OVER-VOLTAGE PROTECTION:

THE CRITICAL DIFFERENCES BETWEEN SPARK GAPS AND DC DECOUPLERS

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ABSTRACT

Both isolating spark gaps and DC decouplers are commonly used to protect against over-voltage conditions on pipeline isolation joints and storage tanks where cathodic protection systems are applied. Though spark gap devices are often applied because of their relatively low cost, they are not designed for many over-voltage conditions that commonly occur on pipelines. Without fully understanding the limitations of spark gap devices, pipeline operators may unwittingly put their pipeline assets as well as operating personnel at risk from over-voltage events such as AC faults and lightning.

This paper provides an overview of why over-voltage protection on isolation joints is needed as well as a brief description of the two most common protection technologies - spark gaps and solid-state DC decouplers. The paper offers a detailed explanation of the limitations of spark gaps for use as over-voltage protection devices on pipelines and explains why properly rated solid-state devices should be used in place of spark gaps for most pipeline applications.

INTRODUCTION

Isolation joints are essential elements of effective cathodic protection (CP) systems and are used extensively throughout pipeline systems to electrically isolate sections of pipe for a variety of reasons. One of the most common applications is to isolate two sections of pipe from each other to prevent unwanted flow of CP current to adjoining pipe sections which may be grounded or protected by a separate CP system. Figure 1 shows an example of an isolation joint installed between a cross country pipeline and a valve station in which a motorized valve and piping is grounded.

In this case, the isolation joint prevents loss of the mainline pipe's CP current to the extensive grounding system within the station. When used to separate two segments of pipeline, each protected with separate CP systems, isolation joints prevent each CP system from interfering with the neighboring pipeline.

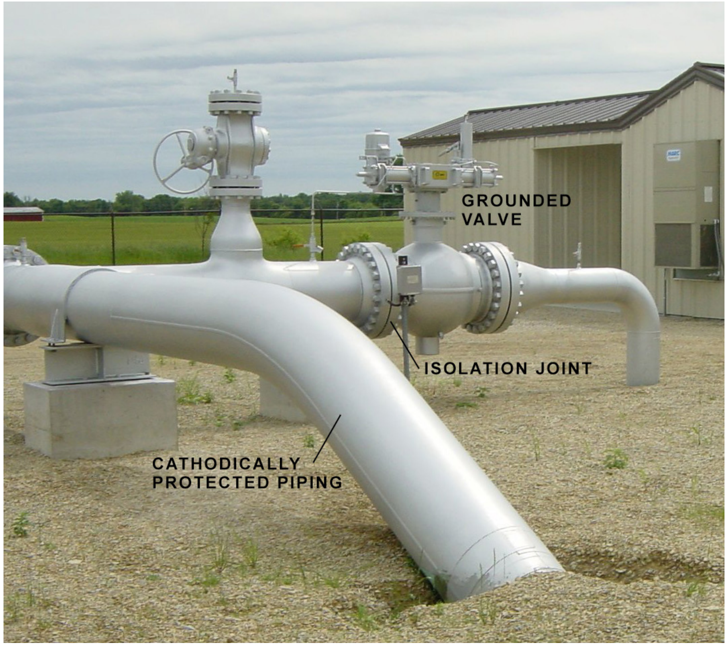


Figure 1. *Isolation Joint installed in a valve station between a cathodically-protected pipe segment and a grounded valve*

The most common types of isolation joints are bolted flange isolation joint kits, monolithic joints and dielectric unions and fittings. These devices are very effective at isolating low voltages associated with CP systems. However, each type has different limits as to the maximum voltage which they can support before the isolation material breaks down and an arc passes through or around the isolation material, often referred to as the "withstand voltage" or "dielectric strength". Typical levels of withstand voltage range from several hundred volts for isolating unions to a few thousand volts for bolted flange isolation joints to 10-15,000 volts for monolithic joints.

ISOLATION JOINTS REQUIRE PROTECTION

Voltages of this magnitude resulting from alternating current (AC) faults and lightning are not uncommon on pipelines. If the joint is exposed to electrical disturbances that cause differential voltages beyond the isolator's withstand voltage, an arc can form across or through the isolation material which can short out the joint and cause permanent damage to the isolation material and/or the joint itself. In some cases, the arc may cause the joint to rupture and result in a loss of product, fire, or environmental damage. Figure 2 shows an example of a bolted joint isolator failure resulting from an AC fault on the pipeline.

Figure 2. *Bolted flange failure due to an AC fault on an unprotected joint*

The high energy from the fault not only burned through the isolating gasket, but also literally welded the two flange faces together. Since the isolation joint was shorted, the CP system was compromised, and the affected pipeline was left without adequate protection until the short was identified and remedied. In this case, the entire bolted flange connection had to be replaced at considerable expense. Similar failures can result in more hazardous outcomes. Figure 3 shows the result of an AC fault on an unprotected dielectric union installed on a gas line. In this case, the surge caused the tubing to rupture and ignited the escaping gas, starting a fire.

Figure 3. *Rupture of a dielectric union resulting from an AC fault*

Due to the obvious safety risks, especially in hazardous locations and to the potential for costly pipeline damage, it is important that isolation joints be protected by controlling the differential voltage across the joint to be well below the isolator's withstand voltage during lightning and fault events. Several international standards address over-voltage conditions affecting safety and equipment damage at isolation joints, some of which are listed in the appendix.

COMMON SOLUTIONS FOR ISOLATION JOINT PROTECTION

When properly protected, excess voltage across the isolation joint is limited by providing an alternate, lower impedance path for current to flow around the joint during over-voltage conditions. Of course, to maintain proper isolation for cathodic protection, the protective device must not conduct direct current (DC) under normal operating conditions. Both solid-state over-voltage protection devices and isolating spark gap devices are commonly used to protect isolation joints from such over-voltage conditions. However, each of these solutions have defined purposes and limitations which must be well understood before designing them into an application.

Solid-State Over-Voltage Protection and Decoupling Devices

Solid-state over-voltage protectors use high power solid-state switching components to control current between two terminals connected across the isolation joint. Under normal conditions, the device remains open, thus maintaining electrical isolation across the joint (for both AC and DC voltage). When the differential voltage across the isolation joint exceeds a prescribed voltage threshold, which would occur during an AC fault or lightning event, the device closes virtually instantaneously, clamping the voltage differential across the joint, thus preventing arcing and protecting it from damage. Immediately following the over-voltage event, the device then automatically returns back to the open state, blocking any DC and AC current from flowing across the isolation joint.

Solid-state decouplers, in addition to protecting the joint from AC faults and lightning, provide a continuous conduction path for steady state AC, which may be induced onto the pipeline from nearby power transmission lines, to continuously pass through the device and across the joint. Examples of an over-voltage protector and a decoupler installed on isolation joints are shown in Figures 4 and 5.

Isolating Spark Gap Devices

Spark Gap devices are commonly used to protect isolation joints from damage due to lightning. When the voltage across the terminals reaches a designated level, referred to as the spark-over voltage, an arc bridges the product's internal electrodes and passes current by way of the arc. Typically, spark gaps require several hundred volts for AC and over 1000 V for lightning for the device to go into conduction.

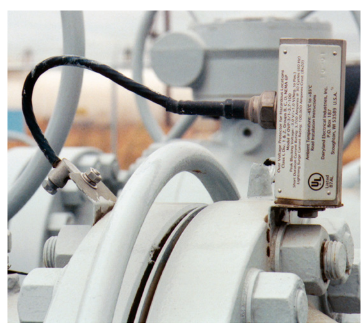


Figure 4. *Solid-state Over-Voltage Protector*

Figure 5. *Solid-state Decoupler*

Spark gap devices are relatively low cost and easy to install. However, one of the key limitations of spark gaps is that their typical ratings for AC fault current are well below the levels commonly observed on pipelines. As a result, solid-state devices are commonly used by the pipeline industry for over-voltage protection on isolation joints, especially on pipelines exposed to potential AC faults.

However, in many places, spark gaps are still commonly used as the sole method of surge protection on isolation joints and other structures simply because the initial installation cost is typically less than that for solid-state devices. This often leads to increased risks by exposing both the pipeline and personnel to unsafe over-voltage conditions.

EXAMINING THE LIMITATIONS OF SPARK GAP DEVICES

The remainder of this paper offers a detailed explanation of the limitations of spark gaps for use as over-voltage protection devices on pipelines and explains why properly rated solid-state devices should be used in place of spark gaps for most pipeline applications.

AC FAULTS: HOW SPARK GAPS AND DECOUPLERS STAND UP

Though AC fault current on structures can result from electrical equipment shorts, on pipelines, faults are more commonly caused by phase-to-ground faults from High Voltage AC (HVAC) transmission towers sharing a utility right-of-way with an underground pipeline as illustrated in Figure 6.

A lightning strike near the tower can ionize the air between the phase wire and the tower, creating a low impedance path for phase current to pass to the tower structure and into the soil surrounding the tower foundation. Depending on the soil conditions and the proximity of the pipeline to the tower ground, high ground potential rise (GPR) conditions can result in the soil surrounding the pipeline. The GPR can cause excessive stress on the pipeline coating and transfer high levels of fault current to the pipeline at coating defects and/or pipeline earthing points.

In addition to fault current conducted to the pipe through the soil, high levels of fault current can be induced in the pipeline from the fault current in the phase wires. Similar to the AC current that can be induced onto pipelines during normal steady state conditions, the induced current during a fault condition can occur along long sections of the pipeline, not just near the fault location.

Though faults are usually short in duration, with typical clearing times of less than 30 cycles (0.5 seconds at 60 Hz), the total current levels conducted and induced onto the pipeline during a fault can be high enough to cause pipeline damage as well as create hazardous conditions for personnel anywhere along the affected pipeline.

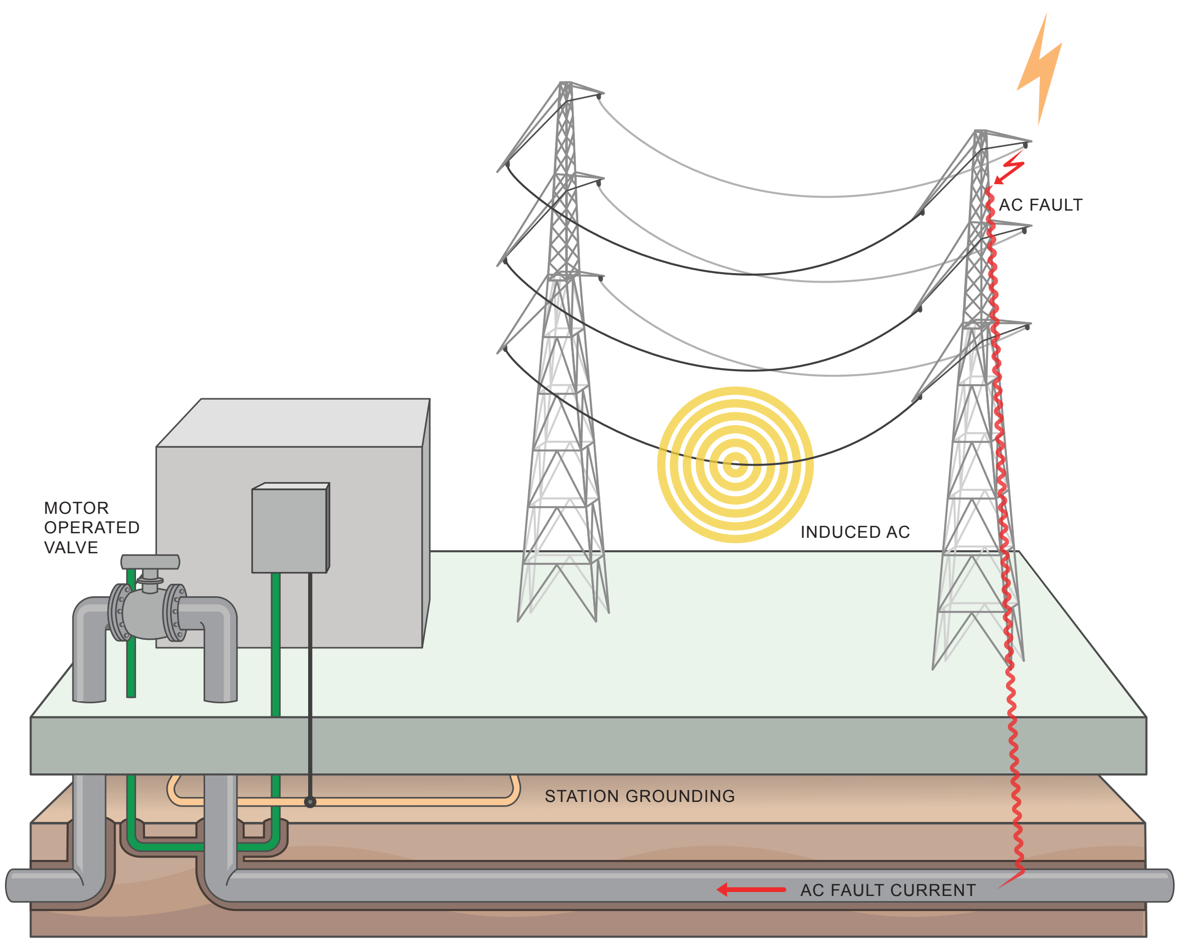


Figure 6. Sources of AC Fault Current on Pipelines

AC Fault Current Levels on Pipelines

Any over-voltage protection device connected to a pipeline, whether used on isolation joints or to isolate CP from grounding systems, must be properly designed and rated to sustain the levels of fault current on the pipeline. Let us work to estimate the approximate magnitude of AC fault current that an over-voltage protective device may experience during a typical fault event. Elevated pipeline voltages resulting from AC faults, whether from inductive or conductive sources, will cause related fault current to flow through the pipeline seeking the nearest low resistance path to ground. In many cases this path is a well-grounded station with isolation joints separating the cross-country pipeline from the grounded station piping as illustrated in Figure 6. The magnitude of the fault current at any one location on the pipeline will vary depending on a complex function of localized pipeline voltages, the overall grounding system design and localized soil resistivities. But in simple terms, the fault current flowing through a single grounding point can be estimated by the pipeline voltage at that point divided by the grounding resistance at that location,

$$I_{fault} = \frac{V_{max}}{R} \qquad (1)$$

Where I_{fault} = localized max. fault current, A_{rms}
V_{max} = localized max. total pipeline voltage, V_{rms}
R = localized grounding resistance, Ω

It is not uncommon for pipeline coating stress voltages to reach several thousand volts during a fault event. A DNV-GL report [5] estimated coating stress voltages ranging from 1.5kV-7.9kV due to a 25kA phase-to-ground fault current, depending on the type of shield wire and pole configuration. Frazier [6] reports predicted total pipe-soil voltages of up to 9kV from a fault on a 345kV power line with over-head shield wires. The NACE SP0177 recommended limits for coating stress voltage resulting from short duration AC faults are 3-5kV for Fusion Bonded Epoxy (FBE) and polyethylene coatings [2]. Similarly, per EN 50443, pipeline voltages referenced to earth and across isolation joints may be as high as $1500V_{rms}$ for 0.2s [4]. Though pipeline voltages during a fault condition can be higher, let us conservatively assume a level of V_{max} to be equal to the maximum coating threshold voltages recommended by NACE SP0177 of 3-5kV for Fusion Bonded Epoxy (FBE) and Polyethylene coatings and 3.0kV for coal tar coating since these values are typically the target voltages for AC mitigation system designers.

The grounding resistance of a single grounding point extending in two directions, for example a station ground, can be estimated by equation 2 [7],

$$R = 0.03 * \sqrt{\rho} \qquad (2)$$

where R= grounding resistance, Ω and
ρ = soil resistivity, Ω-meters

For example, for sandy soils with resistivity of 1000 Ω-m, R = 0.95 Ω. For more conductive soils like clay with resistivity of 100 Ω-m, R = 0.3 Ω.

Substituting these coating threshold voltages and the grounding resistances for various soil types in equation 1, the AC fault current that can be expected to flow through a protective device on an isolation joint located near HVAC lines can be estimated as shown in Table 1. These levels are clearly rough approximations. However, they represent the order of magnitude range of fault current to which protective devices will be exposed on most pipelines. For specific applications, numerical modeling tools should be used to provide precise predictions of fault current along the pipeline and the appropriate ratings required for the protective devices.

Soil Type	Soil Resistivity (Ω-m)	R (Ω)	I_{max} (A_{rms})	
			V_{max} = 3000-5000 V_{rms} (FBE, Polyethylene)	V_{max} = 3000 V_{rms} (Coal Tar)
Clay	100	0.3	10,000 – 16,666	10,000
Sand	1000	0.95	3,158 – 5,263	3,158

Table 1. *Estimated AC fault current through protective devices for different grounding soil types.*

What Happens When AC Faults Reach a Protective Device?

Any device used on isolation joints for over-voltage protection should be properly rated to safely operate following exposure to AC faults. If the device is under-designed for fault current, it will eventually fail either in a closed state – in which the device becomes a permanent short circuit and defeats the purpose of the isolator, or in an open state – in which the device no longer conducts current for faults or lightning and so is unable to provide proper over-voltage protection. Both failure modes are undesirable, but failure in an open state is particularly problematic because it presents a potential safety hazard from over-voltage and/or arcing and exposes the joint to possible permanent damage.

Spark gap devices are effective for protection against lightning and low-level fault currents. However, the total energy from an AC fault is orders of magnitudes greater than that from a typical lightning event, for which spark gaps are primarily designed. This is because an AC fault can last much longer and therefore present much higher total energy than lightning. For example, Figure 7 compares the total electrical charge energy of a 100kA 8x20μs lightning surge (2.3 Coulombs) to that of a 4000 Amp / 0.2 s AC fault (720 Coulombs). In this example, the total charge energy in the AC fault is over 300 times greater than the that of the lightning surge.

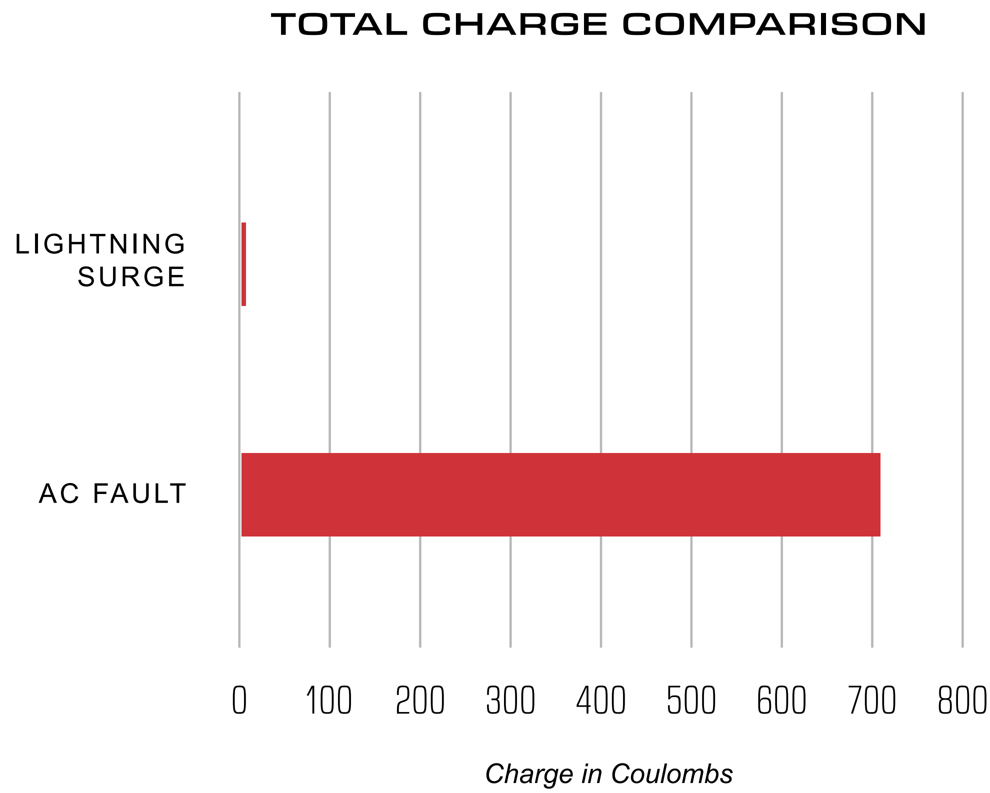


Figure 7. *Energy levels of a typical lightning surge and AC fault*

Spark gaps are not designed or rated to endure this high energy level associated with AC faults. During conduction, the arc formed between the internal gapped electrodes can degrade the electrodes and result in either a failed-open or failed-shorted device. When the device fails open, in some cases the electrodes burn back, increasing the air gap separating the electrodes and thus increasing the spark-over voltage required for conduction upon successive faults or lightning events. In other fail-open scenarios, the terminal components break apart or the entire assembly simply falls apart. In either case the result is a permanent failed-open condition. When the device fails shorted, the high energy dissipation simply over-heats and deforms the internal components such that a permanent short is formed.

For example, figure 8a shows an oscillograph of a new spark gap under an initial fault current test at 2500 A_{rms} / 745 V_{rms} at 60 Hz for 200 ms. Note that once the voltage across the unit (blue trace) exceeds the spark-over voltage (-784 V in this test), the device goes into conduction and passes current (red trace).

Successive tests were performed on this sample, with time between tests to allow for cooling. Upon the sixth test at 2500 A_{rms}, the device had failed open as shown in the oscillograph of Figure 8b. Note that though the voltage across the device is at 1043Vpk, well over the spark-over voltage, no current passes through the unit. In this test, 1043Vpk was the maximum source voltage available in the laboratory. However, on a pipeline during a fault or lightning event, the voltage across the failed-open device could be much higher, leaving the isolation joint unprotected and prone to damage.

Figures 8c shows the internals of this failed spark gap test sample. The internals of the sample prior to testing are shown in Figure 8d. Note in Figure 8c how the electrode appears to have lost material which increased the gap size. In addition, though not shown in Figure 8c, the ceramic housing had cracked during the test, further increasing the gap between the electrodes and thus the spark-over voltage.

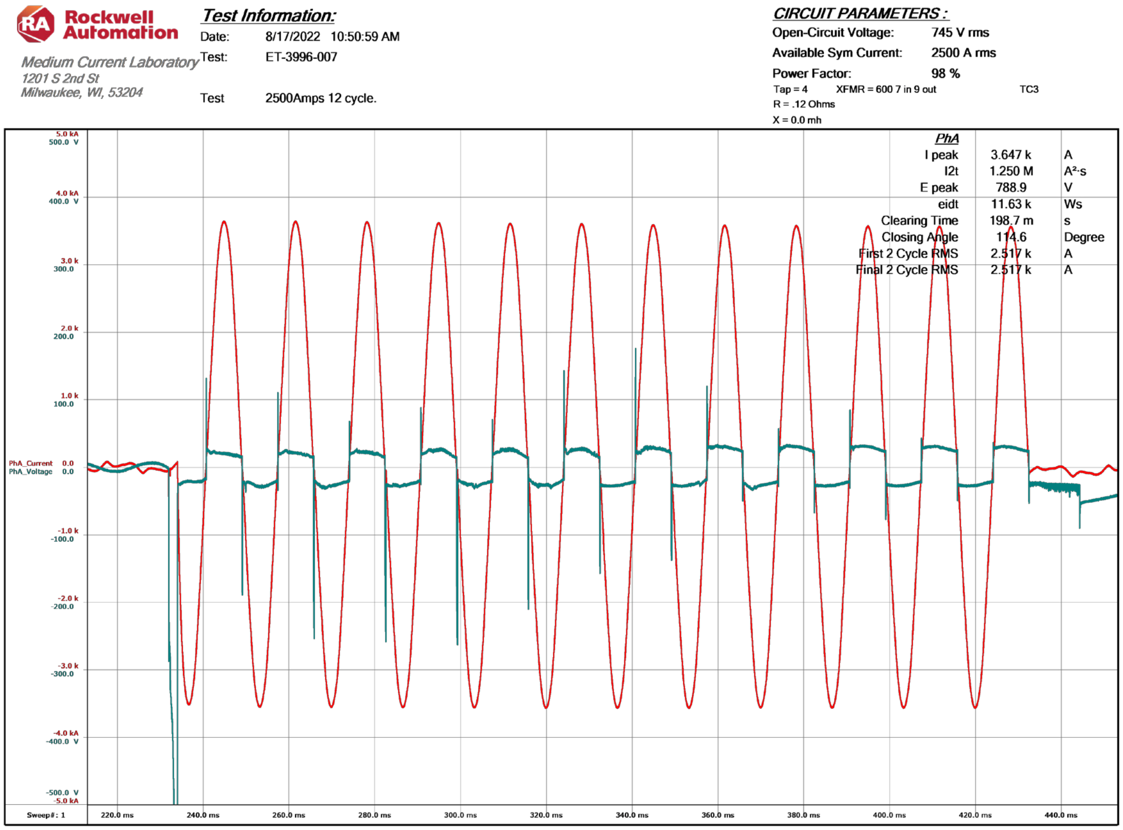


Figure 8a. Oscillograph of a new spark gap under initial fault test at 2500 Arms / 745 Vrms / 200 ms

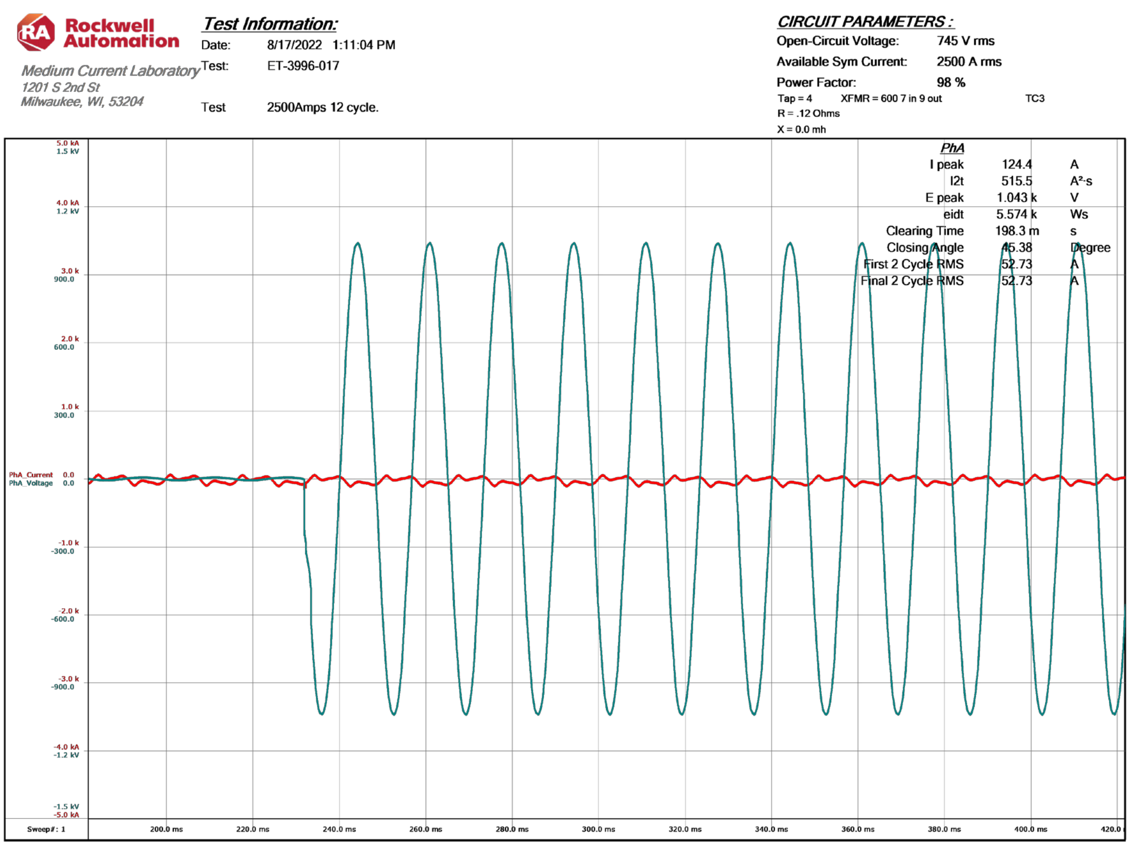


Figure 8b. Oscillograph of a spark gap under subsequent fault test at 2500 Arms / 745 Vrms / 200 ms. The sample failed open.

Figure 8c. *Internals of spark gap following tests at 2500Arms. The sample failed open.*

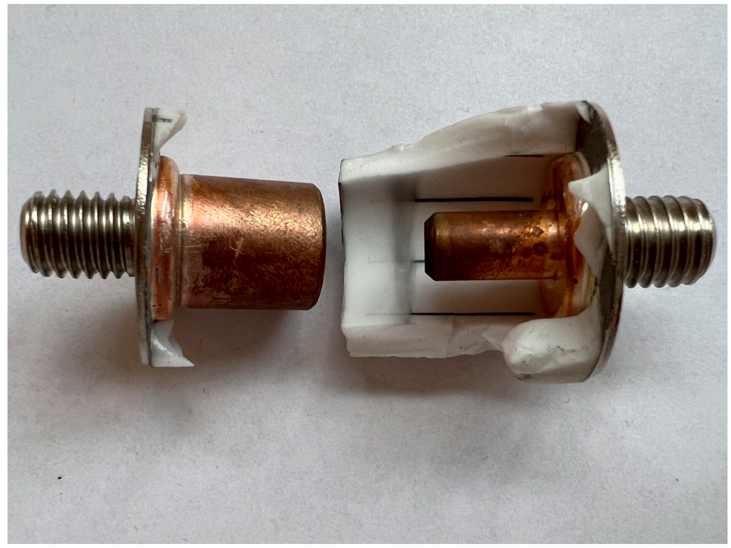


Figure 8d. *Internals of the spark gap prior to testing*

Figure 9a shows an oscillograph of a new spark gap under an initial fault current test at 3700 A_{rms} / 745 V_{rms} at 60 Hz for 200 ms. Following this initial test, the unit was observed to have failed shorted. Though the shorted condition is not indicated in the oscillograph of the initial test, a second test under the same conditions verified that the unit was indeed shorted as shown in the oscillograph of Figure 9b and the photo of the failed unit shown in Figure 9c. Both internal electrodes of this sample had completely melted off and the copper material pooled from end-to-end of the unit, creating the shorted condition.

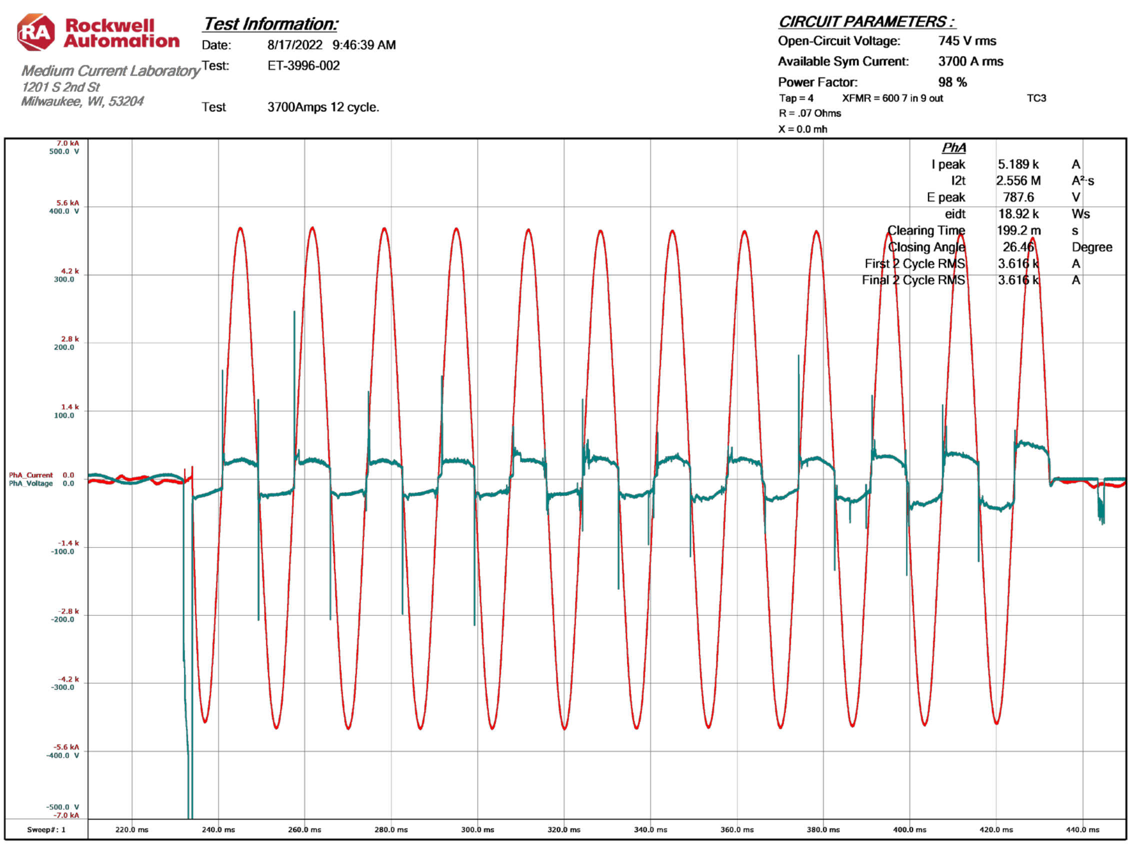


Figure 9a. *Oscillograph of a new spark gap under initial fault test at 3700 Arms / 745 Vrms / 200 ms*

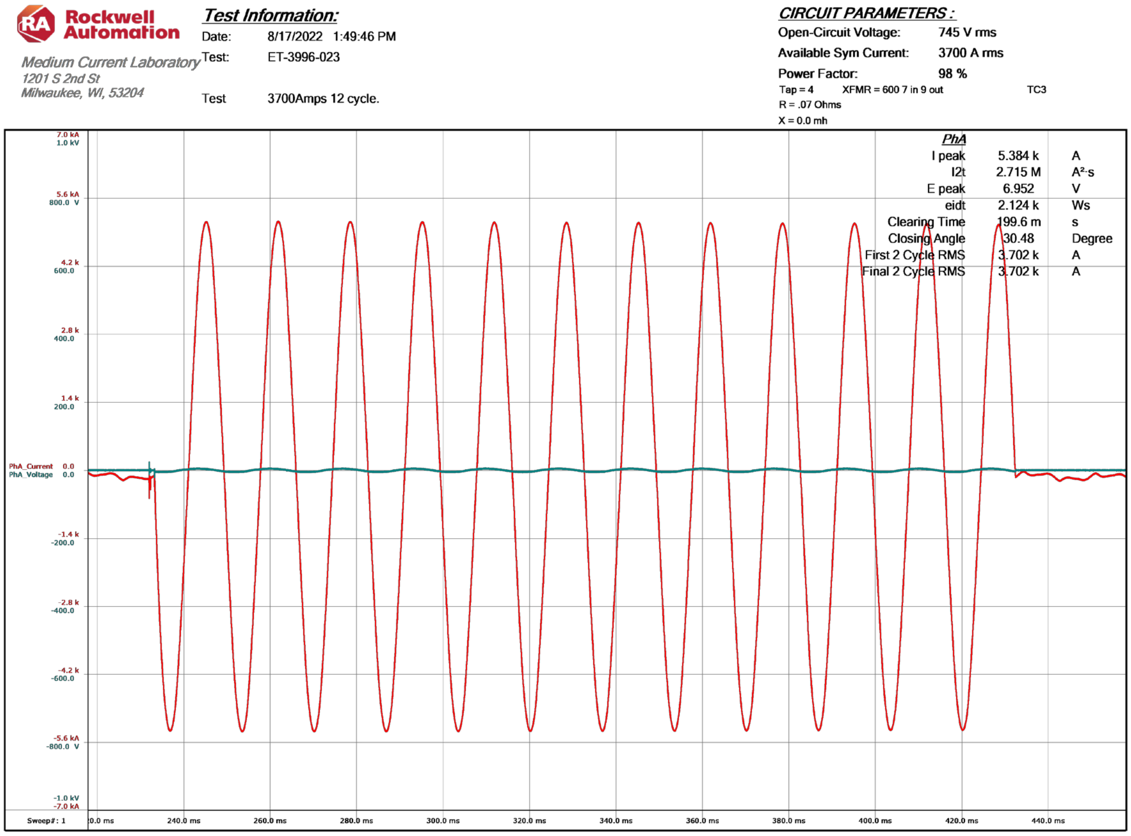


Figure 9b. *Oscillograph of a spark gap under 2nd fault test at 3700 Arms / 745 Vrms / 200 ms. The sample failed shorted.*

Figure 9c. *Internals of failed spark gap tested at 3700Arms. The sample failed shorted.*

Given the failure modes observed during this testing, it is possible at higher, though not uncommon, pipeline fault current levels for a spark gap to fail such that the housing is breached and the arc is exposed to the atmosphere. This type of catastrophic failure is possible when such light duty devices are installed on pipelines where 5kA fault currents and higher are common.

To be fair, these units were tested far above their AC current rating. However, the failure modes observed reveal inherent weaknesses associated with the basic technology of a spark gap. Consequently, most spark gaps are rated to only 500 A_{rms} for 0.2 s, far below the fault levels common to pipelines. Like the sample of Figure 8, spark gaps can often fail in an open state, leaving the isolation joint, storage tank, or wherever it is applied, exposed to potential arcing until it is replaced. And by failing open, this dangerous condition is not easily detected in the field using a basic resistance check.

Alternatively, solid-state decouplers and over-voltage protectors are specifically designed to accommodate such high energy AC faults as well as lightning. Commonly used solid-state devices are rated at $3.7kA_{rms}$ at 0.6 s and are available with ratings up to $15kA_{rms}$ at 0.6 s. For example, Figure 10 shows an oscillograph of a Dairyland SSD-2/2-3.7-100-R during a fault test at $3.7kA_{rms}$ for 0.5 s. This device will endure virtually unlimited fault events of this magnitude if the events are not repeated in close succession. Indeed, solid-state decouplers will fail if subjected to current levels well in excess of their rating.

However, if they do fail, they reliably fail in a shorted state, ensuring the isolation joint is protected until the unit can be replaced.

This data shows that isolating spark gap devices are not designed for typical AC fault conditions common to pipelines located near overhead HVAC power lines. Conversely, properly rated solid-state decouplers and over-voltage protectors, which are designed to sustain high energy fault events, should be used instead of spark gaps wherever there is exposure to AC faults.

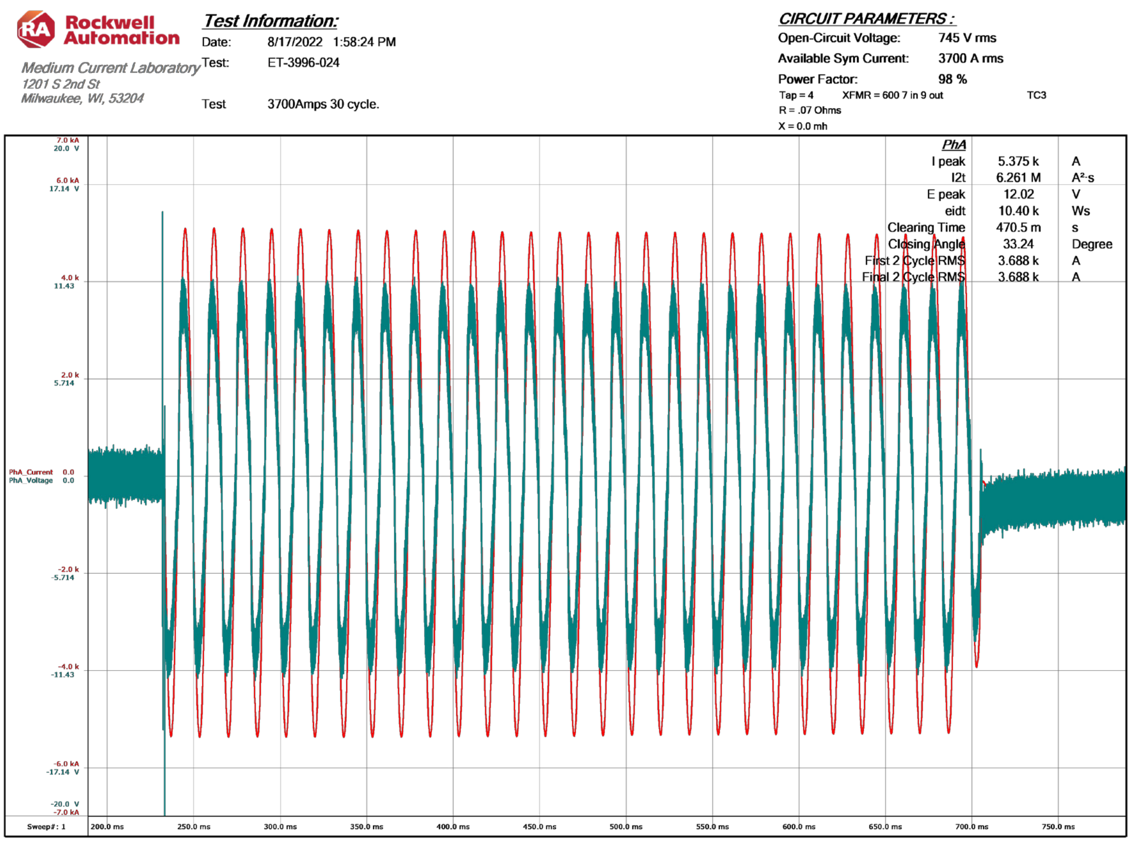


Figure 10. Oscillograph of Dairyland SSD-2/2-3.7-100-R under fault test at 3700 Arms / 745 Vrms / 500 ms

SAFETY: TOUCH VOLTAGE USING SPARK GAPS AND DECOUPLERS

One of the primary functions of over-voltage protection devices is to protect personnel coming into contact with isolation joints as illustrated in Figure 11. Assuming that the AC voltage on the pipeline under normal operating conditions is maintained at a safe level (<15V_{rms} per NACE SP0177 [2] or <60V_{rms} per EN 50443 [4]), it is reasonable to expect the voltage across isolation joints on the pipeline to be at a similar voltage. However, during fault and lightning events, the touch voltage on the pipeline and across isolation joints can be several thousand volts, as explained previously, and so may expose personnel to hazardous conditions if not properly addressed.

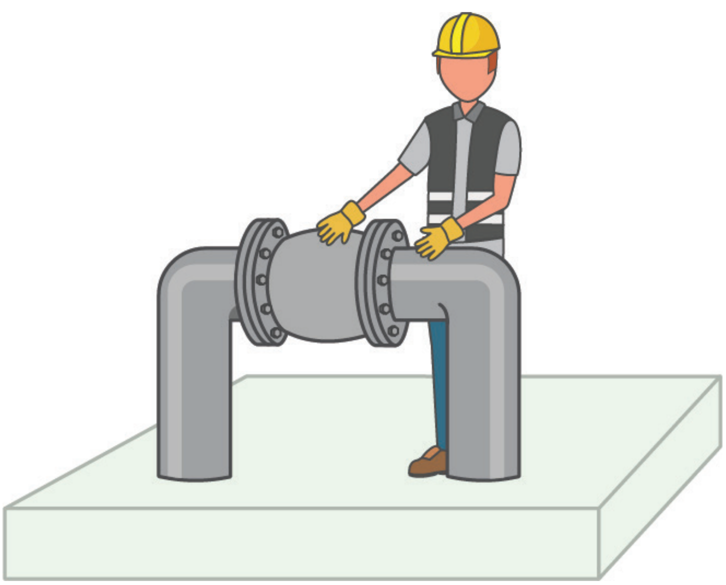


Figure 11. *Touch potential across an Isolation Joint*

Isolation joints fitted with spark gaps may protect the isolation joint from damage due to lightning. But spark gap devices do not prevent personnel in contact with the joint from being exposed to high voltages during a lightning or fault event. Typical spark gap devices are designed to spark-over at several hundred volts (<500V_{rms} for power frequencies and <1250V for lightning). So even when an isolation joint has a spark gap device installed, a differential voltage across the joint of this magnitude can be expected during such conditions. For example, as shown in the oscillograph of the 2500 A_{rms} fault test on the spark gap in Figure 8a, the voltage across the spark gap reached 784V before the device went into conduction.

Alternatively, solid-state protection devices are designed to “clamp” the voltage across the device at much lower levels, typically below 3V at low currents, as shown in the Voltage-Current curve in Figure 12 for a Dairyland SSD-2/2-3.7-100-R having a threshold voltage rating of -2/+2V. Note that as the voltage across the SSD approaches the positive and negative threshold voltage limits, the current increases exponentially and the unit goes into conduction, thereby limiting the voltage across the device. At much higher current levels, the small resistance associated with the terminals and internal bus bars creates some additional voltage drop. But the total voltage across the device during a fault event should not exceed 10V_{rms} as shown in the oscillograph of Figure 10 for the Dairyland SSD-2/2-3.7-100 during a 3700 A_{rms} fault test.

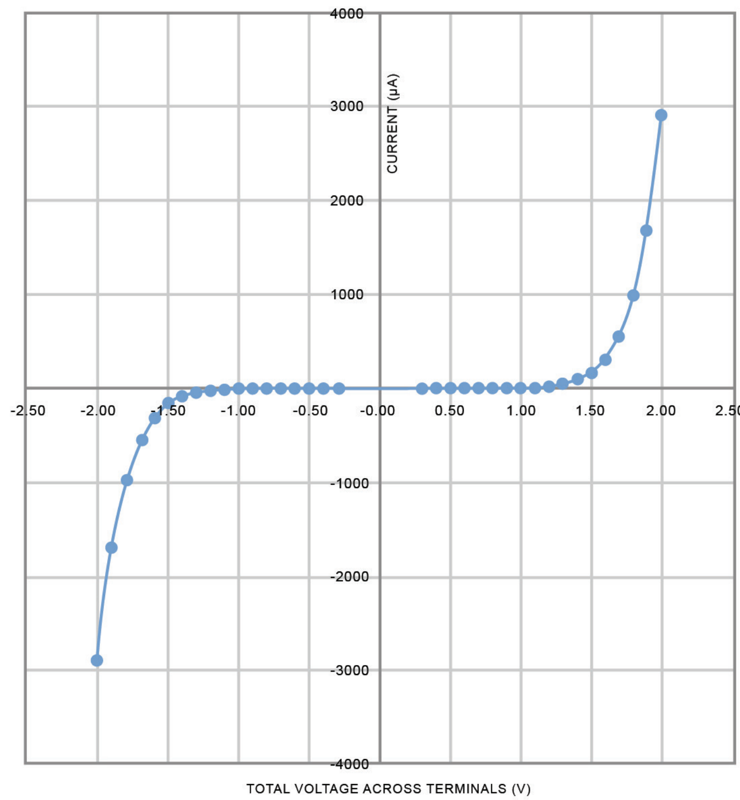


Figure 12. *Voltage-Current curve of Dairyland SSD with -2/+2 threshold voltage*

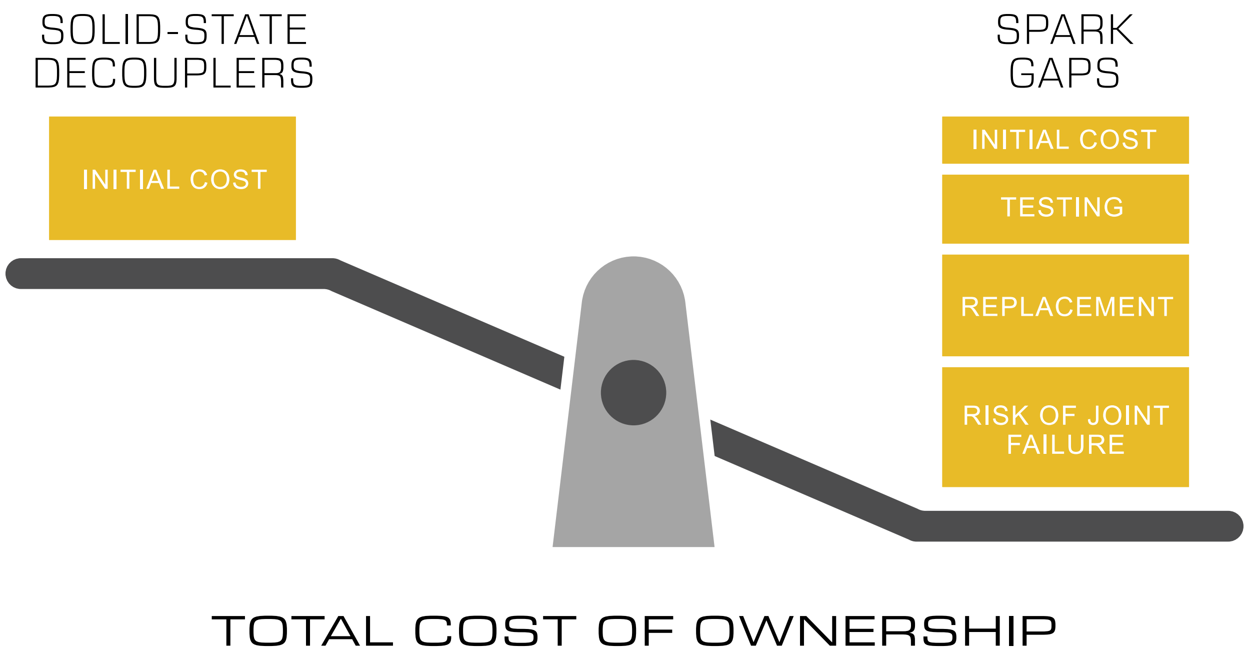
If a device is to be applied on an isolation joint to protect against lightning and fault events, the device should be chosen such that it not only protects the isolation joint from damage but also, and more importantly, that it protects personnel from hazardous over-voltage conditions. Spark gaps alone inherently cannot maintain touch voltages on structures or across isolation joints below several hundred volts, whereas solid-state decouplers and over-voltage protectors are specifically designed to ensure safe voltage conditions wherever they are applied.

RELIABILITY AND TOTAL COST OF OWNERSHIP

The total cost of ownership of an asset includes the asset's initial purchase price and the operational costs associated with owning it. Though the initial purchase price of most spark gap devices is 10-20% of that of a properly rated solid-state decoupler or over-voltage protector, the on-going operational costs related to spark gap devices can far exceed that of solid-state devices.

Reliability is at the heart of the difference in operational costs between the two technologies. Spark gaps are prone to wear and failure over time and so must be tested periodically to ensure they remain functional. The testing is costly and time-consuming, especially for remote locations. Without frequent inspections, there is reason for concern if a spark gap will provide the proper protection during an over-voltage event.

And, of course, there is the added cost of replacing worn spark gaps. In addition, though difficult to quantify, for each device there is the cost associated with the risks of consequences of a failed spark gap device. A spark gap that fails open leaves the isolation joint unprotected and risks failure of the joint during a fault or lightning event. A spark gap that fails closed creates a bond across the isolation joint which can compromise CP systems and risk corrosion protection of the structure. Conversely, properly rated and certified solid-state devices are designed to survive virtually an unlimited number of AC faults and lightning events, if the events are not repeated in close succession. The higher reliability of solid-state devices leads to lower operating and maintenance costs and ultimately lower total cost of ownership for over-voltage protection.



CONCLUSIONS

To ensure prevention of arcing and hazardous over-voltage conditions from AC faults and lightning, protection devices must be installed across isolation joints. Even when pipelines are grounded for AC mitigation, without protection across the isolation joint itself, there is no guarantee that fault and lightning current will not arc across the isolation joint material, damage the joint and/or possibly hurt someone.

Pipelines that share a common corridor with high voltage transmission lines can be exposed to thousands of Amps of current during a phase-to-ground fault. Over-voltage protection devices used on isolation joints or elsewhere on the pipeline should be selected to operate reliably and continuously under such conditions without the need for replacement.

Unlike spark gaps, properly rated and certified solid-state DC decouplers and over-voltage protection devices are designed and built to ensure isolation joints and pipelines are protected from AC faults common to pipelines. Solid-state devices protect personnel from over-voltage conditions and have the lowest clamping voltages than any other DC-isolating protective device. Unlike spark gap devices, reputable makes of solid state decouplers have shown to be so highly reliable that they have no need for periodic testing or replacement, equating to lower operating and maintenance costs.

REFERENCES

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3. ISO 15589-1, Petroleum, Petrochemical and Natural Gas Industries – Cathodic Protection of Pipeline Systems – Part 1: On-Land Pipelines, 2015. Section 7.3.3.
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APPENDIX
STANDARDS RELATED TO OVER-VOLTAGE PROTECTION ON PIPELINES

1. U.S. Code of Federal Regulations for Natural Gas Transportation – Title 49 Part 192

   <u>49 CFR 192.467 – External Corrosion Control: Electrical Isolation</u>

   (e) An insulating device may not be installed where combustible atmosphere is anticipated unless precautions are taken to prevent arcing.

   (f) Where a pipeline is located in close proximity to electric transmission tower footings … it must be provided with protection against damage due to fault current or lightning, and protective measures must be taken at insulating devices. [1]

2. NACE SP0177 – Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems

   <u>4.9. Isolation Joints</u>

   "… a potential hazard may exist across the isolation joint and as a minimum requires fault protection." [2]

   <u>5.3.10. Construction</u>

   "If hazardous AC potentials are measured across an isolating joint or flange, both sides of the joint or flange shall be grounded and/or bonded across." [2]

3. ISO 15589-1 Petroleum, petrochemical and natural gas industries — Cathodic protection of pipeline systems — Part 1: On-land pipelines

   <u>Section 7.3.3</u>

   "To avoid damage from high voltages due to lightning strikes or a.c. fault currents caused by electric power lines, protective devices shall be considered (e.g. appropriate isolating spark gap, surge protective device, and appropriate electrical earthing)." [3]

4. BS EN 50443:2011

   <u>Section 10.2.2.</u>

   "The interference voltage (rms value) of the pipeline system versus earth or across insulating joints at any point normally accessible to any person shall not exceed 60 V" (normal operating conditions) [4]

   <u>Section D.2.2.</u>

   "[Surge Protective Devices] can be used to connect the pipeline to earth or to connect the opposite sides of an insulating joint in order to reduce the amount of the voltages appearing in case of fault conditions …" [4]