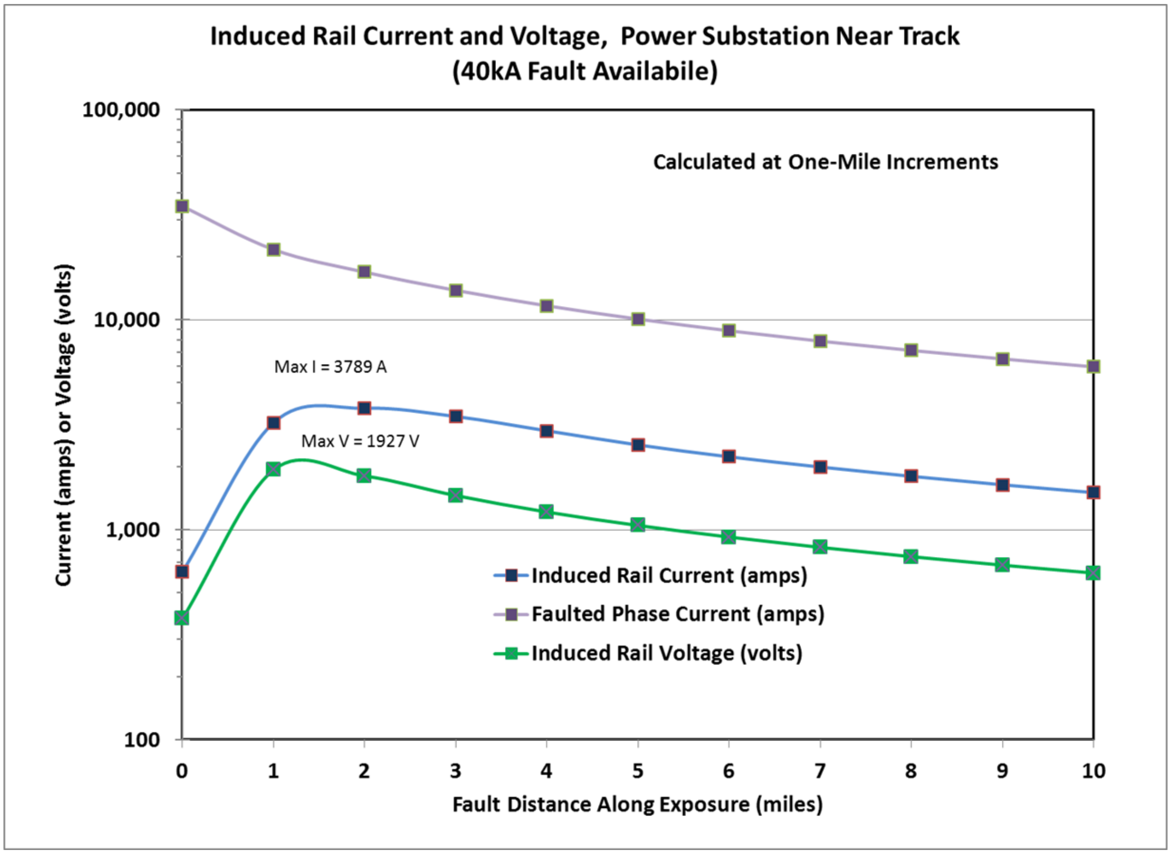


Figure F-8: Induced Rail Current and Voltage as a Function of the Transmission Line Fault Location

b. The modeling of this transmission line fault scenario yields a maximum rail current of just under 4,000 Amperes, and a maximum rail voltage of just over 1,900 Volts for the assumed separation of the fault-sourcing substation, as is shown in Figure F-8. The rail voltage and current curves in Figure F-8 do not show the locations of the maximum values, but depict the envelope of maximum values that occur somewhere for a fault at each of the locations along the parallel exposure. Lower values of rail current are predicted if the sourcing substation is farther from the region of parallel with the track. The rail voltages and currents are a function of position along the exposed track. The maximum rail current tends to occur near the midpoint of the exposed tracks, and the maximum rail voltage tends to occur near the ends of the region of the track that is exposed to the fault.

c. Assuming that the rail-to-ground voltage within the 10-mile exposure is sufficient to fire all of the arresters in a cascading fashion (which it is), then for a rail current of approximately 3,800 amperes, with a duration of 0.1 seconds, an I^2t value of below is obtained:

$$I^2t = (3{,}789 \text{ Amperes})^2 \bullet 0.1 \text{ Seconds} = 1{,}435{,}650 \ (A^2\text{-s})$$

6. Discussion

a. Our objective is to create a range of specifications of a new class of SPDs (known as HEFPDs), that are specifically designed to withstand power-line fault current energies.

b. The lowest-rated HEFPDs rated for a 0.2 second (12 cycles) duration waveform at 1000 amperes was chosen.

c. Now shifting our focus to the other end of the scale of HEFPD energy dissipation capability, how much energy (or I^2t) should the most-capable HEFPD handle?

d. It may not be necessary or even useful to define the specifications of a broad spectrum of HEFPD devices whose I^2t values extend upwards into a range of conditions that would only be experienced in situations where the compatibility of the railroad's signaling equipment and the electric power company's transmission or distribution lines has not been addressed as a combined system. The most extreme conditions conceivable for HEFPDs could only occur when other appropriate mitigative measures such as shielding, buried counterpoise wires, or fault-current-limiting inductors cannot be, or have not been, installed. In most cases these other forms of mitigation can and should be used as part of a comprehensive solution, but there will always be a few special cases in which their use is prevented by specific constraints that lie well beyond the scope of this document.

e. A summary of the worst-case distribution and transmission fault rail currents modeled is shown below:

Table F1: Distribution and Transmission Modeling

INFORMATION SOURCE	MAX. RAIL CURRENT (AMPS RMS)	TIME (SECONDS)	I^2t (A^2s)
Distribution Model (with neutral)	370	2.0	273,800
Distribution Model (no neutral)	312	2.0	194,690
Transmission Model	3,789	0.1	1,435,650

f. Notice in Table 1 above that if the scenarios are ranked by their I^2t characteristics (using their maximum induced rail currents), the double weighting (i.e. squaring) of the current makes the transmission scenario appear to be the true “worst-case” scenario.

g. The relative rankings of the energies dissipated in the three scenarios will remain true regardless of the forward voltage drop that assumed for the HEFPD, provided that the forward voltage drop of the HEFPD remains essentially constant across a wide range of currents.

h. So, which scenario (Distribution-with-Neutral or Transmission) should really define the most stringent requirements that an HEFPD must meet? The best answer is that they both should. The most capable HEFPD must be able to withstand both 3,790 amperes for 0.1 seconds, as well as 370 amperes for 2.0 seconds, because either situation could conceivably result from the worst-case fault events on transmission or distribution lines.

i. In recognition of the numerous uncertainties of the assumptions that were used in the modeling of the worst-case scenarios, we could arguably justify rounding the various values up slightly (consistent with good engineering practices), to obtain the following table of suggested HEFPD ratings below:

Table F2: Proposed Minimum and Maximum HEFPD Ratings

SPECIFICATION	DURATION	CURRENT	1^2T
Lowest HEFPD Rating - Short-Duration	0.1 Sec.	600 A	36,000 A^2s
Lowest HEFPD Rating – Long-Duration	2.0 Sec.	150 A	45,000 A^2s
Highest HEFPD Rating – Short-Duration	0.1 Sec.	4,000 A	1,600,000 A^2s
Highest HEFPD Rating – Long-Duration	2.0 Sec.	400 A	320,000 A^2s

j. In order to provide well-defined performance targets across this range, additional HEFPD models having intermediate ratings may also need to be defined.

Appendix G. HEFPD Harmonic Generation Guidelines

1. Summary

a. This appendix gives a preliminary outline of possible steps for defining HEFPD harmonic limit guidelines for compatibility with grade crossing Constant Warning Time/Motion-detection devices (CWT/MD). The concepts for developing the HEFPD harmonic guidelines that are outlined are described below. After presenting those conceptual steps, an example was given that determines candidate HEFPD harmonic test values that are expected to provide compatibility with prior-generation CWT/MD devices, such as the HXP-3 (based on test data provided by the manufacturer).

b. Harmonic values that are derived in this appendix are used in the main text, Section E.3, as guidelines for harmonic testing of HEFPDs to assure compatibility with CWT/MD systems.

c. The HEFPD 3^{rd} harmonic current output should be limited to a maximum 3.6 mA and

d. The 5^{th} harmonic current output should be limited to 16.5 mA.

2. Proposed Conceptual Steps:

a. Consider the fundamental power interfering frequency 60 Hz that may be present at a level to cause harmonic generation in a HEFPD, since that will be the typically dominant voltage driver of the HEFPD. For testing the 60 Hz voltage will likely be 25 or 50 volts across an HEFPD.

b. Since typical nonlinear devices (HEFPD's) produce dominantly odd harmonics, it is reasonable to only consider odd harmonics and concentrate on the lowest odd harmonic frequencies that are closest to CWT/MD operating frequencies, although other simultaneous harmonics might be influential but are more difficult to deal with at this time.

c. One manufacturer defines the tolerable power-system harmonic interference voltage at the input to their CWT/MD device that results in an undesirable signal to noise level. We *assume* that because the track circuits of concern are typically relatively low impedance, the harmonics generated by an induced fundamental voltage-excited HEFPDs can be considered as a nominally ideal current source at the harmonics for the purpose of developing a harmonic testing guideline. That is, if the HEFPD harmonic test applies an appropriate level of fundamental voltage to the HEFPD device under test (DUT), the measured harmonic values of interest are the nominally short-circuit harmonic currents produced by the HEFPD under test. The goal of the harmonic guidelines is to specify a tolerable short circuit current level for the harmonics of the power-line fundamental.

d. The next step is to select a limited number of (or one) likely field condition(s) that might constitute "worst-case" scenario(s) for evaluation by use of an analysis. model. The purpose of the modeling is to develop a suitable theoretical transfer function $T_I = I_I/(V_I)_{in}$ that relates the HEFPD harmonic interference current source (I_I) to the tolerable interference voltage $(V_I)_{in}$ across a CWT/MD when, for example the HEFPD is connected rail to ground at an IJ location. There are several variables that probably need to be considered, including:

(1) CWT/MD frequency.

(2) Harmonic frequency.

(3) CWT/MD approach length (long or short?).

(4) Track ballast.

e. Track imbalance which is necessary to convert the harmonic current produced by the HEFPD to a rail-to-rail voltage across the input of the CWT/MD device. A shorted insulator (IJ) may be a good 'worst-case' unbalancing condition to evaluate, since prior experience has shown that condition results in greater track unbalance than other unbalancing conditions.

f. Location of HEFPD. The HEFPD should be placed in an appropriate location for effective mitigation of power-line fault events. The location of the HEFPDs influences its excitation by the fundamental frequencies identified in Item 1 above. The HEFPD location is also the location of the harmonic current sources that are generated by the HEFPD. Connection of the HEFPD rail-to-ground at an IJ appears to be one option, which is considered in the example below. However, we may also need to evaluate an HEFPD connected at non-IJ locations or connected rail-to-rail for comparison.

g. HEFPD failure state. The failure state of the HEFPD probably does not affect the harmonic guidelines, but does affect the conditions under which the testing must be performed. That is, is the harmonic test for the normal (non-failed) condition of the HEFPD, or should some type of internal failure (difficult to describe in a guideline) be required for testing.

h. Location of CWT/MD with relative to IJ's location. A CWT/MD that is located at an IJ location may be a "worst-case" location for the CWT/MD from a HEFPD-generated harmonic compatibility standpoint and is likely the best location for a HEFPD for protection of the CWT/MD from power line fault-induced voltage standpoint.

i. Unidirectional or semi-bidirectional operation of CWT/MD. The unidirectional operation may be worst-case because it does not have the shunting effect of a dummy load and additional termination shunt which will tend to lower the induced harmonic voltage across the CWT/MD device.

j. Number and magnitude of rail-to-ground HEFPD interference current sources at a pair of IJs. Four HEFPDs is probably most likely for power fault current protection. One HEFPD connected rail to ground in each rail, on each side of an IJ, which results in a harmonic current source at each of the four HEFPDs. However, the strength and phase of the HEFPD harmonic current source is dependent on the induced power-line voltage that appears across the HEFPDs.

k. The harmonic guidelines should be independent of the CWT/MD frequency, since the HEFPD should work with all available CWT/MD frequencies. One way to achieve this independence is to calculate the harmonic voltage across a CWT/MD at all operating frequencies, for a given harmonic frequency, then use the CWT/MD frequency that has the lowest signal to noise ratio to establish the guideline for that harmonic frequency.

l. One evaluation approach is to model each different frequency CWT/MD (probably) as a high impedance at the HEFPD harmonic frequency, relative to the approach impedance, or the rail to ground impedance. Perhaps initial consideration should be for unidirectional CWT/MD operation on each side of an IJ, with approach length (short or normal) terminated in an NBS. One-to-four HEFPD harmonic current source(s) at each IJ/CWT/MD location might be considered to calculate a transfer function (a numeric value for each different condition) to relate the HEFPD harmonic interference rail-ground source current to the rail-to-rail voltage. A transfer function $T_I = I_I/(V_I)_{in}$ may need to be evaluated (calculated) at each relevant HEFPD harmonic frequency for each CWT/MD operating frequency. The minimum I_I for all CWT/MD frequencies defines the I_I for the harmonic frequency of interest.

3. Example

a. An example at a selected HEFPD harmonic and CWT/MD operating frequency will illustrate the process that is outlined above that may be used to develop a reasonable HEFPD harmonic compatibility guideline.

b. Step 4 outlined the need to determine the harmonic interference voltage at the CWT/MD for each condition of interest. The following illustrates a procedure for determining the CWT/MD voltage.

c. Table G-1 shows the manufacturer-provided interference susceptibility voltage values at selected power-frequency harmonics for one model of constant warning time signaling device at most operating frequencies below 400-Hz. The criterion used by the manufacturer to identify the threshold of interference is that the interference voltage at the input (rail-to-rail voltage) results in a 1% change in the indicated received signal plus interference voltage. That is, for any of the harmonic frequencies, compatibility is achieved when the interference signal at the detector (after filtering) is 1% (or less) of the CWT/MD operating signal.

d. The interference susceptibility data of Table G-1 does not quantitatively identify the approach lengths used for the tests, just “Normal”, “Short”, and “Very Short” approaches. The information also does not indicate the ballast values these data may represent.

Table G-1: Measured Grade-Crossing Constant Warning Time Device Interference (Volts) at CWT/MD Device Input. (Manufacturer Data)

	Normal Approach					Short Approach					Very Short Approach				
Frequency	60 Hz	120 Hz	180 Hz	240 Hz	300 Hz	60 Hz	120 Hz	180 Hz	240 Hz	300 Hz	60 Hz	120 Hz	180 Hz	240 Hz	300 Hz
86 Hz	0.5	?	2.2	4.5	8	0.2	0.1	1.1	2	4	0.1	0.032	0.4	0.9	1
114 Hz	2.2	?	0.8	3.2	5	1	0.0045	0.4	1.6	2.5	0.4	0.0014	0.16	0.56	1
135 Hz															
151 Hz	6	0.5	0.1	1	2.5	2.8	0.35	0.032	0.56	1.2	1.2	0.07	0.016	0.2	0.5
156 Hz	7	0.5	0.08	1	2.5	3.2	0.32	0.025	0.56	1.2	1.4	0.12	0.014	0.25	0.5
172 Hz	9	1	0.008	0.8	1.8	4.5	0.5	0.004	0.32	0.8	1.8	0.2	0.0018	0.14	0.32
210 Hz	12	1.8	0.2	0.1	0.5	6	1	0.1	0.056	0.32	2.5	0.4	0.04	0.022	0.1
211 Hz	12	1.8	0.2	0.1	0.5	6	1	0.1	0.056	0.32	2.5	0.4	0.04	0.022	0.1
230 Hz															
267 Hz	25	5	1.6	0.1	0.1	11	3.2	0.8	0.045	0.032	4.5	1.1	0.32	0.022	0.012
285 Hz	NA	8	2.5	0.25	0.01	22	4.5	1.2	0.12	0.0045	9	1.8	0.56	0.056	0.0018
326 Hz	NA	16	5	1	0.1	NA	7	2.5	0.56	0.056	14	3.2	1	0.22	0.025
348 Hz	NA	18	7	1.4	0.3	NA	8	3.5	0.7	0.18	18	3.2	1.4	0.32	0.07
392 Hz	NA	25	10	2.5	1	NA	11	5.6	1.2	0.45	22	5	2.2	0.45	0.18

4. For analyzing the susceptibility information of Table G-1, consideration has been restricted to the “Normal Approach” and “Very Short Approach” data. Assumptions are that the “Very Short Approach” data is relevant for the “minimum” approach length condition of the operating manual, and the “Normal Approach” data is relevant for “maximum” approach length condition. However, it is not known which ballast resistivity is relevant for the measured susceptibility data, but the result may be rather insensitive to the ballast resistance.

5. To complete the example, representative parameters need to be selected as discussed in Step 4, in order to calculate the harmonic interference source current to rail-to-rail voltage transfer function $T_I = I_I/(V_I)_{in}$ at a representative interference frequency and CWT/MD frequency. The transfer function expression can be arranged as, $I_I = T_I \bullet (V_I)_{in}$ emphasizing that I_I is the unknown of interest, which can be determined by the following sequence:

    a. T_I can be calculated by circuit analysis,

    b. Having a value of T_I permits calculation of I_I from $T_I \bullet (V_I)_{in}$, since $\bullet (V_I)_{in}$ is given in the manufacturer-provided Table G-1.

    c. The minimum value of compatible harmonic source current I_I (for each relevant operating scenario) occurs for the minimum value of T_I at each CWT/MD frequency.

6. Figure G-1 shows two arrangements of HEFPD harmonic current sources at an IJ with a unidirectional CWT/MD device on each side of the IJ’s. As a worst case,

one of the IJ's is shown as failed shorted in each case. For this example, the following are assumed:

a. A Very Short approach, which results in the lowest value of harmonic interference from Table G-1.

b. Approach length terminated in an NBS at the CWT/MD frequency.

c. Interference frequency = 180Hz (third harmonic of 60 Hz).

d. Long track circuit length tends to result in higher harmonic voltage across the CWT/MD device for a given harmonic current source value (nominally 10,000 ft. track circuits for the analysis examples have been assumed).

e. High ballast resistivity tends to result in higher harmonic voltage across the CWT/MD device for a given harmonic current source value (1000 ohm·kft ballast resistivity for the examples, which should certainly be a worst-case assumption, have been assumed).

7. The HEFPD harmonic current source is presumed to be caused by small nonlinearity in the HEFPD circuit, which is excited by rail-to-ground 60 Hz induced voltage. For simplicity, assume that an HEFPD is connected rail-to-ground for each rail on each side of an IJ pair. For simplicity, also assume that the track circuit on each side of the IJs is approximately the same length. For Figure G-1(a), both track circuits (to the right and left of the IJ) are excited by approximately the same magnitude field from a power line, which is representative of a uniform parallel exposure. For that condition, the rail to ground induced 60 Hz voltage on opposite sides of the IJ are approximately 180 degrees out of phase. Thus, for the rail with the intact IJ, the odd harmonic equivalent current source on one side of the IJ will also be nominally 180 degrees different than the equivalent current source on the other side of the IJ. This is shown in Figure G-1(a) as a current source directed in opposite directions on each side of the IJ.

8. Since the IJ in the lower rail in the Figure G-1(a) sketch is shorted, the induced voltage on each side of that IJ tends to cancel, resulting in low voltage across the HEFPDs on each side of the shorted IJ and thus low harmonic generation from those HEFPDs, thus, no harmonic current source is shown for the lower rail of Figure G-1(a).

9. The condition shown in Figure G-1(b) is for the condition where a power line excitation only exists on one side (the left in the Figure G-1(b)) of the IJ location. For that case, induced rail-to-ground 60 Hz voltage occurs on both rails, such that the HEFPDs inject harmonic current into each rail at the IJ location, which tends to result in less harmonic voltage being developed

across the CWT/MD device than for the condition of Figure G-1(a). Similarly, if one track circuit is shorter than the other at a shorted IJ location, less HEFPD-generated harmonic voltage will be developed across a CWT/MD device than for the equal-length track-circuit condition of Figure G-1(a). Thus, the uniform field excitation, with similar length track circuits as for Figure G-1(a) appears to be the worst case for HEFPD-generated harmonic current excitation of a CWT/MD device.

10. The case of Figure G-1(a) has been modeled to calculate the harmonic interference source current to rail-to-rail voltage transfer function $T_I = I_I/(V_I)_{in}$ for the CWT/MD frequencies of Table G-1. Table G-2 summarizes the calculated value of T_I and the allowable third and fifth harmonic HEFPD current to produce the interference voltage at each CWT/MD frequency, based on Table G-1.

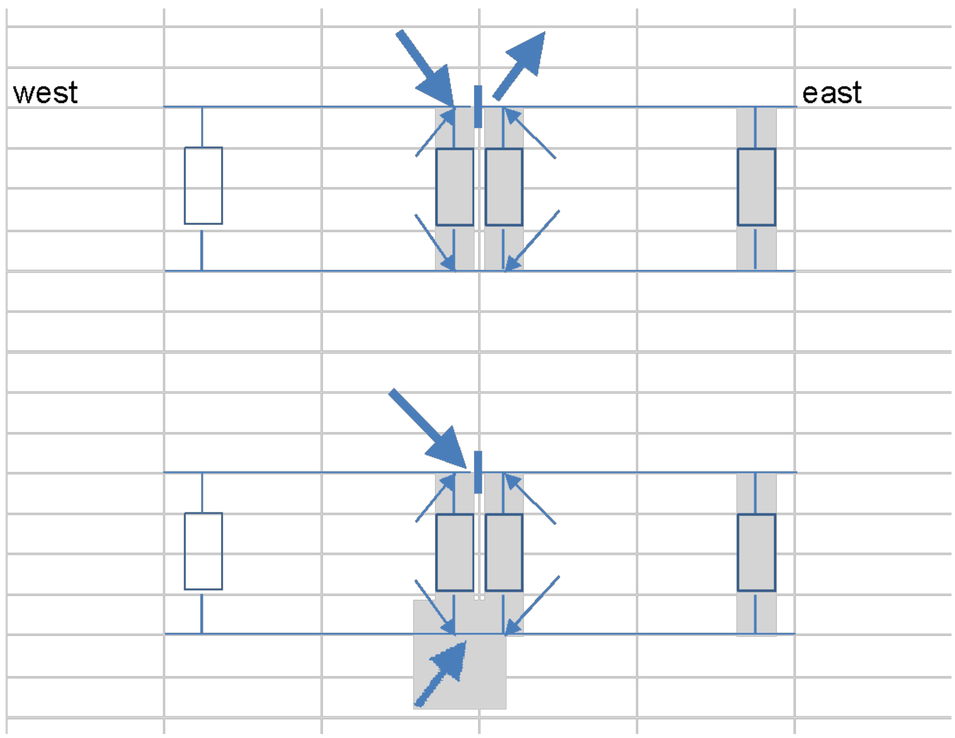


Figure G-1: Two Arrangements of Interference Harmonic Current Sources at CWT/MD Devices.

Table G-2 Calculated Current-Source to Voltage Transfer Function

f-CWT Hz	180Hz (3rd Harmonic of 60Hz)			300Hz (5th Harmonic of 60Hz)		
	CWT Susceptible V from Harmon	Calculated T	Max allowable HESPD Harmonic (milli-amps)	CWT Susceptible V from Harmon	Calculated T	Max allowable HESPD Harmonic (milli-amps)
86	0.4	1.59	635.9	1.000	1.26	1261.8
114	0.16	1.61	257.2	1.000	1.27	1266.6
151	0.016	1.67	26.8	0.500	1.27	636.2
156	0.014	1.70	23.8	0.500	1.27	636.7
172	0.0018	1.99	**3.6**	0.320	1.28	408.2
210	0.04	1.52	60.7	0.100	1.30	129.7
267	0.32	1.54	493.1	0.012	1.38	**16.5**
285	0.56	1.55	866.9	0.012	1.55	18.2
326	1	1.55	1550.4	0.025	1.24	30.9
348	1.4	1.56	2177.3	0.070	1.21	84.5
392	2.2	1.56	3426.8	0.180	1.22	220.3

11. Since it is desirable for the HEFPD to be compatible with all CWT/MD frequencies, the minimum 3rd harmonic and 5th harmonic currents shown in Table G-2 (shown in highlighted cells) should set the limit for the maximum measured HEFPD 3rd and 5th harmonic currents. That is, the HEFPD 3rd harmonic current should be limited to a maximum 3.6 mA and the 5th harmonic current should be limited to 16.5 mA to assure compatibility with CWT/MD systems. Since higher odd harmonics are higher in frequency than the CWT/MD frequencies of Table G-1, quantitative values for compatible higher harmonics and higher CWT/MD frequencies cannot be determined without additional susceptibility information.

12. The foregoing has presented suggested concepts for developing the HEFPD harmonic guidelines. An example has been given to illustrate the application of the suggested concepts and procedures for quantifying the tolerable HEFPD harmonic current-source value for CWT/MD operating frequencies based on susceptibility information provided for the HXP 3, based on information provided by one manufacturer's data. Susceptibility information for newer-model CWT/MDs indicate lower susceptibility than the older models, so HEFPDs that meet these suggested guidelines will also be compatible with the newer models from that manufacturer.

Appendix H. HEFPD Impedance and Harmonic Testing

1. The following describes impedance and harmonic-generation tests that were performed by a consultant on a candidate HEFPD to assess possible test methods. For these tests, the HEFPD is the Device Under Test (DUT). Preliminary planning for these tests included using simple series and parallel tuned circuits as a part of the test circuit. However, initial testing suggested that the filters may not be needed. The tests described below did not incorporate any added filtering.

2. The following provides information and results for these HEFPD tests.

    a. DUT impedance and harmonic generation – Test Setup**.**

    b. The sketch below shows the basic circuit arrangement used to obtain DUT impedance and harmonic sourcing information.

    c. The Crown amplifier is a high-quality adjustable gain 1000 watt power amplifier with output impedance of a few milliohms; with nominally flat frequency response up to 100kHz. The Rion Analyzer is a high dynamic range digital spectrum analyzer. Preliminary tests showed that:

    d. The harmonics of the amplifier and signal source were very small compared to the fundamental component output of the amplifier. Therefore, the fundamental voltage developed across the DUT was measured by a Fluke Model 81 True RMS Voltmeter.

    e. The impedance of the non-activated DUT is high relative to the 50 watt 10-ohm non-inductive resistor that was connected across the output of the amplifier.

    f. The relative high impedance of the DUT permitted the current into/out of the DUT to be measured by a resistor in series with the input lead, rather than with a current probe, as originally planned. The accuracy of high quality current probes is only specified down to about 10mA. The use of a series resistor (R_s) shown in the diagram below permitted more accuracy than can be obtained by using a current probe.

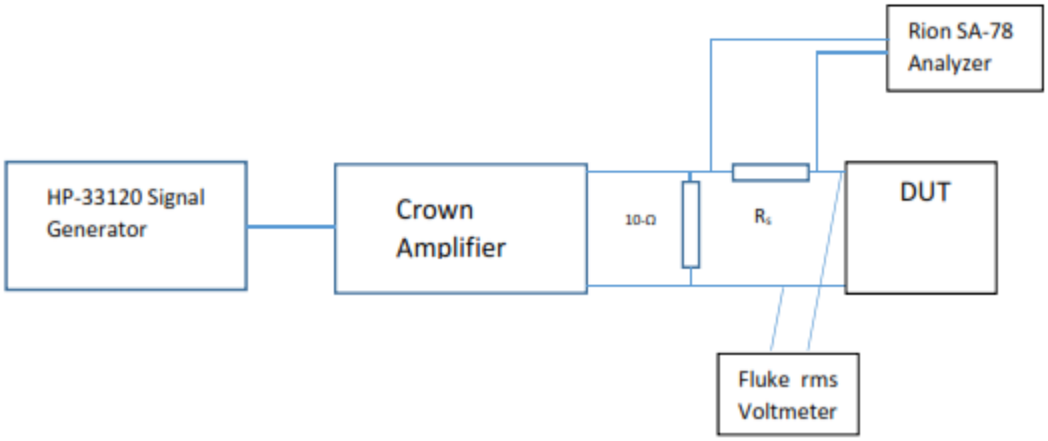


Figure H-1: Harmonic Test Arrangement for Lab Test

3. DUT Impedance

a. The impedance of the DUT was measured at several frequencies using the test arrangement of Figure H-1. Selected frequencies from 60 to 1000Hz were used for the test. At each test frequency, the voltage across the DUT was adjusted, as measured by the Fluke 87 rms voltmeter. The voltage at all test frequencies was 20 volts, except at 1000Hz, for which the voltage was 10 volts. The voltage was reduced to prevent overloading the Rion Analyzer at the sensitivity setting being used. The Rion sensitivity could have been changed to permit using 20 volts across the DUT, but changed the voltage instead, since the voltage level for the test was probably higher than is of interest for the impedance test.

b. The current through the DUT was determined by measuring the voltage V. across R_s with the Rion analyzer to obtain good sensitivity. For this test, the resistance R_s= 10.2 ohm. At each test frequency, the current was calculated as I_{Rs}=V./10.2. The DUT impedance magnitude was then calculated by $Z_{DUT} = V_{DUT}/ I_{Rs}$. The graph below shows the results of the test.

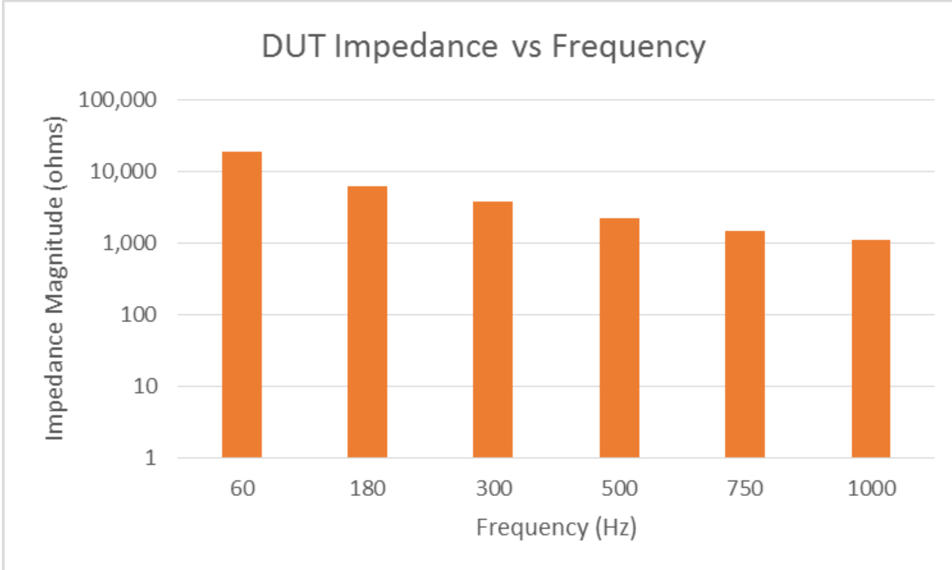


Figure H-2: Measured Impedance of Tested HEFPD.

4. HEFPD DUT Harmonic Generation

a. Testing of the harmonic generation by the DUT used the same circuit shown in Figure H-1. The DUT was excited by a 60 Hz, 20 volt rms sine wave, as measured by the Fluke voltmeter at the input terminals of the DUT. The harmonic current was sensed as a voltage across R_S. Two different values of R_s were used, namely 10.2 ohms and 97.7 ohms. The results of the test are summarized in the figure below. The only harmonics that could be observed were 180Hz and 300Hz, the 3rd and 5th harmonics of the 60 Hz fundamental frequency.

b. The currents that were sensed are well below the value calculated in the Example in the Harmonic Guideline of Appendix G, which are: 3rd harmonic current should be limited to a maximum 3.6 mA and the 5th harmonic current should be limited to 16.5 mA.

c. The measured harmonic current values for the two values of R_s are approximately the same, as they should be because of the high impedance of the DUT and the low impedance of the amplifier and 10-ohm load.

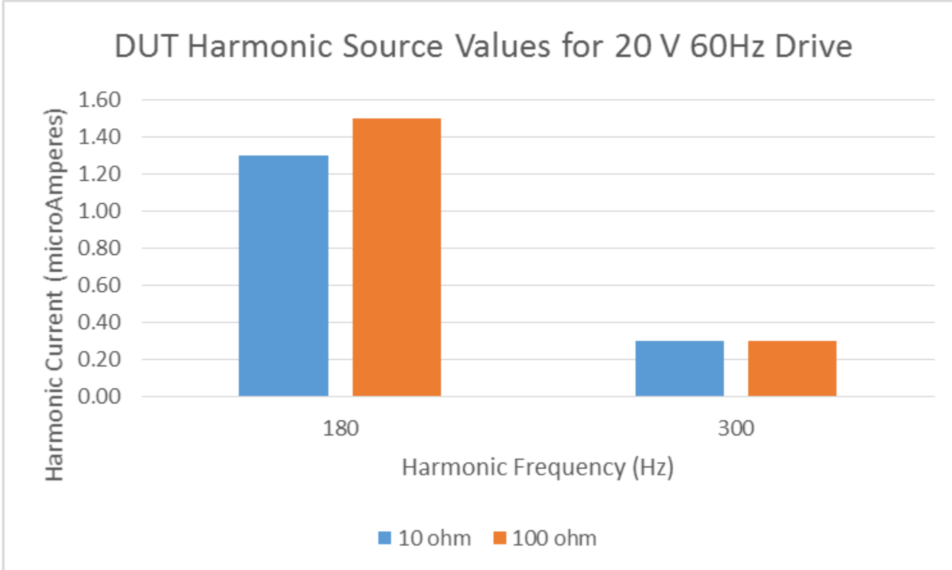


Figure H-3. Measured Harmonics of Tested HEFPD

5. Baseline Test-Setup Harmonics

   a. Measurement of the harmonics without the DUT in the circuit were also obtained using the test arrangement shown below. A 10 times attenuator was used before the Rion analyzer, to not overload the unit.

   b. The table below shows values of fundamental and harmonic voltage measured across the 10-ohm load at the amplifier output. The fundamental voltage across the amplifier load resistance was 20V, the same as for the harmonic testing described for Figure H-1.

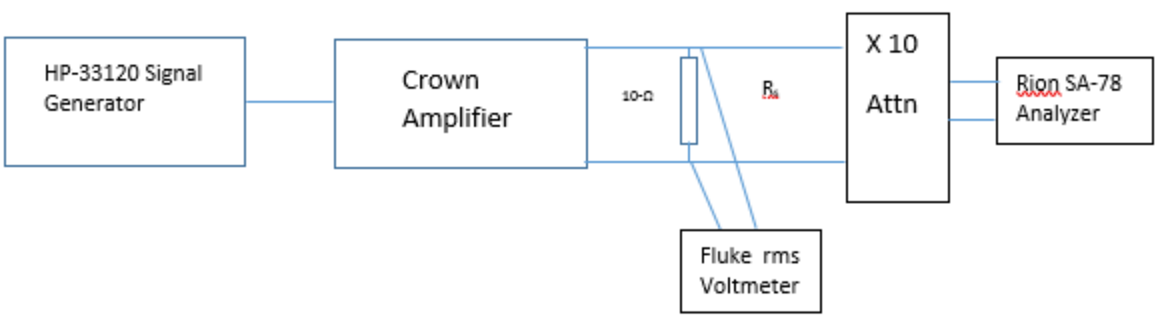


Figure H-4: Baseline Measurement Circuit Harmonic Measurement Arrangement

Table H-1: Voltage Measured Across 10 ohm Resistor in Figure H-4

Measured Frequency	Voltage across load R	Instrument
60 Hz	20V	Fluke 87
180 Hz	7.4mV	Rion SA-78
300Hz	0.95mV	Rion SA-78

6. If the harmonic tests are to be made at a higher voltage than 20 volts across the DUT, a higher wattage 10-ohm resistor will be needed, or the test setup will need to be modified. It is possible that the 10 ohm resistor at the amplifier output might be removed, so that the amplifier looks into the high-impedance of the DUT, which may permit testing at a higher voltage. However, that change in the test circuit has not been evaluated.

7. How are these voltage values interpreted relative to the DUT harmonic test results presented in Appendix G? One approach might be to consider that all the voltages in the above table are applied across the load resistor from the low-impedance amplifier, as is illustrated below.

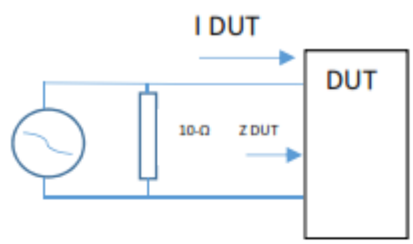


Figure H-5: Equivalent Circuit – Source Currents to DUT.

8. The source (harmonic) voltage is applied across the 10 Ω load resistor in parallel with the DUT.

9. The current through the DUT that is caused by that source voltage is just the voltage divided by the impedance of the DUT at the fundamental or harmonic frequency.

Table H2: Calculated Harmonic Current through DUT from Source

Measured Frequency	Voltage across load R	DUT Impedance	Calculated DUT Current
60 Hz	20V	1.85E+04	1.08mA
180Hz	7.4mV	6.18E+03	1.2μA
300Hz	0.95mV	3.71E+03	0.26μA

10. The table shows:

    a. The measured voltage across the amplifier load resistance, without the DUT.

    b. The measured DUT impedance at the frequencies.

    c. The calculated current that would flow through the DUT impedance by the equivalent harmonic source voltage.

11. Comparison of the calculated harmonic current through the DUT (Table H-2), which would flow as a result of the source voltage, with the measured harmonic currents in the graph of Figure H-3 shows that the calculated harmonic currents in Table 2 are approximately the same as the measured harmonic currents in the DUT lead as shown in Figure H-3, for the test arrangement of Figure H-1. The above suggests that the harmonic currents that are shown in Figure H-3 might be dominated by nonlinearities in the basic test setup.

12. It's unsure that the basic test circuit harmonics (Table H-1) are coming out of the amplifier; they could be generated in the 10-ohm load resistor. At this point, the harmonic source cannot be assured. Regardless, the harmonic current that is measured in the DUT lead, by the arrangement of Figure H-1, is likely to be well below the level of current that could be problematic for a crossing predictor. Thus, the baseline test circuit harmonics that are shown in Table H-1 also appear to be low enough to not contaminate the DUT current measurement, at least for a DUT with as high impedance as this DUT. If the DUT input impedance were to be significantly less, the current that could be supplied to the DUT by the basic test circuit might be misinterpreted as higher harmonic current from the DUT.

Appendix I. Testing to Failure Comments

1. This appendix captures reasons as to why device testing to failure of the HEFPD should not be a requirement of the recommended practice. Certainly, this would not preclude any railroad from specifying such a test if they deem it necessary.

   a. Testing to failure may provide a failure mode but a sufficiently large sample size would have to be tested to statistically verify the failure mode is consistent, which could be quite expensive. A potentially limited market may not justify a manufacturer performing this additional level of testing.

   b. Semiconductor devices are designed and rated to handle a certain amount of energy. Exceeding the limits of a device can cause deterioration at the junctions and eventually cause changes in performance or the resistance of the device. If a device's ratings are not exceeded the unit should continue to perform as expected.

   c. Sizing a device based on available fault current should help to reduce the risk of a failure of a HEFPD. This information can be calculated or obtained from the power utility. A properly rated or an overrated device applied to the track should not experience failures since the energy it experiences should not exceed the design limits of the device. The recommended practices will specify the device be able to withstand multiple surges and still meet the specifications of the device, as discussed in Section E.

   d. Testing to Failure is generally performed to establish the withstand ability of a device and to know when it no longer performs its function as designed. This can occur if the device shorts, opens or changes its operating characteristics. The railroad appears to be concerned about the failure of a device in a low impedance state that could theoretically shorten a highway grade crossing approach with grade crossing predictors and motion sensors. If applied rail to ground it would require the failure of two of these devices to potentially cause such a problem. Current practice on many railroads puts an equalizer between the rail connections as well as a rail to ground arrester on each rail. The single point of failure could be an equalizer (not rated for power fault energy) as sometimes applied today. It is rare under lightning conditions that it would fail in this mode; however, under power fault conditions these lightning arrester devices and equalizers could fail in an unpredictable mode.

   e. An alternative to this testing would be to monitor the HEFPD (with a vital device that monitors the parameters critical to the user's application) to ascertain its health. This monitoring function is not a requirement of the HEFPD. A railroad could monitor the device if it believed it to be necessary based on its application in safety critical areas such as certain grade crossing warning systems.

f. Application of a HEFPD to standard signal track circuits rather than grade crossing warning equipment track circuits should not require the additional testing to failure.

g. The currently used technology for track circuit protection consists of lightning protection devices. Generally, these devices are tested to recommended lightning levels as specified by AREMA. Under these lightning test levels with their associated short time durations the industry standard lightning arresters perform acceptably. Under power fault levels however these devices do not always survive based on the fault current levels and the time they are exposed to these levels. Often a traditional air gap arrester will be damaged severely. The plastic covering is often melted and the device can be shorted or present low resistance. These devices were not designed to handle high levels of fault current, as can be available where power lines are adjacent to the railroad. This existing situation is what raises concern and why the committee feels an HEFPD is required. If a HEFPD is applied to handle the potential fault current, the safety performance of the railroad signal and crossing equipment should be enhanced over today's use of lightning arresters alone.

Appendix J. DC Voltage and Current Requirements for HEFPD Release Test

1. Summary

a. An HEFPD device that will turn off after firing with less than 4 volts dc rail to rail should be useable in all areas that might have naturally occurring battery effects or dc track circuits. If the rail to ground voltage is most important for HEFPD operation, a 3-volt dc voltage for release considerations should be adequate to accommodate dc signaling, track unbalance and naturally occurring galvanic battery effects. The current flowing in the circuit will rarely exceed 1 ampere unless ballast conditions are very poor or the track circuit is very long. Current during shunting by trains or fired surge protectors should never exceed 15 amperes. Thus, for "release" testing of HEFPDs, a dc test circuit with 3 volts open circuit and 15 amperes short circuit is recommended.

b. In poor shunting areas where "Wetting circuits" might be used, it is possible that as much as 10 volts rail to rail could be used to help the track circuit "arc over" the rail and wheel contamination. The normal current in wetting circuits with no trains present could exceed 5 amperes and shunting current exceed 10 amperes. Such circuits are rare enough that they can be covered by a warning note in the HEFPD specifications if they might cause a problem. HEFPDs that cannot meet the higher voltage turn off criteria would still be useful in the great majority of areas.

c. Any device designed to be used in Wetting circuit areas should be able to turn off when rail to rail voltage is less than 15 volts DC, or 8-volts rail-to-ground.

2. More Detailed Information

a. DC Track Circuits

(1) The most vital limiting factor for any track circuit is that the system must detect a shunt of less than 0.06 ohms. Therefore, even though track circuit currents might be set high in poor ballast and problem areas, there is always a limit on how sensitive to shunting the circuit must be.

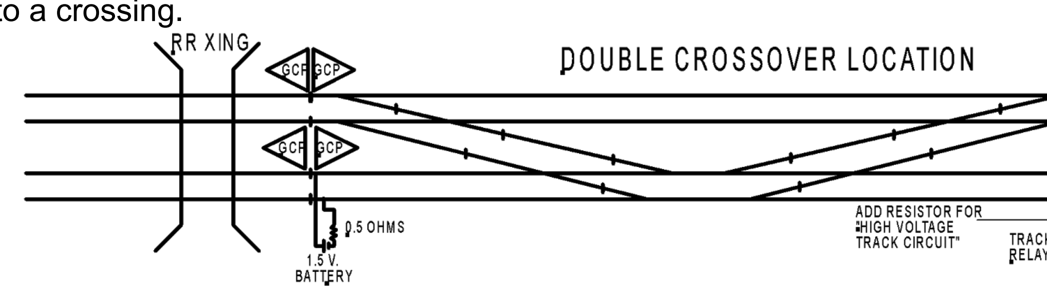
(2) Vital track relays are extremely efficient. The wattage to pick up a relay is only about 25 milliwatts. The working energy for a relay is about twice that, or 50 to 70 mW. The most common track relays have 1, 2, and 4 ohm coils. The following chart is approximate operating values since relays can vary depending on brand or whether it is a shelf mount or plug-in style.

TRACK RELAY OPERATING VOLTAGE AND CURRENT		
1 OHM COIL	0.224 VOLT	0.224 AMP
2 OHM COIL	0.316 VOLT	0.158 AMP
4 OHM COIL	0.447 VOLT	0.112 AMP

(3) The worst case from track circuit voltage would be a maximum of 4 volts, which is two cells of track battery in series. This

case is rare on main lines since DC circuits are mostly used to protect switches. The longer circuits would be 1000’ or so in double crossovers. In high speed crossovers where #30 switches are used, the circuits could reach up to 2000’. Relative to normal track circuits that can be over 7000’, these circuits are short and don’t suffer much current drain due to ballast.

(4) Below is shown a simplified double crossover location next to a crossing.



(5) The worst case for shunt current could exceed 10 amperes if a train is shunting the rails or if surge protectors are fired. Normally, without a shunt, the current will not exceed 1 amp. Of course, if the track is shunted, the current will be maximum, but the rail to rail voltage will be zero. DC resistance of rail is very low, so even if the train is entering the relay end of the track circuit so the rail resistance is in series with the shunt, the voltage will still drop to near 0 the moment the train enters the track circuit.

(6) In areas where shunting might be a problem, a “high voltage” track circuit might be used. A relay with a higher coil resistance and thus, higher operating voltage is usually installed. Then a resistor is added at the relay end to limit the current to the relay and increase its operating voltage. To set up the circuit, the battery series resistance is set as low as possible (0.1 ohm) to get the greatest rail to rail voltage, and the relay series resistance is set as high as possible while still obtaining enough relay voltage for reliable operation. Usually the relay series resistor is adjusted to provide double the relay pickup voltage when the ballast is wet.

(7) Except for areas where there are switches, few DC track circuits are used on main lines. Most of them will be found on spurs, sidings, short lines, and branch lines.

(8) In areas with DC coded track circuits such as Electro Code or DC rate code, it should not be assumed that the track voltage will go to zero during off cycles. The pulses on the rail are

always in the same polarity so ballast battery effect (or capacitance effect) will fill in between the pulses and cause the voltage minimum to “float” above 0. This battery effect can cause DC current to flow through a shunt even during the off time of code pulses, but currents exceeding 1 ampere are rare.

d. “Wetting Circuit”

(1) Normally, it takes over 0.25 volts to “punch through” contaminates on the rail. This is why the battery track current should be set high enough on DC track circuits to assure sufficient rail-to-rail voltage even during wet ballast conditions.

(2) A Wetting circuit may be used on problematic crossings where rust or contaminates cause poor shunting.

(3) Wetting circuits can provide up to 10 volts at 10 amperes to a crossing track circuit.

(4) Wetting circuits can only be used in “dark territory” where AFO circuits are being used to detect trains.

(5) Insulated joints must be installed in at least one rail at the end of the crossing approach in each direction to limit the length of ballast that will drain the voltage.

(6) The high DC rail to rail voltage must be considered if a HEFPD is used where wetting circuits are installed. The HEFPD must be able to extinguish after firing with the higher wetting circuit voltage present.

3. Rail To Rail “Battery Effect”

a. Contaminants in the ballast combined with rust on the rails can turn some track circuits into a battery. Basically, the rust on the rails can become polarized due to DC or pulsed DC signal voltages and become similar to the positive and negative plates in a primary battery. There might be ionized salts or acids from the earth that percolate through the ballast or, more commonly, from chemicals spilled from freight cars which will act as an electrolyte.

b. Normally, the voltage effects are very low, but they can reach high enough values to “swamp out” DC coded circuits. This would require about one-volt at 500 mA.

Appendix K. HEFPD Release Test Criteria for 60 Hz Power Line Inductive Effects

1. Summary

   a. A release test requirement for HEFPDs is predicated on the likelihood that some normal steady-state dc and induced ac voltage may be present rail-to-ground at candidate HEFPD locations. Likely locations for HEFPDs are at signal IJs, since those locations require track arresters to protect the signal equipment, and those locations typically result in the greatest stress on the arresters due to a fault on a nearby power line exposure. Thus, consideration of the steady-state dc and induced ac voltage at signal-system IJ locations and the resultant steady-state dc and induced ac current that might flow through fired HEFPDs at those locations should be considered to ensure that the HEFPDs will release, or return to the normal high-impedance state after an event that results in HEFPD activation.

   b. The dc voltage and current considerations are addressed in Appendix J. This appendix reviews steady-state induced ac conditions that might occur at a representative IJ location that have HEFPDs connected rail-to-ground, to assess representative maximum values of current through fired HEFPDs during a period when the HEFPDs must revert to a de-activated condition. Using considered “worst-case” conditions of induced voltage and track-circuit conditions the analysis described below results in a maximum steady-state induced current through fired HEFPDs of approximately 43 amperes (it is recommended rounding up to 45 amperes) for a maximum personnel safety induced rail-to-ground voltage of 25 volts on each side of the IJs. Alternatively, higher steady-state induced voltage, up to 50 volts, may be experienced by an HEFPD in regions of non-uniform exposure to power-line excitation, but the current steady-state current through an activated HEFPD is expected to be less than 43 amperes.

   c. Therefore, combining these “worst-case” conditions it is recommended that the ac induced steady state voltage for the HEFPD release test use an open circuit voltage source of 50 volts with a short-circuit current capability of 45 amperes rms.

2. Discussion of ac Release Criteria

   a. As a worst case, a long, uniform parallel of signaled track and a power transmission line is assumed. A steady state induced 60 Hz rail-to-ground voltage of 25-volts is hypothesized on each side of an IJ location with HEFPDs connected rail-to-ground on each side of the IJs. The HEFPDs, and possibly other SPDs at IJ locations, are assumed to fire (activate) in response to a high-voltage event. The HEFPDs must release (revert to the de-activated condition) after the high-voltage event has passed.

b. The steady-state magnetic field from the power line needed to induce the 25 volts at the IJs of interest depends on the track-circuit length on each side of those IJs. This scenario was modeled using a consultant's computer program to evaluate the current that would flow through the fired HEFPDs as a function of the track circuit length, and other relevant parameters, such as the soil and ballast resistivity.

c. The figure below shows the calculated current through activated HEFPDs (low Z) on each side of the IJs of interest to a common bungalow ground bus that is connected to a 25 ohm ground, for:

(1) Low (4 ohm·kft) and high (100 ohm·kft) ballast resistivity, and

(2) Low (20 ohm·m) and high (500 ohm·m) soil resistivity.

(3) The figure below shows the calculated current through fired (activated, low-impedance) HEFPDs at a "protected" IJ location versus the track-circuit length. A constant 25 ac volts rms rail-to-ground on each side of the IJs prior to the overvoltage event that causes the HEFPDs to activate is assumed.

(4) The figure below illustrates that the worst-case is for short track circuits with low ballast and low soil resistivity. This result is forced by the assumption of 25-volts rail-to-ground at the IJs of interest. That assumption results in higher field at the track, needed to produce 25 volts for short track circuits, which causes higher rail current when all the IJs are "bypassed" by "activated" HEFPDs or track arresters. From the figure, if a 'short' track circuit is assumed to be ½ mile, with 25 volts steady-state induced rail-to-ground voltage, the limiting steady-state fired HEFPD (arrester) current for low ballast and low soil resistivity (the grey curve) is approximately 43 amperes. Thus, for these conditions, the HEFPD must be capable of releasing with 43 amperes steady-state ac current when a fault event terminates. These curves can be used to estimate the induced ac 'release current' for other track-circuit lengths, with maximum personnel safety induced rail-to-

ground voltage of 25 volts, or 50 volts across each IJ for nominally equal or long track-circuit length.

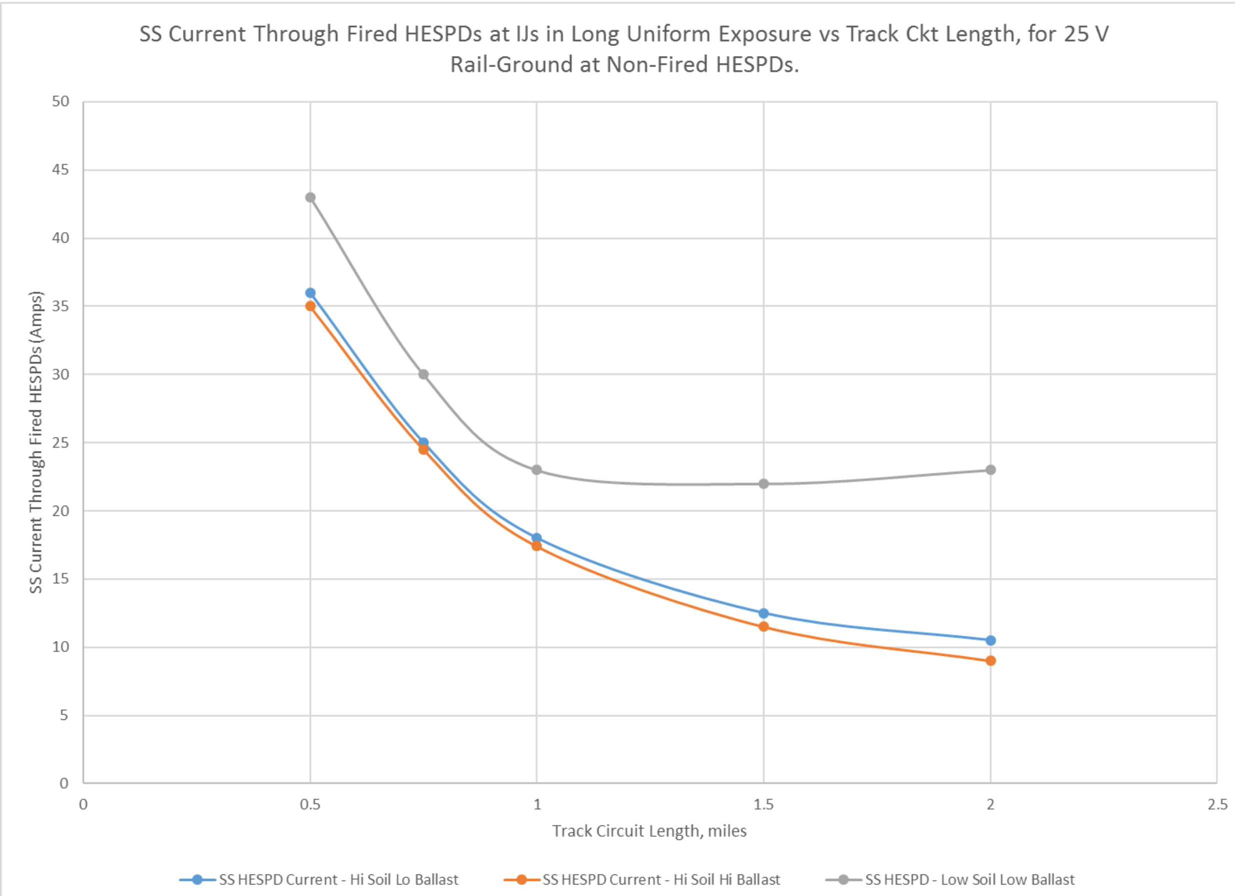


Figure K-1: Calculated Steady-State Current Through Fired HEFPD at IJs.

(5) The above example considers 25 V induced rail to ground on each side of the IJs of interest in the steady-state (before and after an overvoltage event that activates the HEFPDs), which results in 50 V across each IJ.

(6) A limiting case of 50 V rail-ground might also be considered, with 50 v across the IJ, (i.e. 0 V on the other side of the IJ), which suggests no excitation on one side of the IJ. This condition can occur, for example, if the power line sharply departs the exposure near the IJ of interest. One way to hypothesize the exposure, to prevent having more than 50 volts across other IJs in the region, is to assume no other IJs and a long-uniform exposure field on the side of the IJ with 50 volts rail-ground. That case was analyzed to determine the steady-state current that would flow through fired HEFPDs at

the IJs of interest, with low soil and ballast resistivity. The resulting current through the fired HEFPDs was approximately 22 amperes, which is similar to the current with long track circuits, uniform exposure and 25V rail-ground each side of the IJs in Figure K-1. That result makes sense considering the Thevenin equivalent circuit for those limiting-form configurations.

(7) In summary, the above curves indicate that the maximum current through fired HEFPDs is approximately 43 amperes for:

(8) The short track- circuit condition (assumed to be ½ mile) for this analysis,

(9) Low soil and ballast resistivity,

(10) Long uniform power-line exposure on each side of the IJs of interest

(11) Maximum personnel safety induced rail-to-ground voltage of 25 volts on each side of the IJs

(12) Alternatively, higher steady-state induced voltage, up to 50 volts, may be experienced by an HEFPD in regions of non-uniform exposure to power-line excitation, but the current steady-state current through an activated HEFPD will be less than is shown in the above curves.

Appendix L. Application Guidelines for HEFPDs

1. Overview

a. This appendix describes a generic analysis of a hypothetical track/power exposure to illustrate an approach to evaluating important considerations that can be applied to specific exposures. The analysis calculates the induced rail voltage and current over the length of the hypothesized exposure as a function of the location of a fault on a closely parallel power transmission line. Specific signal systems or location of the signals along the track are not identified for the analysis. A goal is to evaluate the worst-case current stress that signal-system protective HEFPDs may be exposed to by magnetic-field coupling from a fault on the hypothesized power-system. An HEFPD must be chosen that is rated to accommodate the predicted current/duration for the exposure conditions.

b. The results of this appendix also suggest that for the geometry and fault current values that are assumed for the analysis, HEFPDs may not be needed at signal locations that are not at IJs, if properly-sized HEFPDs are used for power fault protection at all IJ locations.

2. Parameters of Hypothesized Exposure

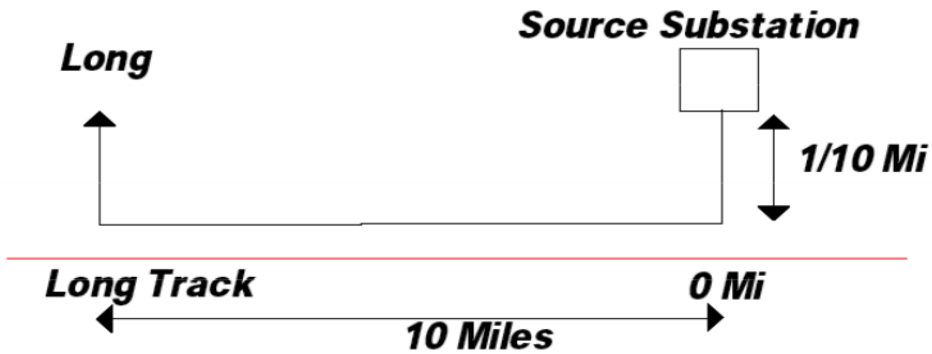


Figure L-1: Geometry of Example Exposure.

a. Figure L-1 shows a sketch of the longitudinal plan view of the exposure geometry. A long segment of track is paralleled for a 10-mile distance by a transmission line that connects between two nearby substations. One substation is assumed to be at one-mile from the exposure, while another is approximately 1/10 mile from the parallel exposure.

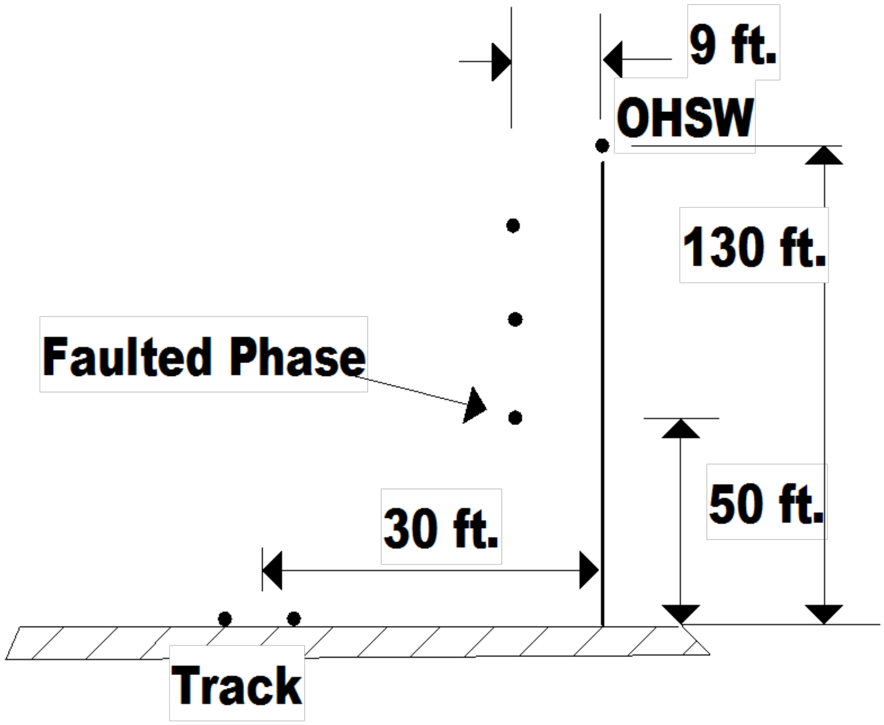


Figure L-2. Cross-Section Geometry in Exposure

b. Figure L-2 is a typical cross-section sketch in the exposure. The power line geometry is representative of a 138-kV transmission line. For this investigation, it has been assumed that both substations have significant fault-sourcing capability of 40 kA short-circuit current. That level of substation short circuit current is rather high and is not likely to be often encountered. The fault-current sourcing from both substations to a fault on the transmission line is common and often results in higher induced rail voltage for a fault that is located midway along the exposure.

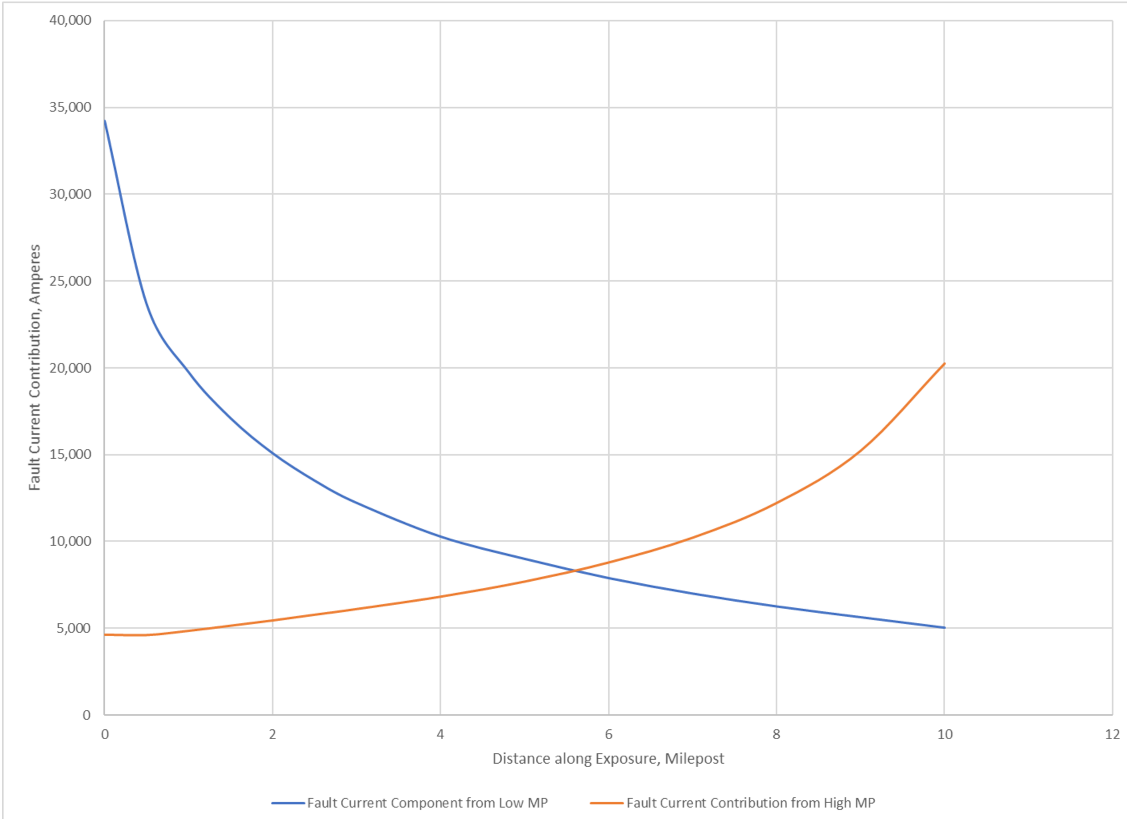


Figure L-3. Assumed Current Supply from Each Substation to a Fault Along the Parallel Exposure.

c. Figure L-3 shows the calculated current that is expected to flow from each substation to any faulted location along the exposure. For example, for a fault at MP2 along the parallel exposure, approximately 15,000 amperes will flow to the fault from the substation on the low MP end of the exposure, while approximately 5,500 amperes flows to the fault from the other substation.

3. Track Circuit Considerations

a. As noted above, no specific types of track signal systems or their locations are assumed for this example. However, track signal circuits that have insulated joints (IJ) and signal equipment connected rail-to-rail at some locations within the exposure are assumed. At those IJ locations, rail-to-ground and rail-to-rail connected HEFPDs are assumed for overvoltage protection of the equipment. Figure L-4 is a sketch that shows HEFPDs connected to a ground on each side of a rail insulated joint. Magnetic-field coupling from the fault current in the transmission line will induce rail-to-ground voltage on each side of the rail IJ.

b. For this example, assume that relevant overvoltages that are coupled into the rails by a fault on the adjacent power transmission line will be of sufficiently high voltage to activate (fire) the rail-to-ground HEFPDs. Activation of these HEFPDs will result in a low impedance connection between the rail and the ground (typically the grounding system of the signal-equipment bungalow) on each side of the IJ for the duration of the power line fault event.

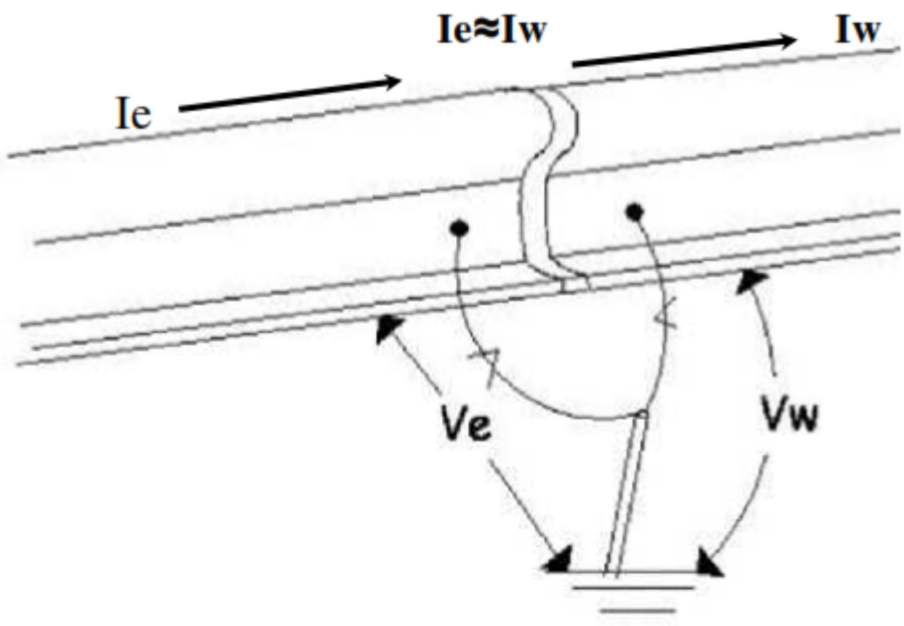


Figure L-4: Sketch of Rail Insulated Joint with HEFPD Electrically Connected from Rail-to-Ground on Each Side of the IJ.

c. Once the HEFPDs activate, the equivalent voltage sources in the rail will force current to flow through the activated HEFPDs. While the HEFPDs are activated, most of the current in the rail will flow around the IJ through the HEFPDs, with typically only a small percentage flowing to ground at the grounding connection, as is illustrated in Figure L-4.

d. For these analyses, the location of the signal system IJs, which may be located at any location along the exposure, are treated as unknown variables.

e. Of specific interest is worst-case location for the IJs, where the fault induced rail current tends to be the highest when all the track

HEFPDs are activated.

f. Signal equipment, connected rail-to-rail, may also be at non-IJ locations along the track. For example, at grade-level signaled road crossings, or audio overlay locations. These other signal locations are also protected by rail-to-ground and rail-to-rail connected HEFPDs, which may also be activated by a power line fault event. The current through these non-IJ located rail-to-ground HEFPDs is primarily controlled by the fault-induced rail-to-ground voltage.

g. For these analysis, the non-IJ located signal systems and associated HEFPDs, which may be at any location along the exposure, are also treated as unknown variables. Of specific interest is worst-case location for these HEFPDs, which tends to be at locations along the track that experience the highest rail-to-ground induced voltage.

h. Thus, in summary, the stress on IJ-located rail-to-ground HEFPDs tends to be greatest at locations where fault-induced rail current is the highest. The stress on non-IJ located rail-to-ground HEFPDs tends to be greatest at locations where fault-induced rail-to-ground voltage is the highest. These locations of maximum stress for IJ and non-IJ located rail-to-ground HEFPDs generally are not the same.

4. Fault-Induced HEFPD Current Stress

a. A basic premise is, if the protective rail-to-ground HEFPDs activate and survive the fault-induced current that is forced to flow through the HEFPD for the duration of the fault, the track signal equipment will also likely survive the fault event.

b. As noted above, for these analyses it is assumed that the fault-induced rail voltage is sufficiently high to activate (fire) HEFPDs at track IJ locations throughout the exposure, although specific locations for the IJs are not assumed. There is interest in both the fault-induced rail voltage and current. The rail current and voltage are influenced by the soil resistivity and the ballast resistivity, in addition to the location of the fault within or outside of the exposure region.

c. For simplicity, a single value of soil resistivity (100 ohm·m) has been chosen as representative, but lower values will result in less induced voltage, while higher values will result in higher values of induced voltage. The analysis has been performed for high (100 ohm·kft) and a low (2 ohm·kft) values of track ballast resistivity, which encompass the likely range of track ballast resistivity that might be encountered.

d. The fault induced rail voltage and current have been calculated for a fault that occurs at each mile along the exposure, such that the fault currents that are shown in Figure L-3 flow from each substation to the fault. Figure L-5 shows the calculated rail voltage and current as composite curves for faults at one mile increments along the exposure. Each composite voltage or current curve shows the maximum voltage or current at any location along and beyond the parallel exposure that is caused by any of the fault locations analyzed.

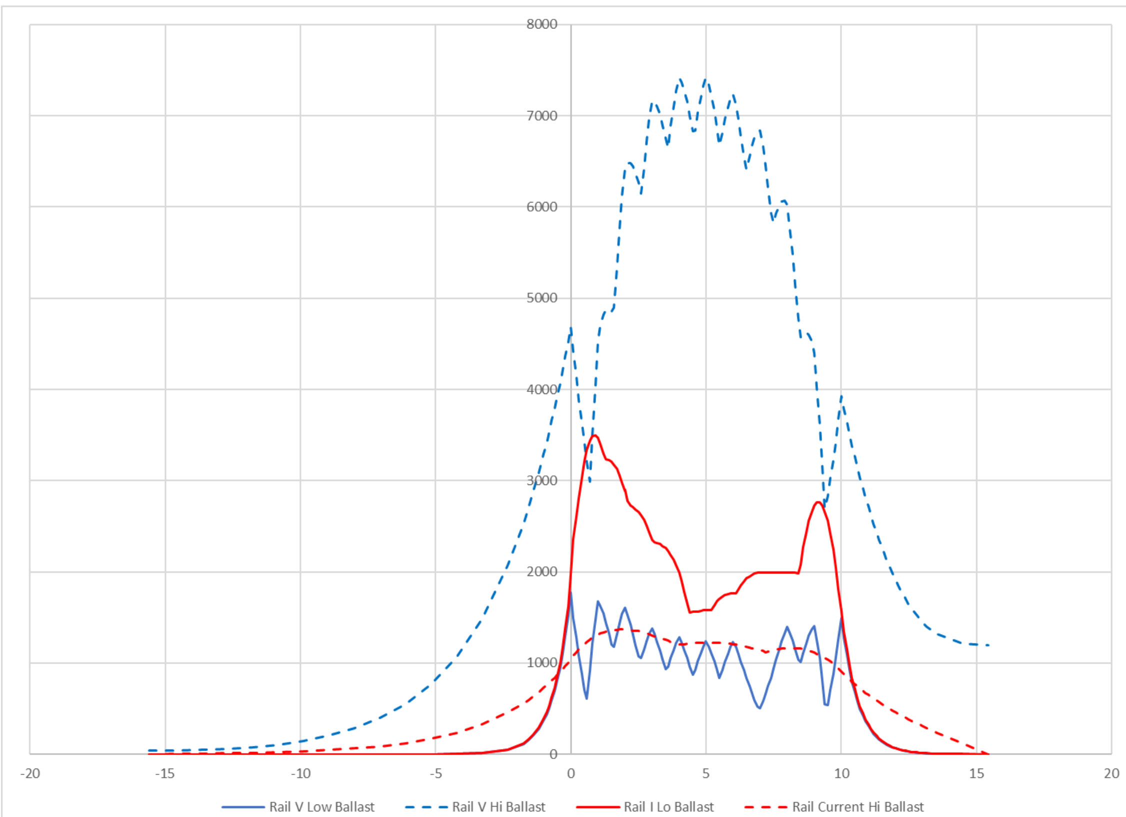


Figure L-5: Composite Calculated Maximum Rail Voltage and Current versus Fault Location Along Exposure for Low & High Values of Track Ballast Resistivity

e. The figure has two composite voltage (blue) and two (red) current curves, the solid red or blue curves are for low-ballast resistivity conditions, while the dashed curves are for the high ballast-resistivity conditions. It is seen that the calculated voltage is higher with high ballast resistivity, while the calculated current is higher for low ballast resistivity.

f. The composite voltage and current response curves are informative, but so are the individual curves for each assumed fault location. Figure L-6 shows curves of the calculated rail current along the exposure, with a separate curve for each analyzed fault location. Notice that each rail-current curve tends to have a minimum at the location of the fault. The maximum rail current values tend to occur near the ends of the exposure. For faults near the ends of the exposure, (and for faults that are beyond the ends of the exposure) the rail current is nominally constant over most of the exposure, but is significantly less than the maximum values of rail current.

g. The rail current versus location shown for any curve will tend to flow through HEFPDs that are connected rail-to-ground if IJs were to be placed at that location along a curve (see the discussion associated with Figure L-4). Knowledge of the maximum fault-induced rail current is important, because if track IJs are located near the maximum predicted current locations, that maximum current will tend to flow through the rail-to-ground HEFPDs that are protecting the equipment at that IJ location. The curves of Figure L-6 illustrate that properly sized HEFPDs for this hypothetical exposure may have to be rated for as much as 3500 amperes to reliably protect arbitrarily-located track-circuit IJs with associated signal equipment.

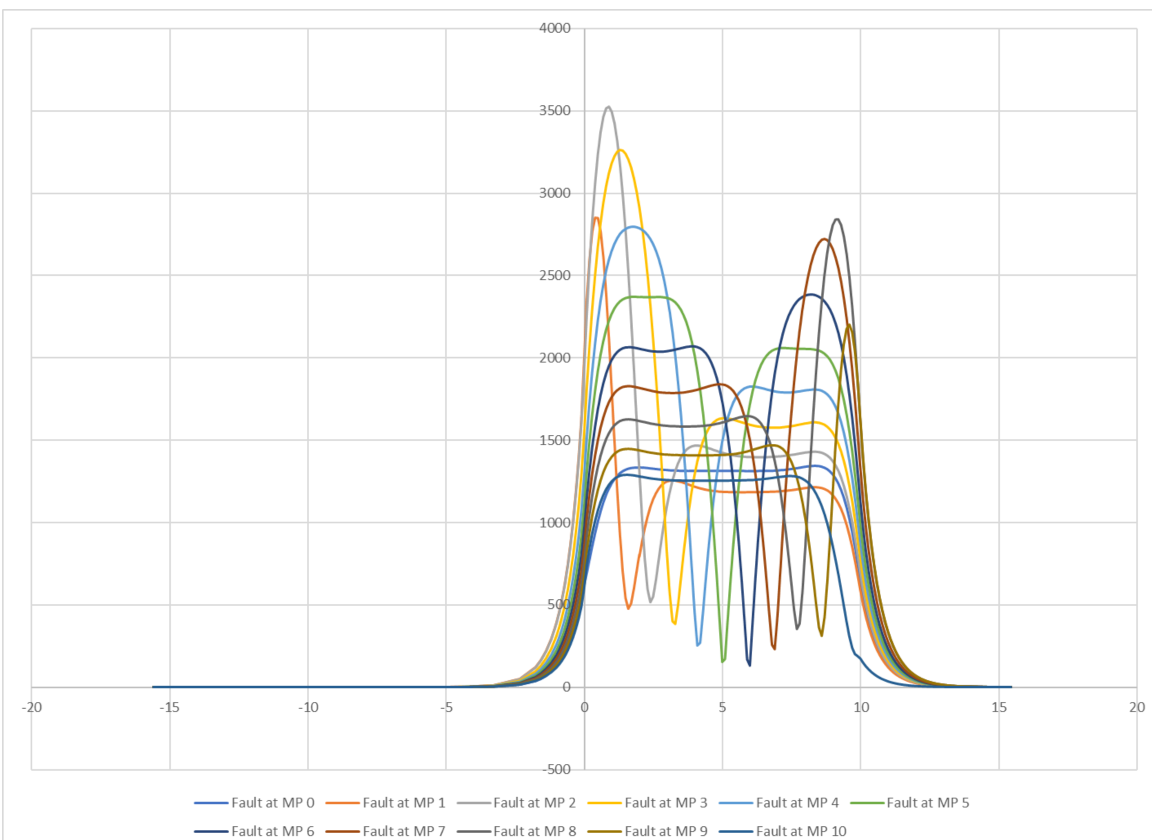


Figure L-6. Fault-Induced Rail Current Curves for Faults at One-mile Increments Along the Parallel Exposure for Low Assumed Track Ballast Resistivity.

h. Figure L-6 also shows that some possible IJ locations within the exposure region are expected to be subjected to significantly less current than the maximum, which reinforces the recommendation that an analysis of the power fault coupling for specific exposures be made prior to installing HEFPDs to verify the required rating.

i. Another condition of interest is whether HEFPDs need to be used at signal locations that are not at IJ locations. The current that will be forced to flow through HEFPDs that are connected rail-to-ground at non-IJ locations is controlled by the fault-induced rail voltage. Figure L-7 shows curves of the calculated rail voltage along the exposure, with a separate curve for each analyzed fault location. Notice that each rail-voltage curve tends to have a maximum near the location of the fault.

j. An assumption for the analysis is that all rail-to-ground HEFPDs at non-IJ locations are fired (activated) and are in a low-impedance state during the fault event.

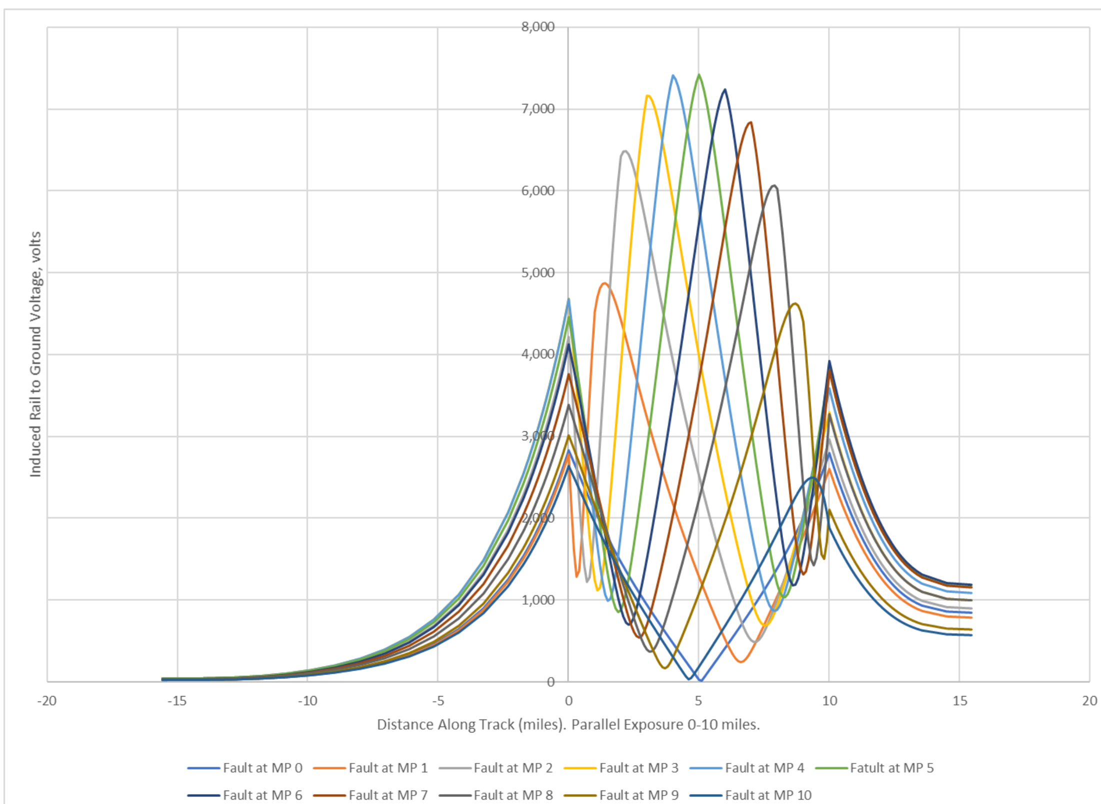


Figure L-7. Fault-Induced Rail Voltage Curves for Faults at One-mile Increments Along the Parallel Exposure for Assumed Hih Track Ballast Resistivity

k. The analysis is generic, such that specific signal locations are not specified prior to the analysis. Therefore, the worst-case signal locations, for example grade crossing locations, can be considered. The worst-case locations for non-IJ located grade crossing equipment would be at or near the peaks of voltage that are shown in Figure L-7.

l. The voltage analysis results in Figure L-7 do not directly show the stress that a rail-to-ground HEFPD would encounter. Therefore as a next step, a fired rail-to-ground HEFPD on each rail, at each of the peak voltage locations (near the fault location) have been assumed, and calculated the current that would flow through the HEFPD due to the fault coupling to the track.

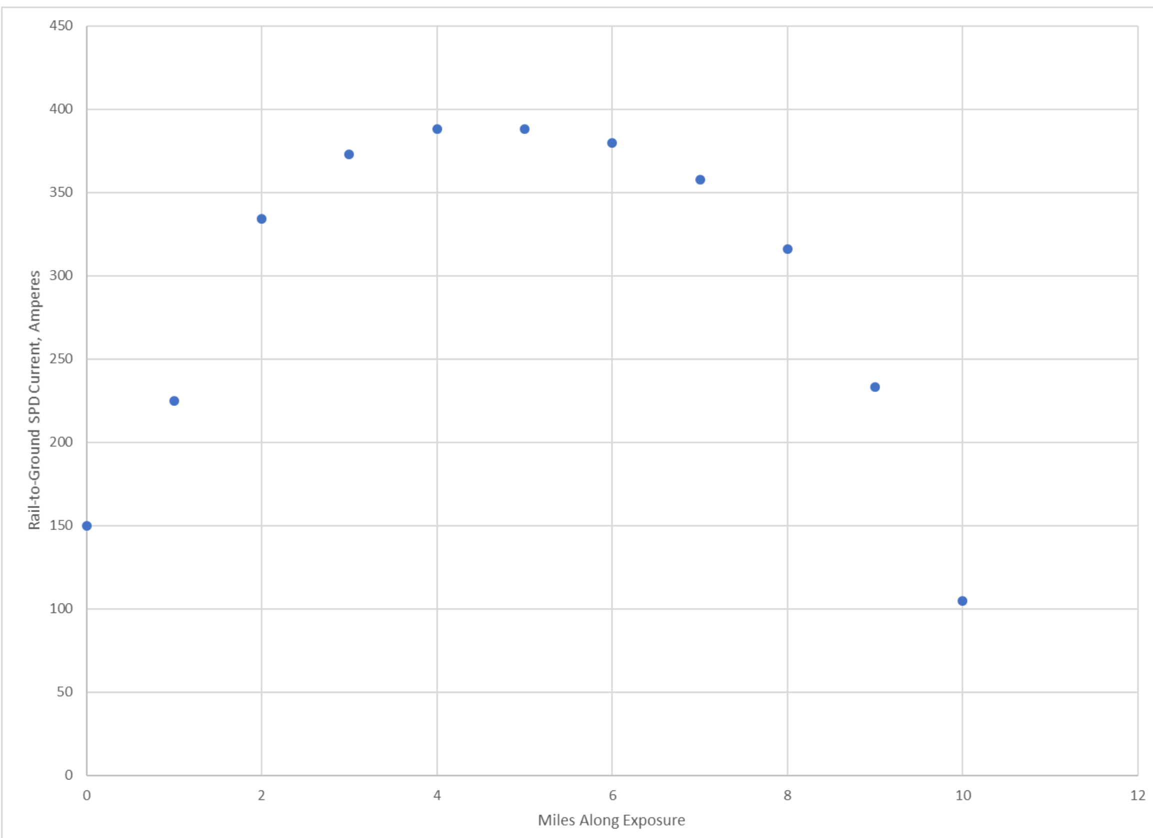


Figure L-8: Calculated Maximum Fault-Induced Current through Rail-to-Ground HEFPDs at non-IJ Locations

m. Figure L-8 shows the calculated maximum magnetic-field fault-induced current that would flow through a non-IJ rail-to-ground

HEFPD at different locations along the exposure, if a fault on the transmission line occurred at that same location. For this analysis, the bungalow ground was assumed to be 10 ohms. Smaller values of bungalow ground resistance would result in higher current, while higher values of bungalow ground resistance would result in lower values of HEFPD current. Comparison of these values to HEFPD and SPD current/time capabilty allows the user to select the appropriate device and ratings for the exposure, and may be within the rating of an SPD.

n. These results suggest that for the geometry and fault current values assumed for this analysis HEFPDs may not be needed at signal locations that are not at IJs, if properly-sized HEFPDs are used for power fault protection at all IJ locations.

Appendix M. 60 Hz Fault Withstand Tests on Signal Lightning Arrestors

C&S Division, AAR Committee Reports & Technical Papers 1984

Exhibit F-5 Electrical Protection & Grounding

60 HZ Fault Current Withstand Tests on Signal Lightning Arresters

Abstract

Fault withstand capabilities of different railway signal circuit lightning arresters were determined in high current tests. These tests simulated induction of 60 Hz currents, of up to 1000 A, into railway signal circuits by fault currents occurring in parallel power transmission lines.

The tests were not designed to show the effects on the arresters of lightning surges, and should not be taken to indicate the capability of the arresters in handling lightning surges.

Introduction

Tests were carried out in 1978 by M.V. Lat of the Research Division of Ontario Hydro to determine the fault current withstand capabilities of low voltage lightning arresters used on CP Rail signal circuits. These tests were conducted to assist in a joint study by Ontario Hydro and CP Rail on surge protection of CP signal circuits running parallel with 500 KV transmission lines.

The purpose of the test program was to determine whether or not currently available lightning arresters for signal lines could handle 60 Hz currents which might be induced into the signal lines by faults on the 500 Kv power system, and also to determine the mode of failure of such devices, since it could affect the operation of the signal system.

Different models of signal protectors were subjected to 12 cycles or 200 milliseconds of 60 Hz currents ranging from 100 to 1000 A RMS. These parameters represent the worst operating conditions that such signal protectors could experience. Each sample was thoroughly tested and examined prior to and immediately following the test. Particular attention was given to several performance characteristics, as outlined below.

Test Evaluation Criteria

All signal circuit protectors were evaluated against desirable performance requirements, defined as:

(a) High damage threshold; the device should withstand currents as high as 500A for 12 cycles (200 mS) without permanent damage.

(b) Sparkover voltage stability; minimal or no change of protector sparkover voltage should occur, after discharging heavy 60 Hz currents, with respect to values either specified by the manufacturer or obtained before high current tests.

(c) Leakage current stability; current through the device, at nominal operating voltage, should not increase beyond manufacturer specified limits, or values determined before high current tests.

(d) Fail-safe mode of destruction; the device should provide equipment protection from overvoltages during its failure, and remain open-circuited if it fails.

(e) Non-violent mode of failure; the device failure should not cause personnel safety hazards or physical damage to other equipment.

Additional Comments on Tests

1. The tests were not designed to, and did not, test repeatability and cumulative effects of a number of test firings.

2. The sample size for each arrester type was very small, typically 5. Thus, each individual test result was generally based on the test firing of one arrester.

3. All types of arresters were not tested. Arrester types were selected for tests because they were in use at the time and because sufficient samples were available at the time of the tests. Some arresters may have been redesigned since the time of the tests, and would therefore have different characteristics if tested at the present time.

4. The tests were not designed to show the effects on the arresters of lightning surges, and should not be taken to indicate the capability of the arresters in handling lightning surges.

5. The type of 60 Hz voltage breakdown testing used, i.e., application of a high AC voltage with a 0.5 amp capacity, may have burned open some small shorts, which would have been undesirable on Vital Signal Circuits. The significance of an arrester remaining shorted may well be that the short would be permanent and capable of conducting dangerous currents.

Test Setup

As shown in the diagram of Figure 1, the sample arrester was energized from a power transformer through a current limiting inductor. The size of this inductor determined the test current, while the open circuit voltage of 2400 VAC RMS assured the sparkover of the sample arrester during the test. The 12-cycle duration of the test current was controlled by the "make switch" and the "circuit breaker".

Each sample was tested to determine its 60 hz sparkover voltage and the leakage current prior to and immediately following the high current test. These characteristics were determined using a small 1800 V RMS transformer with a 0.5 A short circuit current capability.

Subsequently, the arresters were tested with four different test current levels: 100 A, 250 A, 500 A, and 1000 A. Both the current and the arc voltage were monitored and recorded in every test. A typical test record is shown in Figure 2.

Detailed Test Results

The test results for all signal arrester models are shown in tables that follow, each accompanied by comments on the most significant aspects of the test results for the particular model. The following arresters were tested:

1. US&S USG Series arrester
2. US&S USG-A Shunt arrester
3. Safetran Clearview 485 arrester
4. Safetran Heavy Duty 615 arrester
5. Safetran Equalizer 700 arrester
6. Safetran Heavy Duty Power Line 701 arrester

7. TII 16A 3-Element Gas Tube arrester
8. Josyln Visi Guard 2301-01 Gas Tube arrester
9. McGraw Edison Secondary Power Line model AS1A1 arrester.

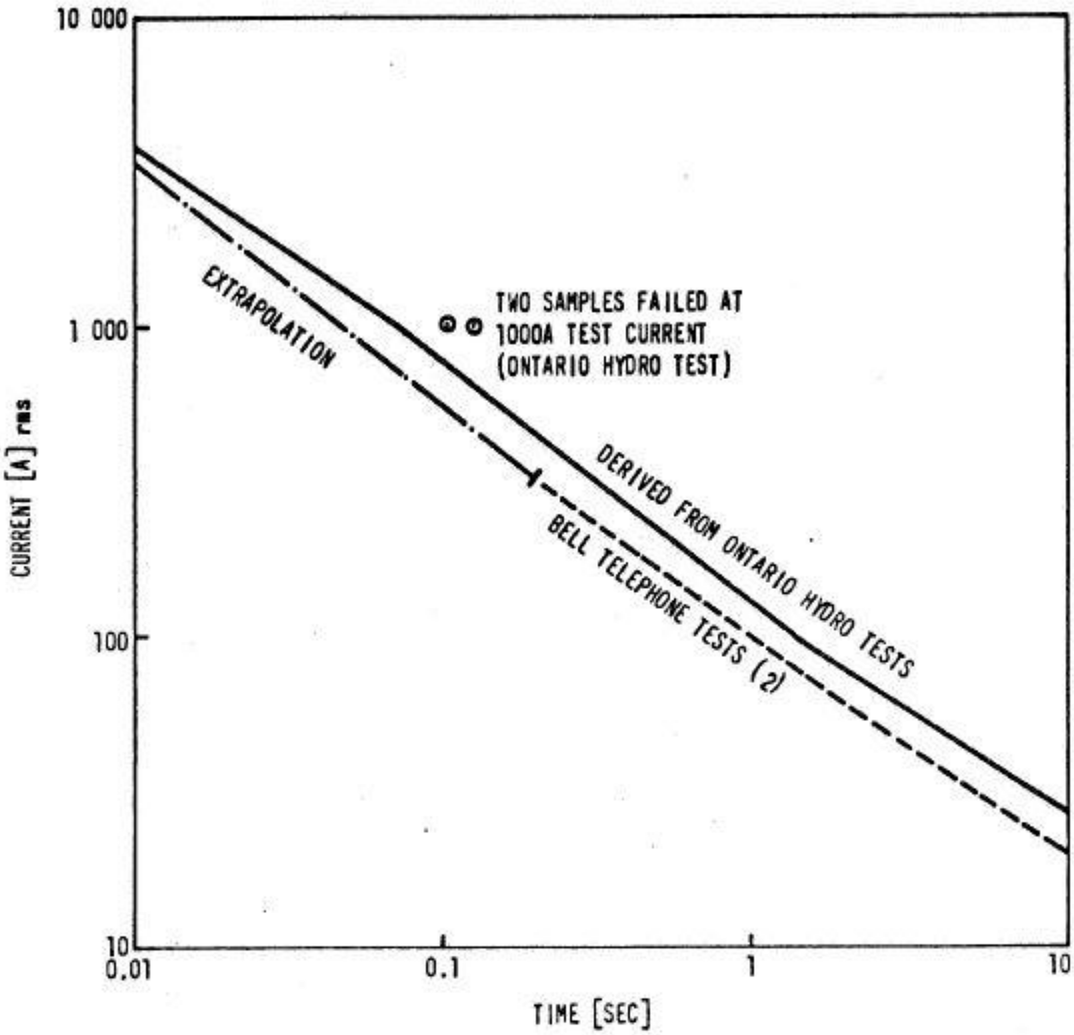


FIGURE 3

60 Hz WITHSTAND CHARACTERISTICS OF DEVICE I (GAS TUBE)
DERIVED FROM ONTARIO HYDRO TEST RESULTS
(NOTE CLOSE CORRELATION WITH BELL TELEPHONE TEST RESULTS)

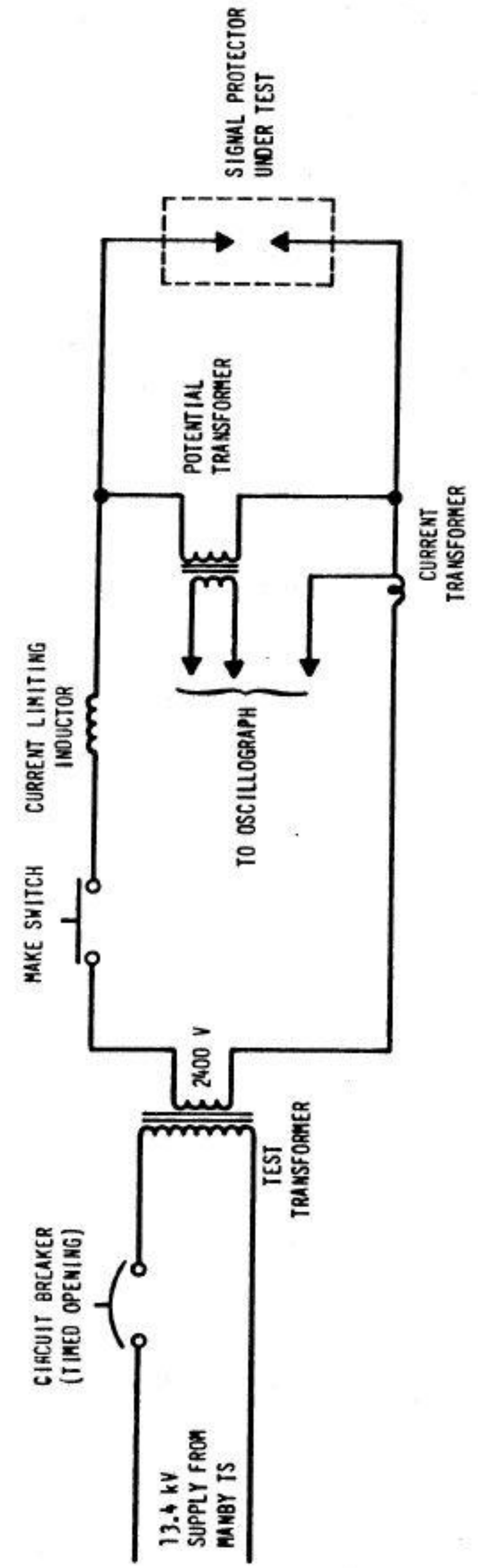


FIGURE 1
TEST CIRCUIT

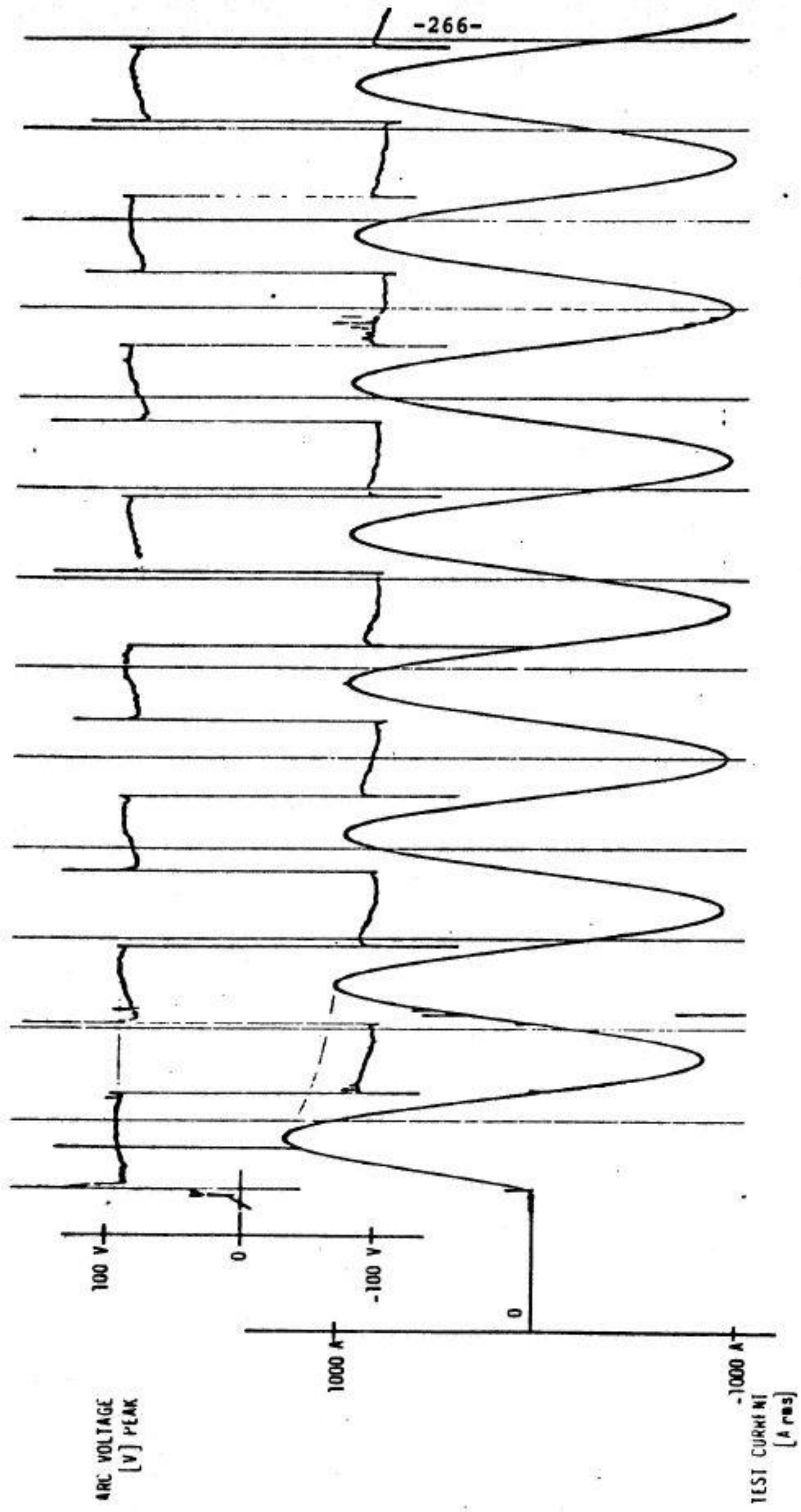


FIGURE 2

TYPICAL WAVEFORMS OF TEST CURRENT AND DEVICE ARC VOLTAGE

1. US&S USG SERIES ARRESTER*

Description: Type: - signal arrester

Design: - simple air gap
- sparkover voltage = 350 - 850 V RMS
- leakage current = <1 uA

Test Data

Test Current	Sparkover Voltage After Test	Leakage Current After Test	Max Arc Voltage (Approx)	Extent of Damage to Device
1000 A	No Change	Slight Increase	39 V	Extensive Electrode Melting
500 A	No Change	Slight Increase	31 V	Extensive Electrode Melting
250 A	No Change	Slight Increase	35 V	Extensive Electrode Melting
100 A	No Change	Slight Increase	25 V	Electrodes Partly Melted

Comments

The electrode spacer and gap cover of this arrester model are made of plastic material called "ablative plastic". When exposed to electric arc this material will not carbonize and its decomposition creates a gas blast, which prevents bridging of the air gap by molten electrode metal.

The gap cover comes into physical contact with only one of the electrodes, thus eliminating all possibilities of leakage or short-circuiting across the surface of the cover.

Although the passage of test current reduced the sparkover voltage to about 50% of its original value, it was still within manufacturer's specifications. The leakage current also increased, but never exceeded 100 uA. In general, of all the arresters tested, this unit appears to be the least affected by fault current discharges up to 1000 A. It is likely to cope satisfactorily with induced 60 Hz momentary fault currents.

*Note this is not the USG-A series arrester. It is expected that the USG-A would perform in a similar manner.

2. US&S USG-A SHUNT ARRESTER

Description: Type: - equalizer type signal arrester

Design: - simple air gap with non-linear resistive spacer
- sparkover voltage = 60 - 130 V rms
- leakage current = <25 mA

Test Data

Test Current	Sparkover Voltage After Test	Leakage Current After Test	Max Arc Voltage (Approx)	Extent of Damage to Device
1000 A	Increased	No Change	32 V	Gap Severely Melted
500 A	Increased Slightly	No Change	24 V	Gap Severely Melted
250 A	No Change	No Change	18 V	Minor Damage
100 A	Increased	No Change	14 V	Minor Damage

Comments

This device is very similar to the USG Series arrester, except for the gap spacer, which is made of silicon carbide. Consequently, this device has a much lower sparkover voltage and a much higher normal leakage current.

This arrester passed all test current levels without shorting. Its sparkover voltage and leakage current changed from the initial values, but still remained within specifications. Its ability to cope with induced currents is considered to be satisfactory.

3. SAFETRAN CLEARVIEW 485 ARRESTER

Description: Type: - signal arrester

Design:
- simple air gap with multiple arcing points, intended to eliminate short circuit failure mode
- **sparkover voltage range = 400 - 800 V rms (before test)**
- **leakage current range = <1 uA (before test)**

Test Data

Test Current	Sparkover Voltage After Test	Leakage Current After Test	Max Arc Voltage (Approx)	Extent of Damage to Device
1000 A	Decreased to 100 V (25% nominal)	Greatly Increased (>10 mA)	50 V	Destroyed
500 A	No Change	Increased (>0.5 mA)	41 V	Destroyed
250 A	No Change	Greatly Increased (>7 mA)	40 V	Partly Damaged (10 of 16 teeth burned off)
100 A	No Change	Increased (>0.2 mA)	185 V	Partly Damaged (6 of 16 teeth burned off)

Comments

This arrester was subject to heavy deposits of oxidized electrode material, (brass, which consists of copper and zinc) created by the intense heat of the 60 Hz power arc and concentrated onto the gap spacers by the transparent plastic cover.

The oxide deposits resulted in large increases of leakage current, from below 1 uA before the test, to as high as 10 mA after the test. Furthermore, sparkover always occurred over the contaminated surface of the spacer, rather than in the gap -- an effect which would eventually short circuit the arrester. Operating the protector without its plastic cover was found to reduce this problem by decreasing the amount of oxide deposits on the spacers, but this may not be acceptable or practical in the field.

4. SAFETRAN HEAVY DUTY 615 ARRESTER

Description: Type: - heavy-duty signal arrester

Design: - simple air gap
- sparkover voltage range = 200 - 900 V RMS
- leakage current = <1 uA

Test Data

Test Current	Sparkover Voltage After Test	Leakage Current After Test	Max Arc Voltage (Approx)	Extent of Damage to Device
1000 A	Device Shorted	Device Shorted	28 V	Electrode melted, Metal bridge
500 A	Device Shorted	Device Shorted	26 V	Electrodes melted, Metal bridge
250 A	Device Shorted	Device Shorted	No Record	Some melting
100 A	No Change	Negligible Increase 1 uA	20 V	Some melting

Comments

This type of arrester is susceptible to metalization of its insulating electrode spacer by deposits of electrode material, made molten by the intense heat of the high current discharge. These deposits cause short circuiting of the arrester as observed in these tests. Considerable oxide deposition on the electrode spacer was observed to form at all test current levels. Where short-circuit mode of failure is undesirable, this arrester would not be satisfactory.

5. SAFETRAN H.D. EQUALIZER 700 ARRESTER

Description: **Type:** - equalizer type signal arrester

Design: - simple air gap shunted by non-linear resistance

- sparkover voltage range = 150 - 260 V rms
- leakage current = 0.1 mA to 1 mA

Test Data

Test Current	Sparkover Voltage After Test	Leakage Current After Test	Max Arc Voltage (Approx)	Extent of Damage to Device
1000 A	Device Shorted	Device Shorted	22 V	Electrodes Melted
500 A	Device Shorted	Device Shorted	22 V	Electrodes Melted
250 A	Small Reduction	No Change	16 V	Some Melting
100 A	No Change	Doubled	15 V	Some Melting

Comments

Electrodes in this arrester are separated by a very small air gap that is easily bridged by molten material produced by the arc. As for the Heavy Duty arrester, this arrester may not be suitable where short-circuit mode of failure is objectionable.

6. SAFETRAN H.D. POWER LINE 701 ARRESTER

Description:

Type: - heavy duty power line arrester

Design: - five air gaps in series, capable of operating on circuits with large short circuit capacity. Gaps are graded with resistive spacers.

- sparkover voltage range = 600 - 1000 V rms
- leakage current = 0.1 to 0.2 mA

Test Data

Test Current	Sparkover Voltage After Test	Leakage Current After Test	Max Arc Voltage (Approx)	Extent of Damage to Device
1000 A	No Change	Increased 10 fold	98 V	2 of 5 gaps shorted
500 A	No Change	Increased 10 fold	87 V	All gaps open
250 A	No Change	Increased 10 fold	80 V	All gaps open
100 A	Decreased to 380 V (60%)	Increased 10 fold	74 V	1 of 5 gaps shorted

Comments

The device is a multiple gap unit, intended for protection of low voltage (115 V) power supply circuits. Since its functioning depends on proper operation of all the gaps (there are five in series), the shorting of one gap could result in the eventual failure of the entire device. On the basis of the tests done on five units, the probability that at least one gap will be shorted after an exposure to a 60 Hz fault current is 60%, and 20% for more than one gap to become shorted, for all current levels employed in these tests.

7. TII 16A GAS TUBE ARRESTER

Description: Type: - signal arrester mounted in Harmon holder

Design: - three terminal gas discharge tube
- glow voltage range = 170 - 190 V rms (line to ground)
- leakage current = <2 uA

Test Data

Test Current	Glow Voltage	Leakage Current	Max Arc Voltage (Approx)	Test Energy (min)	Extent of Damage to Device
1000 A	Nil Device Shorted	Device Shorted	33 V	2600 J	Tubes melted in midsection after 6 cycles
500 A	Decreased to 130 V (70%)	No Change	21 V	2060 J	Midsection heated to red glow
250 A	Decreased to 147 V (80%)	No Change	26 V	1130 J	Small area of midsection heated
100 A	No Change	No Change	19.5 V	360 J	No visible damage

Comments

This unit is a simple three-terminal gas tube arrester, without any additional series or parallel components. In normal operating practice the two outer (line) terminals are connected to the line conductors while the midsection is grounded. This gives simultaneous surge protection for both lines to ground and line to line. In all tests, the current was passed through both line terminals (connected together) to the ground (midsection) terminal.

Two samples tested at 1000 A, failed consistently after absorbing 2600 to 3000 J of fault energy. These protectors failed when their midsection electrode melted, with one line terminal becoming permanently shorted to ground and the other remaining open. Gas tubes depend on rare inert gas (neon or argon) at very low pressure, in the gap area for their low and consistent sparkover characteristics. Once air at normal atmospheric pressure enters the gap area of a damaged gas tube, the sparkover voltage can increase up to 10 to 20 times (well above 2000 V) of their nominal value. This can practically leave all equipment without surge protection.

At 500 A and below 12 cycle test duration, the device passed the test without physical damage, exhibiting slight change of breakdown characteristics (but still remained within manufacturer's specifications). Allowing for some safety margin, the destructive energy limit (E_D) was determined to be 2000 J. Using this limit and the arc voltage characteristics (as recorded during the tests) the 60 Hz withstand characteristics of the gas tube were calculated for a current range from 10 to 10,000 A.

The results are shown in Figure 3, indicating close agreement with the data from the Bell Telephone Co. Tests. Since the Bell tests were done on only one line terminal to ground, their E_D is lower (1500 J).

The unit exhibited predictable characteristics so that it may be applied over a wide range 60 Hz currents and time durations, as defined in Figure 3. However, its mode of failure is either a short circuit or a very large increase of sparkover voltage, therefore, it should not be applied in locations where its maximum ratings could be exceeded.

References

Field Experience with Gas-Filled Protectors on Communication Lines, J.E.R. Lemieux (Bell Telephone Co.), AIEE Communication and Electronics, July 1963, pp. 441 - 448.

8. JOSLYN VISI GUARD 2301-01 ARRESTER

Description:

Type:
- signal arrester

Design:
- gas discharge tube in series with resistive element
- glow voltage = 250 - 260 V rms
- leakage current = <1 uA

Test Data

Test Current	Glow Voltage After Test	Leakage Current After Test	Peak Voltage Across Device During Test	Cycles to Resistor Melting	Extent of Damage to Device
1000 A	Nil Tube Damaged	Nil Tube Damaged	2000 V	1/4	Destroyed, arc transferred outside
500 A	Nil Tube Damaged	Nil Tube Damaged	1000 V	1	Destroyed, arc transferred outside
250 A	Nil Tube Damaged	Nil Tube Damaged	1000 V	3	Destroyed, arc transferred outside
100 A	Nil Tube Damaged	Nil Tube Damaged	300 V	Did not melt	Gas tube cracked

Comments

The Visi-Guard is a gas discharge tube in series with a resistive element. This element is made of Nichrome wire (R = 0.3 ohm) and it evaporates when high currents are passed through the device. Evaporation of the element results in rapid buildup of arc voltage (up to 2000 V), followed by venting of the vapor through the bottom of the device. Both of these conditions force the arc to transfer outside onto the terminals, where it causes extensive damage.

9. MCGRAW EDISON SECONDARY POWER LINE ARRESTER MODEL AS1A1

Description: Type: - power line surge arrester

Design: - enclosed air gap in series with a non-linear resistive element (valve block)

- sparkover voltage >1800 V rms
- leakage current = <1 uA

Test Data

Test Current	60 Hz Voltage Peak Developed Before Failure	Cycles to Fail	Arc Voltage Across Failed Unit	Extent of Damage to Device
1000 A	3000 V	<1/4	300 V	Exploded during test
500 A	2600 V	1/4	185 V	Exploded shortly after test
250 A	2900 V	1/4	140 V	Exploded with long time delay
100 A	3300 V	<1/4	75 V	Block destroyed, Did not explode

Comments

The McGraw Edison unit is an air gap in series with a silicon carbide valve block, hermetically sealed in hollow porcelain housing. The valve block, being a high impedance element in the circuit, is easily destroyed by the high fault current surge.

Most of the units tested, failed explosively, since the high current arcs created sufficient internal pressure to burst their porcelain housings. The explosive mode of failure may be hazardous, and may damage other equipment.

The resistive valve block tends to develop rather high voltage drops across the arrester at currents in excess of 100 A, which could also damage the protected equipment.