Protection of Pipelines from Over-Volatage Conditions

**INTRODUCTION**

Cathodically-protected pipelines are commonly located in service corridors shared with overhead high voltage AC (HVAC) power lines. Consequently, these pipelines are subjected to various forms of electrical interference which often result in over-voltage conditions on the pipeline. These over-voltage conditions can lead to safety hazards for pipeline personnel as well as equipment damage such as pipe wall damage, pipe coating voltage stress damage, AC corrosion and damage to isolation joints.

Over the past few decades, the pipeline industry has developed system solutions to address and mitigate the effects of these over-voltage conditions. The design techniques, materials and equipment used for AC mitigation systems and isolation joint protection are well-developed and employed on much of the world’s pipelines. Yet there remains much misunderstanding about the need for and proper application of these solutions, especially related to isolation joint protection. As a result, many pipeline operators experience unnecessary maintenance costs and safety hazards.

**SOURCES OF OVER-VOLTAGE ON PIPELINES**

The most common form of AC interference is steady state AC voltage that is induced on a pipeline due to the magnetic field associated with current flow on a nearby power line during normal operation. The level of induction is affected by many factors, including powerline load current, separation distance of each phase from the pipeline, phase transpositions, changes in pipeline distance or orientation, soil resistivity and coating quality. This induced voltage can create a shock hazard for pipeline personnel as well as create accelerated corrosion at pipe coating defects due to AC discharge.

A second method by which AC energy can be transferred to pipelines occurs during AC faults. AC faults on the powerline occur when some form of insulation breakdown has occurred and result in a very short term, high amplitude current flow. This may originate from electrical equipment (i.e., motor operated valves) shorting to the pipeline or from phase-to-ground faults. AC phase-to-ground faults are often initiated by lightning striking a powerline and causing AC current to short through the tower structure into the ground and onto a nearby buried pipeline. During such a fault, the amount of induced current onto the pipeline can also rise significantly, albeit for a short duration. Similarly, high energy electrical interference from lightning can transmit onto pipelines through AC towers and their grounding systems. The result on a coated pipeline, without mitigation, is unacceptable touch voltage and step voltage for workers, and possible pipe wall and/or coating damage and damage to isolation joints.

**PROBLEMS RESULTING FROM OVER-VOLTAGE**

**PROBLEMS RESULTING FROM STEADY STATE INDUCED AC**

The pipeline industry has acknowledged the shock hazard associated with induced AC for some time. NACE Standard Practice SP0177 [1] outlines guidance of keeping AC touch voltage limited to below 15V for human health. This level assumes values for maximum safe current and human body resistance and should be considered a guideline. European standard EN 50443:2011 specifies a maximum touch voltage of 60V [2]. AC induction can vary widely due to seasonal soil variations and power line loading. Therefore, when measuring to determine if a pipeline has safe touch potentials, voltage readings should be obtained using a data-logger over a period of time, to assure that peak potentials have been identified.

Beyond personnel safety issues, AC corrosion is also a chief concern resulting from induced AC. Even when low levels of induction are unmitigated, or when mitigation systems yield partial AC voltage reduction, the remaining value may seem insignificant, however, AC corrosion phenomena can easily occur. AC corrosion can be found when adequate AC current density exists at small coating defects. An unwanted consequence of new, high resistance coatings, AC induced current exchange between the pipeline and soil at small coating defects can achieve very high current densities – the amount of current flow per square unit of area. Industry studies point the user to concern at values approaching and exceeding 100A/m2. Note that at a more comprehensible scale, this equates to 10mA per cm2 – a value easily achieved on many pipelines. Coupons designed with a 1 cm2 area are useful in taking current density measurements to determine risk. In general, only areas with low soil resistivity typically have AC corrosion occurring at small coating
defects. See NACE document 35110 [3] and EN 15280 [4] for more information on AC corrosion phenomena. AC mitigation consultants should always consider AC corrosion while performing analyses for worker safety, as it necessarily involves possible further reduction of the resulting mitigated AC voltage from that level adequate for human health issues. This in turn has effect upon the final grounding system design to achieve that criteria.

PROBLEMS RESULTING FROM AC FAULTS AND LIGHTNING

AC faults and lightning carry much greater electrical power than steady state AC interference and so have the potential to be far more damaging and hazardous. Both AC faults and lightning can cause pipeline walls to melt and damage coatings. Though they are relatively short in duration, since they can be transmitted along a pipeline for great distances, pipeline personnel can be at risk of shock even far from the location of the fault or lightning strike. AC faults, though much lower in voltage than lightning, are typically much more damaging since the duration of a typical fault is much longer - on the order of 200ms compared to less than 30µs for a typical lightning strike.

Isolation Joint Damage

Isolation joints are commonly used to electrically isolate sections of pipe from each other to prevent unwanted flow of cathodic protection (CP) current to adjoining pipe sections which may be grounded or protected by a separate CP system. The most common types of isolation joints are bolted flange isolation joints, monolithic joints and insulated unions and fittings. These devices are very effective at insulating low voltages associated with CP systems. However, they each have limits as to the maximum voltage which they can support before the insulating material breaks down, often referred to as the “voltage withstand”. Typical levels of voltage withstand range from several hundred volts for insulated unions to a few thousand volts for bolted flange isolation joints to tens of thousands of volts for monolithic joints. Differential voltage across unprotected isolation joints due to AC faults and lightning can exceed these levels and result in arcing through or around the insulating elements. Arcing can damage and short out the joint and possibly ignite any flammable material in the pipeline.

Figure 1 shows an example of arcing damage resulting from lightning on an unprotected bolted flange isolation joint. The joint was located between a gas transmission pipeline and a storage well in rural Pennsylvania, US. Following a summer thunderstorm, the pipeline CP voltage was observed to be lower than normal and testing indicated that the flange was shorted. The arcing contaminants had created a short circuit along the path of the arc, allowing CP current to drain to ground. The joint was repaired by replacing the flange bolt insulation and adding a solid-state over-voltage protector. After the repair, the CP levels returned to normal.

Figure 2 shows the result of AC fault damage to a bolted flange isolation joint. Note what appears to be a weld on the face of the flange where the fault arced across the insulator. In a case such as this, the joint is either replaced at enormous cost or left permanently shorted, thus compromising the CP protection of the entire section of pipeline.

Figure 3 shows an example of damage to isolation unions due to an AC fault at a natural gas regulator station in New York state, US. The isolation unions separated a CP-protected pipeline from grounded pressure sensing lines. The AC fault transferred to the pipeline and caused arcs across the unions which had no over-voltage protection. The arcs melted holes in the unions, causing a gas leak which was ignited by the fault current and resulted in a fire.
Fortunately, the pipeline industry has developed effective solutions to mitigate these damaging effects of over-voltage. The main intent of AC mitigation systems and isolation joint protection devices is to dissipate unwanted voltage and/or minimize voltage differences at discontinuities along the pipeline resulting from AC interferences and lightning. Properly designed systems following well-established industry guidelines have proven to be highly effective at reducing safety hazards and risks to pipeline equipment [5].

**AC MITIGATION SYSTEMS**

The general technique for mitigating induced AC pipeline voltage is to connect the pipeline at appropriate locations to a suitably low impedance grounding system in order to collapse the voltage to a safe value. Although designed primarily to reduce pipeline voltages due to induced AC and AC faults, these grounding systems also reduce the hazards and damaging effects of lightning. The grounding system is commonly bare zinc ribbon or copper wire run in parallel with the pipeline as shown in figure 4.

The design process typically begins with software modeling by specialized consultants, inputting various factors such as soil resistivity, separation distance and voltage to arrive at a voltage map at all points along the pipeline. Then, by applying low impedance grounding points at various locations along the affected area, the AC effects under steady-state and fault conditions can be modeled, and the grounding system design can be optimized to address worker safety and AC corrosion issues. Depending on many variables such as the separation distance and geometry between the pipeline and power lines, power levels, soil resistivity, pipeline coating, etc., spacing of grounding connections may vary between a few hundred meters to several kilometers.

In order to preserve the efficiency of the CP system, properly designed AC mitigation systems include the means to isolate the pipeline from ground for DC current flow while maintaining the low impedance path for AC and lightning. International corrosion control standards call for accomplishing this through the use of DC decouplers or other devices which are described and compared in section 5 of this paper. Some of the relevant sections from these sources are listed below:

**NACE SP0177, section 4.10.1**

“The coordinated selection and installation of electrolytic grounding cells, solid-state DC decouplers, polarization cells … or other devices between the affected structure and suitable grounds should be considered where arcing and induced AC potentials could develop. ... Polarization cells and solid-state DC decouplers should be considered for steady-state AC interference applications, …” [1]

**EN 15280:2013, section 9.3.1.3**

“To avoid disadvantages due to direct bonding, earthing systems are commonly not directly bonded to the pipeline but connected via decoupling devices which provide an electrical path for the a.c. current from the pipeline to earth while simultaneously blocking d.c. current.” [4]

**ISO 15589-1, section 7.3.6**

“If an earthing system is required, it shall be made compatible with the cathodic protection system. When allowed by regulations, this may be achieved by installing suitably rated d.c. decoupling devices in the earthing circuit.” [6]
ISOLATION JOINT PROTECTION

Over voltage protection devices connected across isolation joints are designed to provide a conduction path for faults and lightning around the joint and thus limiting the voltage across the joint to safe levels. This protects the isolation joint while maintaining electrical isolation at lower voltages. In addition to protecting the joint from damage, appropriate over-voltage protection devices ensure safe touch potential across the joint in the event of an AC fault so that personnel are protected.

Several international standards address over-voltage conditions affecting safety and equipment damage at isolated joints. Some relevant sections from these sources are listed below:

U.S. Pipeline Safety Regulations. 49 CFR 192.467
(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.” [7]

NACE SP0177
5.3.10. “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.” [1]

4.9. “… a potential hazard may exist across the isolation joint and as a minimum requires fault protection.” [1]

ISO 15589-1, section 7.3.3
“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).” [6]

BS EN 50443:2011
10.2.2. “The interference voltage (rms value) of the pipeline system versus earth or across the insulating joints at any point normally accessible to any person shall not exceed 60 V.” [2]

D.2.2. “[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 …” [2]

DECOUPLING TECHNOLOGIES

Numerous isolation devices are used by the cathodic protection industry as part of over-voltage protection systems. Some have very defined purposes and limitations and should be applied as specified by the manufacturer. The more commonly-used devices are described below.

SOLID-STATE DECOUPLERS AND OVER-VOLTAGE PROTECTORS

Solid-state over-voltage protectors use high power solid-state electronic switching components to create a switch between the two structures to be isolated. Under normal conditions, this switch remains open, maintaining DC isolation between the structures. When the differential voltage across the terminals exceeds a prescribed voltage threshold, which would occur during a fault or lightning event, the switch closes virtually instantaneously, collapsing the voltage across the terminals and electrically bonding the structures. Immediately following the over-voltage event, the device then automatically switches back into the OFF state to maintain isolation.

Solid-state decouplers, in addition to bonding structures during AC faults and lightning, provide a continuous conduction path for steady state AC to pass through the device and across the joint at all times. By shorting steady state induced AC current, a decoupler reduces AC voltage on the pipeline and prevents the AC voltage from triggering the solid-state switch. Examples of an over-voltage protector and a decoupler installed on isolation joints are shown in Figures 5 and 6.

Figure 5. Solid-State Over-Voltage Protector

Figure 6. Solid-State Decoupler
POLARIZATION CELLS

The polarization cell is an electrochemical switch comprised of pairs of stainless steel or nickel plates immersed in a solution of potassium hydroxide. It responds to low voltage DC current by polarizing the plates and reducing the flow of DC current. It passes higher voltage DC, steady state AC, AC faults and lightning current.

Since the introduction of solid-state devices in the 1980’s, polarization cells have become much less common due to their need for regular maintenance of fluid levels, large package size, and the fact that when they fail, they create an open circuit, which creates a potential safety hazard.

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, an arc bridges the product’s two electrodes and passes current. Typically, spark gaps require several hundred volts for AC and over 1000 V for lightning for the device to go into conduction.

APPLICATION REQUIREMENTS

Decoupling products must be selected with careful examination of their electrical characteristics relative to the intended purpose in order to assure proper application.

Low Impedance for AC Faults and Lightning

One of the most basic requirements of decoupling devices is to provide a low impedance path for AC faults and lightning. During such an event, the voltage across a solid-state device clamps at the threshold voltage, which is typically 3 volts or less. Under the most extreme AC fault conditions, the maximum voltage across the terminals is less than 10V. Under lightning surge conditions, this maximum voltage is approximately 100V. This assures that over-voltages will be clamped to low levels during faults or lightning events, providing a significant advantage for personnel safety and for applications such as isolated joint protection. In comparison, spark gaps do not provide protection until they “spark-over”, which typically requires hundreds (for AC) to thousands (for lightning) of volts across their terminals, exposing personnel and equipment to this voltage until the device conducts.

Sufficient Device Ratings

The typical AC fault rating for pipeline applications near HVAC towers is 5kA and levels up to 15kA are not uncommon. Most solid-state devices have the ability and ratings to handle AC fault current at these levels. Spark gaps, however, are not designed to handle such AC faults and so are typically not rated above 500A at 0.2 sec. As a result, spark gaps often fail when exposed to typical AC faults.

Low Impedance for Steady State AC

To be effective for use as part of AC mitigation systems, decoupling devices must be able to continuously conduct steady state induced AC. This includes devices used across isolation joints if grounding points on the opposite sides of the joint are part of the same AC mitigation system. Solid-State decouplers and polarization cells both continuously conduct steady state AC. Most solid-state decouplers introduce only a few milliohms of impedance and so do not significantly affect the pipeline voltage. Spark gaps are not designed to pass steady state AC and so cannot be used for AC mitigation applications.

Low Maintenance

Given the remote location of many pipelines, low maintenance and reliability of decoupling devices is extremely important. Since polarization cells require regular inspection to maintain liquid levels, these devices have become much less popular over recent decades. Since spark gaps often fail when exposed to AC faults, they too require frequent testing to ensure proper spark-over operation.

Low DC Leakage Current

To maintain the efficiency of CP systems, it is important to minimize DC current leakage to ground through decoupling devices. Since many modern pipeline coatings provide such effective isolation, CP rectifier currents are often so low that several milliamps of DC current loss to ground through a decoupling device can negatively affect CP performance. When installed across isolation joints, spark gaps provide excellent DC isolation with no leakage current. Solid-state decouplers, when properly applied within the threshold voltage range, typically have less than 10µA DC leakage.

Hazardous Location Ratings

Many user sites are formally classified as hazardous locations, which are defined by international standards such as the International Electrotechnical Commission (IEC) according to the concentration of flammable gases or liquids present. Electrical devices must meet certain design and quality requirements to be used in these locations. If a site is classified or otherwise treated as a hazardous location, then an over voltage protection product having third-party certifications (UL, ATEX, IECEx) for this environment should be used.

Fail-Safe Design

If exposed to fault current values beyond their ratings, over voltage protection devices should always fail safely and uneventfully in the shorted mode (fail as a dead-short), bonding the two points together for safety. This assures that over-voltage conditions will be addressed – whether the product is working or failed.
Most solid-state devices are considered truly “fail-safe” and product certifications should provide verification as such. Most spark gaps have an open gap, which will always remain an open gap. If the spark gap were to fail, it would be as an open circuit. After failure, most spark gaps provide no over-voltage protection and a potential safety hazard is created, as voltage can rise to unsafe levels. Similarly, when polarization cells fail, either from fluid evaporation or tank rupture, they fail as an open circuit and cease to provide safety grounding.

CONCLUSIONS

Buried pipelines are subject to multiple threats from AC interference and lightning which affect pipeline safety and integrity. Thankfully, well-established system solutions on pipelines, including AC mitigation and isolated joint protection, exist that, when properly applied, mitigate much of the negative effects of these threats. Decoupling devices play a critical role in these mitigation solutions to isolate CP-protected pipelines from earth and other CP systems while providing bonding for AC and lightning.

However, not all DC decoupling devices are created equal. Many DC decouplers available have not been well validated by reputable third-party certification agencies to meet stated performance criteria. In addition, spark gap devices should not be used for most applications located near HVAC power lines since they will not pass low voltage steady state induced AC to earth and they are not properly rated to handle AC faults levels that are typically observed on pipelines in these locations. It is important to understand the performance strengths and limitations of the devices before application.

REFERENCES


7. 49 CFR 192.467, External Corrosion Control: Electrical Isolation, U.S. Pipeline and Hazardous Materials Safety Administration, DOT.