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Mitigation of Arcing Risks to Pipelines Due to Phase-to-Ground Faults at Adjacent Transmission Powerline Structures

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ABSTRACT

Although the probability of a phase to ground fault occurring at a specific transmission powerline tower and resulting in an arc to an adjacent pipeline may be quite small, the risk cannot be ignored due to the severity of the potential consequences. A sustained arc to a pipeline could result in melting of the pipe wall and catastrophic failure of the pipeline. Additionally, the powerline fault current would be transferred directly to the pipeline via the arc, resulting in safety risks, the potential for additional arcing risks at crossings with foreign structures, and a risk of damage to isolating flanges and to cathodic protection equipment upstream and downstream of the fault location.

In order to ensure there is no risk of arcing, a critical or “safe” separation distance between the pipeline and any part of the powerline tower foundation or grounding system must be maintained. This paper discusses how to determine the critical separation distance that is required to avoid an arc based on research, literature and standards, and explores mitigation options in circumstances where this distance cannot be feasibly maintained. Calculations and mitigation measures from a case study and a pilot site will be presented.

Keywords: AC Mitigation, AC Interference Pipelines, Arcing, Powerline Fault, Transmission Powerlines, High Voltage AC (HVAC), Phase-to-ground Fault

INTRODUCTION

This paper discusses how to determine the critical separation that is required to avoid an arc based on research, literature and standards, and explores mitigation options in circumstances where this critical distance cannot be feasibly maintained. An arcing investigation program implemented by a California gas and electric utility is presented as a case study, with specific risk assessment and mitigation details provided for a pilot location.

BACKGROUND

General

A phase-to-ground fault on a powerline, usually initiated by lightning, results in the conduction of electrical power indirectly from one or more AC powerline phase conductors via the metallic tower to ground, as illustrated in Figure 1, or directly to ground as a result of an overhead conductor falling to ground.

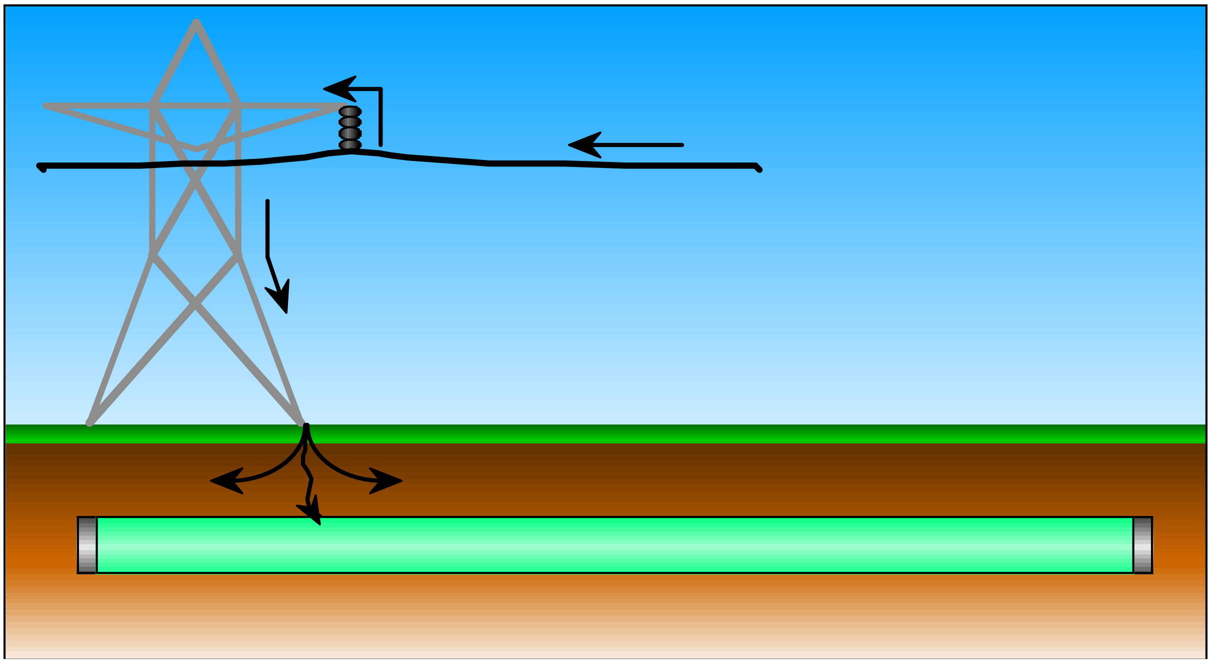

Figure 1: Illustration of a Powerline Fault to Ground at a Tower near a Buried Pipeline

Powerline phase-to-ground faults typically occur during inclement weather such as high winds, ice storms, or electrical storms wherein, for the latter case, the fault is initiated by a lightning strike in the vicinity of the powerline phase conductors and the pipeline. As shown in the lightning flash density map in Figure 2, the probability of a lightning strike is relatively small, especially in California, where the lightning ground flash density is relatively low (less than 0.5 fl/km^2/yr). Furthermore, it should be noted that a lightning arc to a pipeline itself is not a major concern unless it is sustained by a 60 Hz phase-to-ground fault, as it does not contain enough energy to result in damage to the pipeline. According to statistics gathered by a major electrical utility on electrical transmission lines in California, the average number of outages or faults on their entire transmission lines system is 933 per year, which equates to 0.03 faults per kilometer of transmission line per year. These statistics include different types of faults, so the number of faults resulting in a phase-to-ground fault at a tower and an arcing risk to an adjacent pipeline, would be even less. Although the risk of a fault at a specific tower is relatively small, in the event of a sustained phase-to-ground fault, the resulting nature of the damage to a nearby pipeline can be particularly severe under some conditions and the electrical transmission of the fault current and voltage along the pipeline can produce a voltage hazard to personnel and damage to cathodic protection systems.

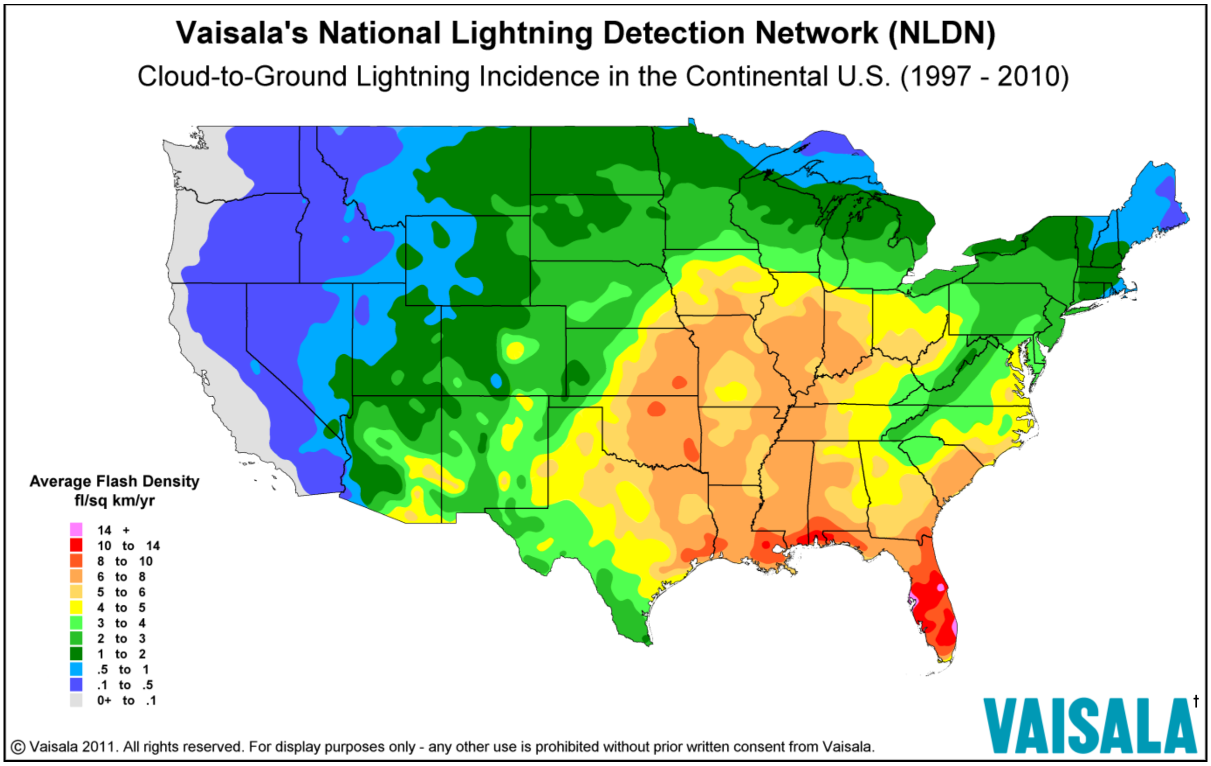

Figure 2: Lightning Flash Density Map for the USA[(1)]

If a pipeline is in proximity to the foundation or grounding of a faulted powerline structure, there is a risk of an arc developing from the powerline grounding to the pipeline, which could result in damage to the pipe wall and/or the coating.

Even when the separation distance between the pipeline and the powerline structure exceeds the critical distance and arcing is prevented, significant hazards can still exist for pipeline personnel and to the coating integrity of the pipeline under fault conditions, due to induced voltages and the resulting ground potential rise (GPR) at the faulted tower.

Shield wires on a powerline protect the phase conductors from lightning strikes and when a fault does occur at a tower, they distribute the fault current to adjacent towers, reducing the amount of fault current discharging at the faulted tower. Based on experience, the current discharge is typically less than 20% of the total fault current. This means that the voltage rise of the faulted tower would be less than if the entire fault current passed to ground at a single tower, thereby also reducing the arcing distance. If there are no shield wires, as is typically the case in California, then all of the fault current enters the earth at the faulted tower which produces a greater voltage rise at the tower and a longer arcing distance, generally representing the worst case.

[†] Trade name.
[(1)] Reproduced from www.vaisala.com with permission of Vaisala Oyj, P.O.Box 26, FIN-00421 Helsinki, Finland

Critical Separation Calculations

Sunde[1] has produced equations (1 and 2 below) to calculate the critical separation distance (r) to avoid a lightning arc, based on the lightning fault current and soil resistivity as follows:

$$\text{For } \rho < 100\ \Omega\text{-m} \qquad r = 0.08\sqrt{I_f \rho} \tag{1}$$

$$\text{For } \rho > 1000\ \Omega\text{-m} \qquad r = 0.047\sqrt{I_f \rho} \tag{2}$$

where:
r = distance over which lightning arcing can occur (m)
ρ = soil resistivity (Ω-m)
I_f = lightning fault current (kA)

The Sunde equations are related to arcing due to lightning, hence the current in the formula is the lightning current. For the vast majority of lightning strikes (95%), the lightning current is less than 100 kA. Considering this as a worst case, the calculated critical separation distance for 100 Ω-m and 1000 Ω-m soil is 8 m and 14.8 m, respectively. Where the soil resistivity is between 100 and 1000 Ω-m, then Equation 1 will produce the largest r value which should be considered the critical separation distance for preventing a lightning arc.

A more recent paper by Mousa,[2] determined a more conservative calculation of the distance that a lightning arc could occur between a transmission tower and a pipeline. Mousa based his calculations on case studies and a more detailed investigation of the properties of breakdown in soil. He also determined that an ionized zone would develop around the tower electrode, and that the arc would initiate from the edge of this zone (i.e. the maximum arc length is the distance from the edge of the ionized zone around the electrode to the pipe).

According to Mousa, the separation ($X - A'$) between structures is calculated as (Equation 3):

$$X - A' = \frac{GPR}{E_b} \tag{3}$$

In the above, GPR (Ground Potential Rise) is calculated as shown in Equation 4:

$$GPR = \left(\frac{I \times \rho \times E_0}{2 \times \pi}\right) \times 0.5 \tag{4}$$

where:
I = magnitude of the lightning current in amperes
ρ = soil resistivity in Ω-m
E_o = Breakdown voltage (V / m)

Resulting in Equation 5:

$$X - A' = \frac{\left(\dfrac{I \times \rho \times E_0}{2 \times \pi}\right)^{0.5}}{E_b} \tag{5}$$

The Canadian Electricity Association[(2)] (CEA) report 239T817 – *Powerline Ground Fault Effects on Pipelines*[3] describes the tests that were conducted to determine the voltages required to sustain a lightning initiated arc to a pipeline through various soil types over a range of distances. The test results were used to develop a regression formula (Equation 6) giving the critical voltage to sustain a lightning initiated arc as a function of the separation distance in native soil:

$$V_S = 5.801 + 0.0703D \tag{6}$$

where:
D = separation distance (cm)
V_S = tower voltage rise (kV)

The CEA performed similar testing to determine the flashover distance assuming that there is no lightning initiated arc. The test results were used to develop both linear regression (Equation 7) and geometric regression formulas (Equation 8) to determine the critical flashover voltage to initiate and sustain an arc due to flashover (i.e. not lightning initiated) in native soil as a function of the separation distance in cm. Note that the geometric regression Equation 8 provides more accurate results than the linear regression formula when the tower voltage rise is low (i.e. less than 20 kV), but provides unrealistic results at higher voltages.

$$V_{flash} = 18.01 + 0.1082D \tag{7}$$

$$V_{flash} = 8.086D^{0.3056} \tag{8}$$

where:
D = separation distance (cm)
V_{flash} = tower voltage rise (kV)

As there is not enough energy in lightning to cause damage to the pipe wall, the Sunde or Mousa equations should only be used to determine which CEA equation is applicable. If the pipeline and tower grounding separation distance is less than the critical distance for a lightning arc, and there is a risk of a lightning initiated arc, then Equation 6 (for sustained arc) should be used to determine the critical separation distance. If there is no risk of a lightning arc developing, then Equation 7 and/or 8 (for flashover) should be used to determine the critical separation distance.

DISCUSSION OF MITIGATION MEASURES

Mitigating the Risk of Arcing

If the separation distance between the pipeline and any grounded part of a high voltage powerline structure is found to be less than the critical separation distance, then mitigation is required.

Although moving of an existing pipeline or powerline tower is the best technical solution, it is typically not feasible due to the high costs involved. However, there are some other types of mitigation that can be considered.

[(2)] Canadian Electricity Association (CEA), 275 Slater Street, Suite 1500, Ottawa, Ontario, Canada K1P 5H9

Some of these involve modifications to the powerline, such as moving or removal of a ground electrode on a wooden pole to increase the separation distance to the pipeline, or improving of the tower grounding, which would result in a lower resistance to ground and a corresponding reduction in the tower voltage rise. Another option could be to shield the portion of the pipeline that is “too close” to the tower using a dielectric material, however this would have the negative side-effect of also shielding the pipeline from cathodic protection current. One “shielding” approach that could be considered would be to install a sealed dielectric casing (such as high density polyethylene (HDPE)) around the pipeline in the vicinity of the tower and fill it with gel to minimize the risk of water entering the casing and causing corrosion. It is unknown how well the seal and gel would hold up over time, so this section of pipe would need to be monitored on a regular basis to ensure that it is not corroding inside the casing.

A third approach is the installation of screening electrodes alongside the pipeline on the tower side of the pipeline. The purpose of the screening electrodes, as schematically illustrated in Figure 3, is to intercept the arc and thereby shield the pipeline and coating from the harmful effects of an arc fault.

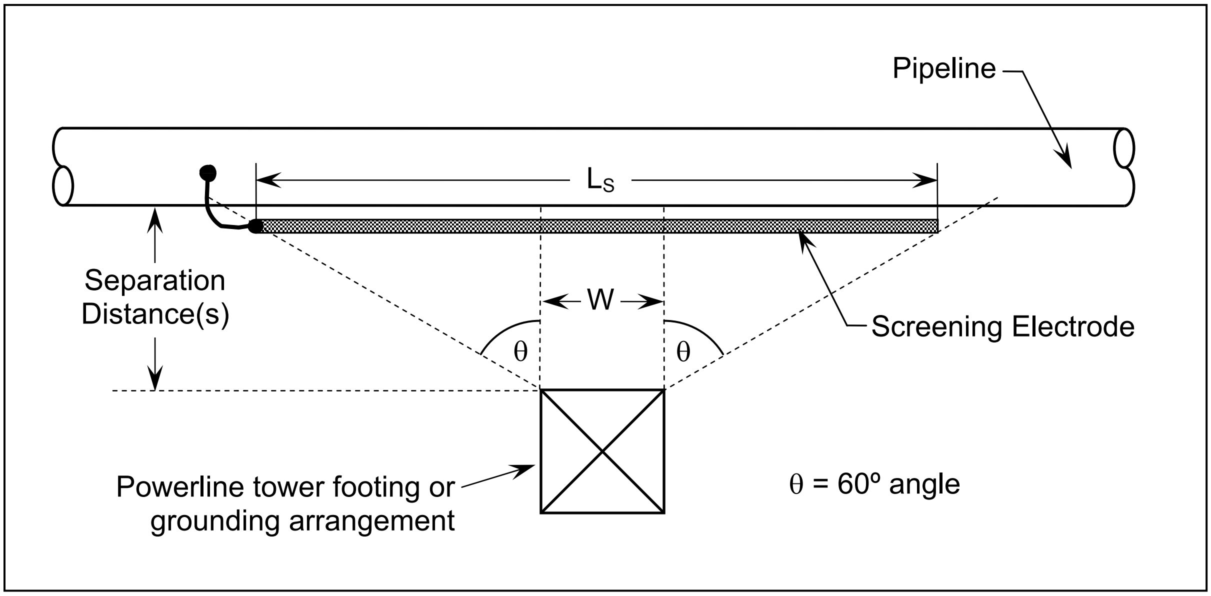

Figure 3: Screening Electrode Arrangement at a Powerline Tower to Prevent Arc Damage and Coating Damage to the Pipeline

The screening electrode should be centered on the centerline of the tower and about 1 m from the pipeline and extend a distance beyond the width of the tower for a total distance (Ls) as calculated in Equation 9.

$$Ls = 2 \times \left(1.73 \times S\right) + W \quad (9)$$

where:
Ls = total length of screening electrode arrangement (m)
S = separation distance between the pipe and tower or grounding system (m)
W = width of tower footing or grounding system

The screening electrode can be composed of a non-galvanic material, such as copper cable, connected to the pipe through a DC decoupler or directly, if the screening electrode is composed of packaged zinc anodes or a zinc ribbon surrounded by sulfate rich backfill. When individual packaged electrodes are used, the end-to-end spacing between them should not exceed their individual length. The individual packaged zinc anodes can be connected to an insulated header cable to reduce the number of connection points to the structure. If the zinc screening electrodes are located where the existing pipe-to-soil on-potential is more electronegative than -1100 mV_{CSE}, then they should be connected through a DC decoupler, so that the zinc electrodes do not pick-up cathodic protection current.

Unfortunately, under fault conditions, there are downsides to installing screening electrodes. It would increase the risk of an arc developing, as the screening electrodes are bare metal and installed closer to the powerline structure, and therefore a much more attractive path for the arc than a coated pipeline. Due to the low resistance path, more fault current would be transmitted along the pipeline, upstream and downstream from the fault location, than would be without the screening electrodes. The resulting concern about distributing a shock hazard along the pipeline and increasing the risk of flashover to other crossing structures or across insulators must be assessed before adopting screening electrodes.

Installation of screening electrodes directly connected to the pipe will require the use of coupons in order to facilitate the measurement of true polarized pipeline potentials. When screening electrodes are connected via a DC decoupler, true polarized pipeline potentials can be determined either via the use of coupons or by extending the off cycle when interrupting all influencing current sources.

CASE STUDY: ARCING INVESTIGATION PROGRAM

General

Pacific Gas and Electric Company[†] (PG&E) is one of the largest combination gas and electric utilities in the United States. The company provides natural gas and electric service to approximately 15 million people covering a 70,000-square-mile (181,300 km^2) area in northern and central California.

The company operates over 6,400 miles (10,300 km) of gas transportation pipelines and 42,000 miles (67,600 km) of natural gas distribution lines, as well as, 18,616 miles (29,959 km) of electrical transmission lines and 141,215 miles (227,264 km) of electrical distribution lines.

In 2012, the utility implemented a proactive program to investigate and mitigate the risks to its existing pipeline infrastructure from AC interference due to paralleling and proximate high voltage transmission lines, as required by the Code of Federal Regulations (CFR) 192.467(F). This program includes assessment of safety and AC corrosion risks under steady-state and fault conditions, as well as, an assessment of the risk or arcing from a nearby powerline structure.

Arcing Risk Assessment Program

The identification and assessment of locations exhibiting an arcing risk involves a three-tiered approach.

Tier 1.

Utilizing the Geographic Information System (GIS), all locations where the separation distance between a pipeline and a transmission line structure is less than 25 ft (7.6 m) (with an appropriate buffer to account for accuracy) were identified. The 25 ft (7.6 m) criterion is based on PG&E Standard 068177 Overhead Transmission Line Design Criteria, which incorporated known worst case soil resistivities and fault duties in their system.[4] The assessment identified 7,041 sites requiring further investigation. The sites were further prioritized based on whether they were located in High Consequence Areas (HCA) and whether the GIS locations had sub-meter accuracy, which reduced the total to 905 sites. Of these sites, 500 sites were selected for further investigation under Phase 1 of this program. This included 300 sites with the smallest separation distance and 200 sites that were selected based on other criteria.

† Trade name.

Tier 2.

This stage involves performing a site survey, obtaining the required powerline data and calculation of the required critical separation distance to minimize the risk of arcing of identified Phase 1 sites.

The site survey includes the following measurements:

- Measure the actual separation distance between the tower grounding and the pipeline, either via use of a pipe locator or by excavating and measuring.
- Measure the soil resistivity at the site to 100 ft (30.5 m) depth.
- Measure the resistance of the tower grounding using the 3 pin test (only to be performed if there are no shield wires or counterpoise on the line).
- Structure number

The powerline data would then be obtained, including the following:

- Powerline circuit voltage and name
- Phase-to-ground fault current (line maximum or for specific structure)
- Shield wire data (typically no shield wires)
- Structure grounding details

The site survey and powerline data was then used to determine whether the pipeline was inside or outside of the arcing distance. As there is still some contention in the industry on what approach to utilize in order to establish the critical separation distance to avoid an arc, a conservative approach was utilized ensuring that both the Sunde and CEA equations were satisfied.

The following approach was used to determine whether there is a risk of arcing:

1. Calculate the voltage rise of the tower using the fault current and the resistance of the tower grounding system.

2. Calculate critical separation distance to avoid a lightning arc using Sunde Equations 1 or 2 with a lightning current of 100 kA.

3. If there is a risk of a lightning initiated arc, calculate the critical separation distance to avoid a sustained arc using the CEA Equation 6 and the calculated tower GPR.

4. If there is no risk of a lightning initiated arc, then calculate the critical flashover distance using the CEA Equations 7 (tower GPR greater than 20 kV) and 8 (tower GPR less than 20 kV).

5. If the calculated critical separation distance is less than the actual separation distance, there is no risk of fault arcing. If not, further analysis (Tier 3) and possibly mitigation would be required.

6. Calculate critical separation distance using Sunde Equations 1 or 2 using the powerline fault current and soil resistivity measured at the site (for reference).

Upon completion of Phase 1, a statistical analysis will be performed to re-evaluate the identified locations in Tier 1, and then to incorporate lessons learned to prioritize the remaining locations.

Tier 3.

Tier 3 involves design of the mitigation measures to minimize the risk of arcing and further calculations and modeling, if required. If there are any above grade pipeline appurtenances in proximity to the tower, modeling would need to be performed to determine whether there is a safety risk to personnel or the public during a fault, due to the GPR at the tower and due to induced AC voltages on the pipeline. A gradient control grid or other mitigation measures may be required to protect personnel and the public from unsafe touch or step potentials.

Results

By August 2013, 185 of the Phase 1 sites had been assessed. Of those 185 sites, the measured separation distance exceeded the critical separation distance to avoid an arc at 111 locations (60%). However, at 74 locations the pipeline was found to be located within the critical separation distance and further analysis and possibly mitigation will be required.

Wooden pole structures with minimal or no grounding accounted for the majority of the locations where the critical separation distance was not exceeded (45 locations), while only 29 locations were due to proximate steel towers. In summary, 46% of the locations with wooden poles and 33% of locations with steel structures did not meet the critical separation criteria to avoid an arc.

Mitigation

If the separation distance between the pipeline and grounding of the transmission tower is less than the critical separation distance to avoid an arc, then further assessment and possibly mitigation is required. As the majority of transmission lines in the area are owned and operated by the same utility that operates the gas pipelines, several mitigation options that involve modifications to the powerlines were available, which may not always be the case. Selection of the optimal mitigation strategy is typically site specific, but generally would follow the approach summarized below:

1. If the powerline structure is a wooden pole with ground rods, the ground rods should be removed or moved to a location that is beyond the critical safe separation distance.

2. If the powerline structure is an ungrounded wooden pole, ground rods should be installed on the pole at a location that is beyond the critical separation distance.

3. If the pipeline is within a meter of the tower footing, it is recommended that the pipeline be moved to a distance beyond the critical separation distance. This assumes that moving the pipeline is an economically feasible option.

4. If the power utility is agreeable, install additional grounding (i.e. such as a deep ground well) connected to the tower to reduce the voltage rise of the tower and reduce the critical safe separation to a value that is less than the actual separation distance.

5. Install an HDPE casing around the pipeline in the area extending beyond where the actual separation distance is less than the critical distance. The casing should be sealed and filled with gel to prevent moisture from entering and causing corrosion. The carrier pipe will be shielded from the cathodic protection system and should be monitored to ensure that water does not enter the casing and that the pipe is not corroding.

6. As a last resort, screening electrodes could be considered to intercept the arc. However, this approach is not recommended as it will increase the probability of an arc developing and in the event of an arc will result in the transfer of high fault voltages along the pipeline. These transferred voltages could pose

risks to personnel and CP equipment, as well as foreign pipelines and other facilities. Modeling would need to be performed to assess these safety risks. Installation of dead-front test stations and grounding grids at nearby above ground appurtenances to protect personnel from unsafe touch potentials, as well as, additional mitigation measures to protect isolation flanges and cathodic protection equipment from damage, may be required.

PILOT MITIGATION SITE

General

A site in California was selected as the pilot site for the first arcing risk investigation and mitigation system design. As shown in the site map in Figure 4, tower 009/068 of a 230 kV transmission line was located inside of the valve station in close proximity to station piping, above grade valves and the station fence. The subject powerline has no shield wires.

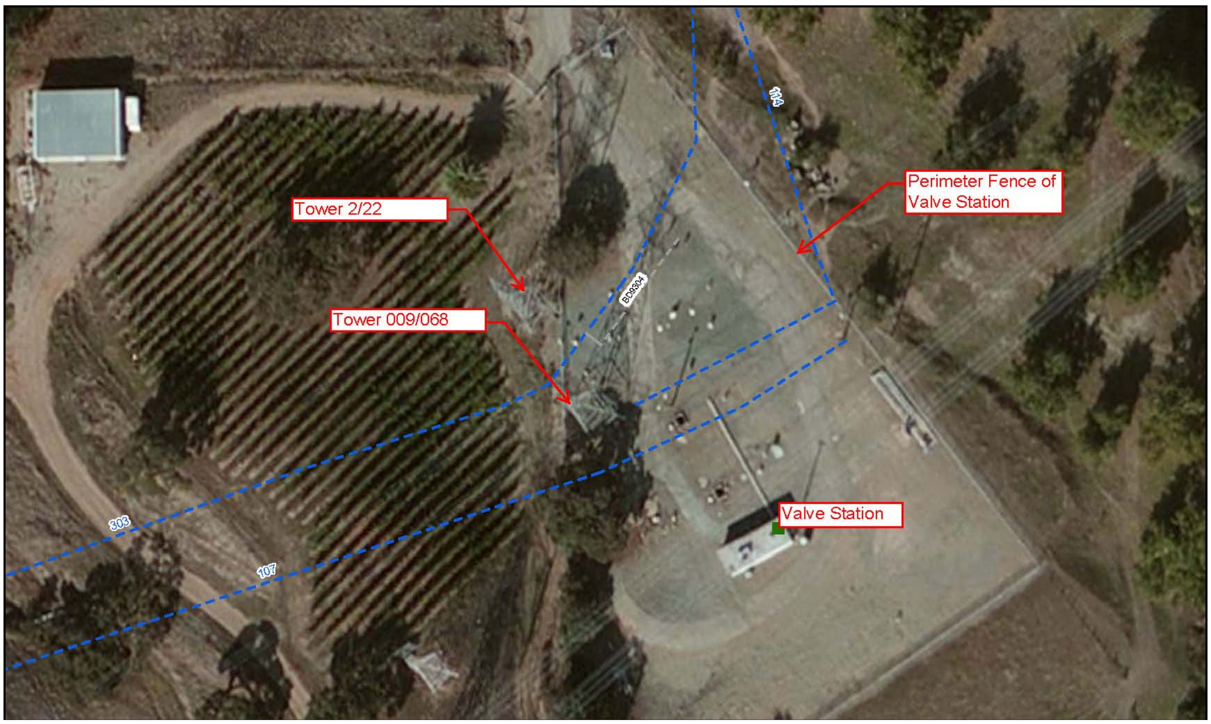

Figure 4: Pilot Site Map

Procedure

All of the piping in the vicinity of tower 009/068 was excavated and the separation distances to the closest tower footing were measured. Soil resistivities were measured using the Wenner 4-pin method around the yard up to 20 ft depth (6 m). The tower grounding resistance was measured using a 3-pin test.

Powerline and pipeline data was received and reviewed. The critical separation distance to avoid an arc was calculated for the subject tower, following the approach outlined under Tier 2 of the Arcing Risk Assessment Program.

Additional soil resistivity measurements were taken up to 100 ft (30.5 m) depth in order to design the required mitigation system.

Results

The distances to the piping in proximity to the tower are summarized in Figure 5. An NPS 4 blow-off line was found to be only 19 in (48 cm) from the closest footing, and an above grade blow-off valve only 56 in (142 cm) away. The separation distance between the NPS 20 mainline and the closest footing was found to be 65 in (165 cm), and between the NPS 24 transfer line routed between the tower legs and the closest footing was 84 in (213 cm). The station fence was located approximately 48 in (122 cm) from the closest footing.

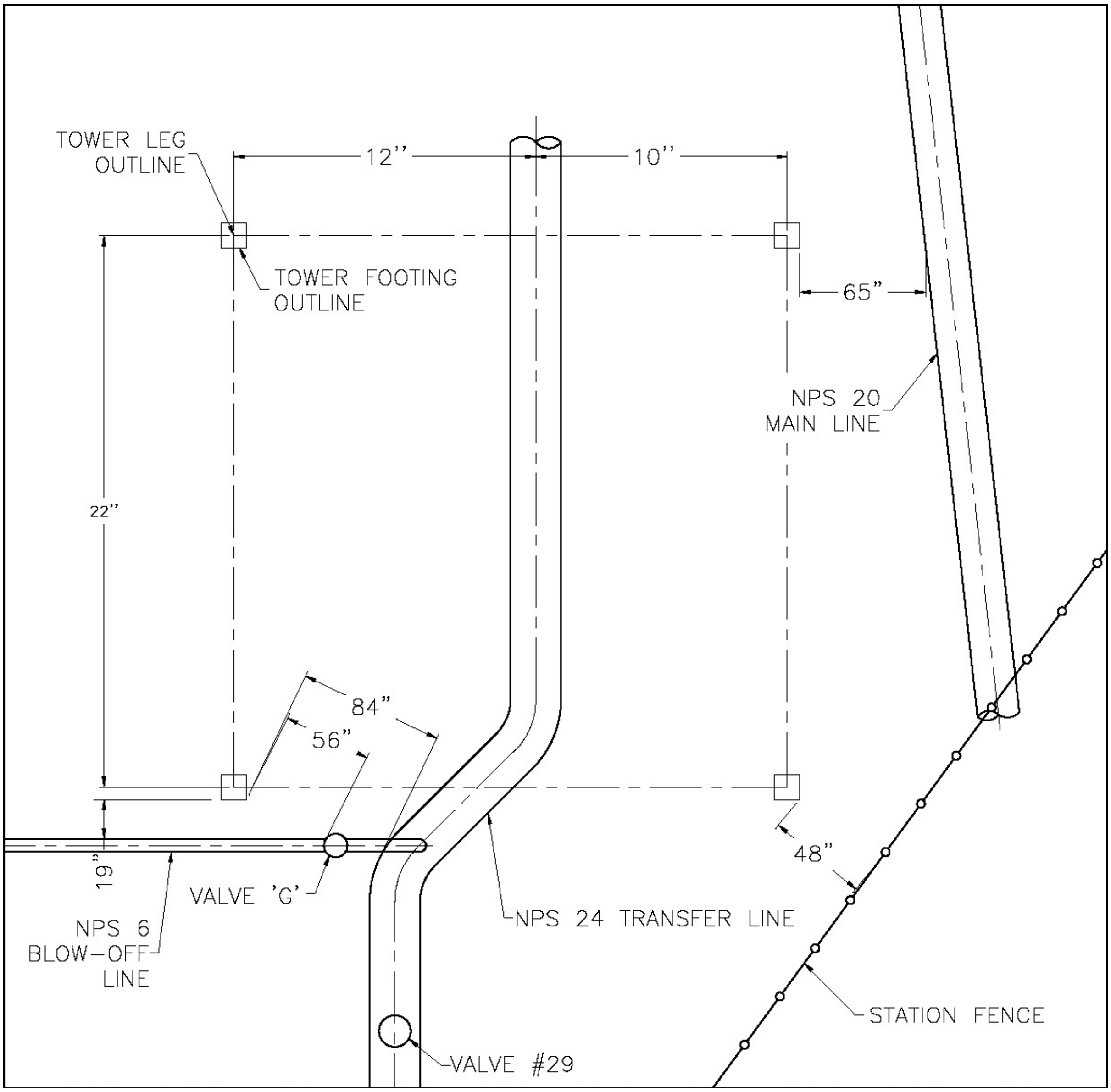

Figure 5: Piping Layout Sketch

The site survey data and a summary of the critical distance calculations are provided in Table 1. Based on the Sunde equation and a lightning current of 100 A, a lightning arc distance of 28.8 ft (8.81 m) was calculated. As such, the critical separation distance was calculated using the CEA equation for a sustained arc, resulting in a distance of 21.9 ft (6.7 m). The powerline arcing distance using Sunde (i.e. inserting the powerline fault current in the Sunde equation) was also calculated for reference. As all three of the adjacent pipelines, and the station fence are well within the critical arcing distance, mitigation measures were required.

Table 1
Summary of Arc Distance Calculations at Pilot Site

Pilot Site - Calculation Summary	
Transmission Line Voltage (kV):	230
Tower ID:	009/068
Tower Resistance (ohms):	3.4
Soil Resistivity (ohm-m):	122.8
Bolted Fault (kA):	17
Adjusted Fault (kA):	15.6
Tower Voltage Rise (kV)	52.6
Sunde Lightning Arc Distance (ft)	28.8 (8.8 m)
CEA Distance – Sustained (ft):	**21.9 (6.7 m)**
Sunde Powerline Arc (ft):	11.9 (3.6 m)

Mitigation

Due to the close proximity of the blow-off line (19 in (48 cm)) to the tower leg, the only viable option was to move the line to a location providing a clearance to the tower of better than 8 to 10 ft (2.4 to 3.0 m).

Once the blow-off line was removed, the closest remaining line was the NPS 20 mainline, with a separation distance of 65 in (165 cm). It was recommended that the risk of arcing to the mainline and the other remaining lines, be mitigated by installing additional grounding connected to the tower, thereby reducing the tower resistance. Calculations indicated that installation of a 1.0 ohm groundbed would allow a pipe-to-tower separation distance of as little as 5.2 ft (1.6 m) (assuming a lightning initiated arc).

An additional consideration in the selection of the mitigation approach was that the tower is located inside a pipeline station. A fault at the tower would result in unsafe touch potentials at above grade equipment inside the station, including the station fence and the tower itself. To ensure personnel safety at the site, the touch potentials were modeled using specialized software and the mitigation system designed to ensure they remain below acceptable limits as defined in IEEE(3) Standard 80 "Guide for Safety in AC Substation Grounding".[5]

The final mitigation design is summarized below:

- Remove and relocate the NPS 6 blow-off line maintaining a minimum distance of 8 ft (2.4 m) from the tower footings.
- Install a 100 ft (30.5 m) deep ground well a minimum of 150 ft (46 m) away from the station
- Connect tower 009/068 to two additional adjacent towers (2/22 and 2/21) and to the deep ground well. Grounding resistance of the system would be less than 0.85 ohm resulting in a critical separation distance of 4 ft (1.2 m).
- Replace the metal station fence within 10 ft (3.005 m) of the tower with non-metallic fencing to minimize the risk of arcing and unsafe touch potentials at the fence.
- Install a non-metallic fence around the tower to minimize the risk of unsafe touch potentials at the tower.
- Install an insulating layer of crushed stone (6 in (15 cm) thick) or asphalt (3 in (7.6 cm) thick) across the entire station extending 3.3 ft (1.091 m) outside of the perimeter fence.
- Install DC decouplers across any isolation flanges inside the station to protect the isolation flanges from mechanical damage and to ensure electrical continuity in AC between all piping inside the station.

(3) Institute of Electrical and Electronics Engineers (IEEE), Three Park Avenue, 17th Floor, New York, NY 10016

SUMMARY AND CONCLUSIONS

The risks and consequences related to an arc developing to a pipeline due to a fault at an adjacent tower are discussed. Calculations to determine the arcing distance for lightning, for a sustained arc and a flashover arc are summarized and a procedure for determining the critical distance is proposed.

The equations developed by Sunde (Equations 1 & 2) and Mousa (Equation 5) are utilized to calculate whether there is a risk of a lightning arc to the pipeline from an adjacent tower. If the pipeline is located within this lightning arc radius, then the CEA regression formula for a sustained arc (Equation 6) should be used to determine the critical distance to avoid a sustained arc. If the pipeline is located outside of the lightning arc radius, then the CEA regression formulas for flashover (Equations 7 & 8) should be used to calculate the critical distance to avoid a flashover arc.

Recommended mitigation measures for existing pipelines and powerline structures, are typically site specific and need to also consider the potential safety risks to personnel and other infrastructure related to transfer of high AC voltages to the pipeline. In most cases it is not feasible to move the pipeline or powerline to a location outside of the critical distance, and other mitigation options such as improved grounding of the powerline structures, the use of dielectric shields around the pipeline, or possibly the use of screening electrodes to intercept the arc need to be considered.

An extensive arcing risk assessment program is summarized. Over 185 locations have been assessed to date, with 74 identified as being at risk and possibly requiring mitigation measures. The procedure and results of the assessment performed at the pilot project site are discussed in detail, including the mitigation measures that were designed and have been partially implemented.

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