GBX Response to REX-009 Attachment 05

CANADIAN ASSOCIATION
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Canada's Oil and Natural Gas Producers

GUIDE

Influence of High Voltage DC Power Lines on Metallic Pipelines

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Overview

This guide provides members with a comprehensive resource to assist you in evaluating the electromagnetic influence on your pipelines presented by an adjacent HVDC power line. The guide introduces the operating principles of the HVDC system, contrasts it with AC system behaviors and introduces a screening guideline for gauging impact upon pipeline facilities.

Note 1: This version of the guideline applies ONLY to the two new HVDC transmission line projects in Alberta (ATCO Electric (EATL) and AltaLink (WATL)). Use in other situations, configurations, or projects is outside of the scope of this guideline.

Additional guidance and support for the use of this guideline by pipeline owners and their consultants is available from AltaLink and ATCO Electric, see below.

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2. AltaLink – Liang Jiao, (403) 267-2175, liang.jiao@altalink.ca; David Mildenberger (403) 267-3458, david.mildenberger@altalink.ca

Note 2: Revisions to this document are expected over the next few months as experience with the guideline increases. Please contact your applicable electrical utility and/or the CAPP HVDC Committee to ensure that the latest version the guideline is being used.

Figures

1 Project Scope

The interaction between AC power lines and metallic pipelines is the subject of national standards [1] and guidelines [2] that together cover both analysis and mitigation issues. There appears to be no similar guideline for HVDC lines, especially those being proposed for the province of Alberta. This document is focused upon the EATL (Eastern Alberta Transmission Line) and WATL (Western Alberta Transmission Line) HVDC lines currently being constructed.

While the same electrical coupling mechanisms apply to both AC and HVDC lines, there are also significant response differences between them and by understanding steady state and fault phenomena that can arise within HVDC systems a proper approach to their analysis in the context of electrical coordination with metallic pipelines can be carried out. The purpose of this guide is to introduce HVDC systems with particular focus upon lines being built in Alberta, provide sufficient background information, and to provide users of this guide a systematic approach in dealing with analysis and mitigation aspects of HVDC system influences upon metallic pipelines. Both similarities and differences with AC lines are emphasized within this guide. It should be emphasized this guide only applies to land based HVDC systems that do not utilize ground electrodes for steadystate DC ground currents as may arise due to specific operating conditions. Section 2 will provide more elaboration on this operational aspect.

The CIGRE[1] guideline [2] though dedicated to AC lines is a comprehensive reference with many sections allowing the development of simple calculation and measurement methods. The complexity of the HVDC interaction unfortunately precludes simple calculation methods and must really be approached with sophisticated computer software such as the SES[2] CDEGS suite of software. Nevertheless, the CIGRE Guideline is a valuable reference and many of the analytical concepts carry over to DC line application.

[1] CIGRE - Conseil international des grands réseaux électriques (International Council on Large Electric Systems)
[2] SES – Safe Engineering Services & Technologies Limited

1.1.2 Inductive Coupling

Inductive or magnetic coupling occurs whether the pipeline is buried or aerial. Depending upon the degree of parallelism, induced voltages can be in the kV range during fault conditions for AC lines. For HVDC lines, under fault conditions, the collapse of the current can lead to high momentary induced voltages.

Unlike AC lines, under steady state conditions, the HVDC line induced voltages tend to be negligible, with only the potential to cause telephone interference problems. Therefore under steady state conditions there are no pipeline integrity issues (neither corrosion nor coating related issues) nor shock hazards.

1.1.3 Conductive Coupling

The discharge of current through the grounding electrode at the tower can lead to a ground potential rise, GPR, in the vicinity of the faulted tower. With a current discharge, a voltage gradient exists in the soil around the tower relative to a remote earth. An insulated pipeline in the vicinity of the tower's potential gradient will experience a voltage across its insulating coating due to the difference between the pipeline (near zero voltage relative to a remote earth) and voltage rise in the adjacent soil. If high enough, the voltage stress could puncture the insulating coating possibly damaging the pipeline.

During HVDC line fault conditions, a ground current will also arise but a number of factors make this situation fundamentally different from AC faults. The current distribution factors are different for HVDC. This will be discussed in Section 2.0.

1.2 Impacts to Pipeline

The effects of any electrical disturbance upon the pipeline may be categorized as:

- Safety Problems
- Damage to Pipeline coating
- Damage to metal
- Damage to insulating flanges
- Damage to equipment connected to the pipeline

Safety issues are shock hazards to people who may come in contact with the pipeline. The danger increases as the intensity of the current increases along with its duration. For HVDC faults both the magnitude and duration of the event tend to be shorter than an AC event. Though less severe, the safety assessment requires a different interpretation of existing standards.

1.3 How to use this Guide

To assist in the usage of the guide, the process workflow starting from identification of pipeline/HVDC line interaction to eventual decommissioning of the pipeline (or HVDC line) is illustrated in Figure 1. A typical sequence would be:

1. To start the process accurate location (Section 9.1) of the affected utilities must carried out by either the electrical utility or pipeline owner.
2. The affected parties then meet to discuss the project. At this stage, the preliminary screening guideline (Section 7.6) could be applied to assess the severity of the interaction. The project could end at this stage if it is agreed the interaction poses no coating integrity or safety issues. Agreement that no action is required is documented between the electrical utility and pipeline owner.
3. If the preliminary screening suggests potential problems, an assessment study needs to be carried out by a qualified consultant. More details of this process are presented in Section 8 of this guide.
4. The need for mitigation (if any) would be the main deliverable of the study. The model developed can then be used to assess the effectiveness of different mitigation options. The final report should present a recommended mitigation plan that meets the objectives at least life cycle cost.
5. After acceptance of the mitigation plan, cost allocations are finalized and an implementation schedule is agreed upon. The user's typical project process ensues along with the development of safe work procedures to be applied during construction, operation and maintenance of the pipeline.
6. After successful commissioning of the facilities, the facilities are maintained till final decommissioning of the pipeline or the HVDC line is no longer in service. Management of change processes also have to be included to ensure that when changes to the HVDC system or pipeline systems are implemented no unmitigated hazards are present.

2 HVDC Fault Currents

2.1 HVDC System Description

In this section, a short description of the HVDC system is presented along with a detailed description of the different line fault modes.

Older HVDC systems tended to be comprised of two terminal stations and a single interconnecting line[4]. Full wave rectifiers convert the source voltage from AC to DC for transmission and full wave invertors convert DC back to AC. These systems tended to be of bipole configuration, comprising of a positive pole and a negative pole while using ground as a neutral return for any unbalance current. If the positive pole voltage were at +500 kV, then the negative pole would be at -500 kV, and a loop current not involving ground would flow. If a ground fault occurred with the positive pole, its fault current would flow to ground prior to detection and blocking. The negative pole would continue to operate (as a monopole) using ground as a return[5]. At each station, a ground electrode (up to 1 km in earth surface diameter) was needed for collecting the ground return current during either monopole or bipole operation. With normal bipole operation an unbalance current up to 5% of rated current[6] could flow. Ground electrode location was crucial since it was desirable to keep surface gradient currents to a minimum over most of the line to avoid corrosion issues with other infrastructures.

The proposed Alberta HVDC lines will not be utilizing ground electrodes. Instead an overhead return conductor, DMR (Dedicated Metallic Return) will be used to carry any unbalance current or return current under monopole conditions hence no stray DC current flows through ground under normal conditions. Figure 2 depicts the simplified schematic layout for the HVDC system in its stage 1 development. The EATL system has the longer line length of 500 km, whereas the WATL line is approximately 350 km. There is no connection between the EATL and WATL systems other than indirectly through the underlying AC system backbone.

In stage 1, monopole operation will occur with the DMR line typically in parallel with the negative pole. In stage 2, a second convertor will be added on each end to allow bipole operation. The DMR would only carry the steady state unbalance current under this configuration. Only the rectifier end will be grounded, leaving the inverter floating[7]. The HVDC system is capable of bidirectional control and under some circumstances the terminals can switch roles. Rated load current for both the EATL and WATL systems is 2000 Adc.

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[4] The vast majority of HVDC installations are still of this type

[5] This mode of operation had a time limit of typically 30 minutes for land based systems

[6] For a rated current of 2000 Adc this would amount to 100 Adc of ground injection

[7] The invertor end is grounded via a surge capacitor for lightning protection purposes – DC currents are blocked

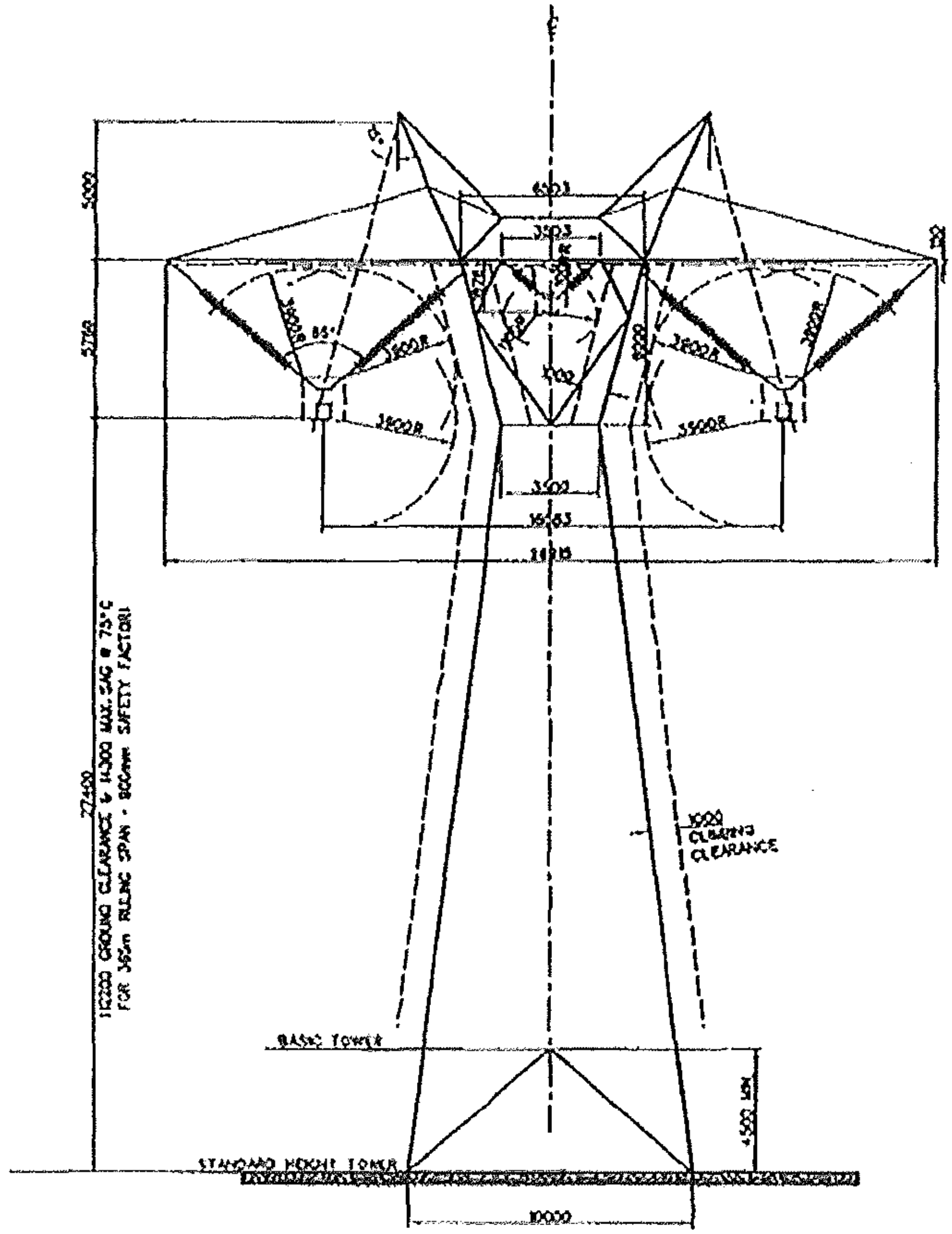

Figure 3 EATL and WATL Tower Design

2.3.1 Fault Current Comparison AC versus DC

In the DC fault case there is no fault contribution from the inverter end whereas in an AC fault, contributions can arise from both ends. In Figure 2, the DC current can only flow in one direction due to the rectifier/inverter characteristics. For comparison purposes each simulated fault is fed from only a single source, also the AC fault magnitude was set near the DC fault peak value. Results are shown in Figure 4 and Figure 5 for the back flashover event.

The initial step in fault current is similar for both cases. The first wave reflection from the source bus returns in 211 μsec for the AC fault and 240 μsec for the DC fault.

The reflection coefficient at the DC rectifier terminal is more complex due to the DC filter and some control action occurring later in the event but the two responses are initially very similar which from the pipeline perspective cannot be differentiated, the initial induced voltage spike will be similar. The initial conducted GPR will also be similar. It is only after the first 2 msec that the DC nature of the fault manifests. In the CIGRE Guideline [2], the initiating event leading to power frequency fault current is not discussed nor is the initial AC transient, the focus is more on the quasi-steadystate nature of the fault current. Due to the multi-frequency nature of the HVDC current, this initial transient will be part of the analysis but if an analogy with an AC system is made, only the tail voltage beyond the initial step change would normally be considered.

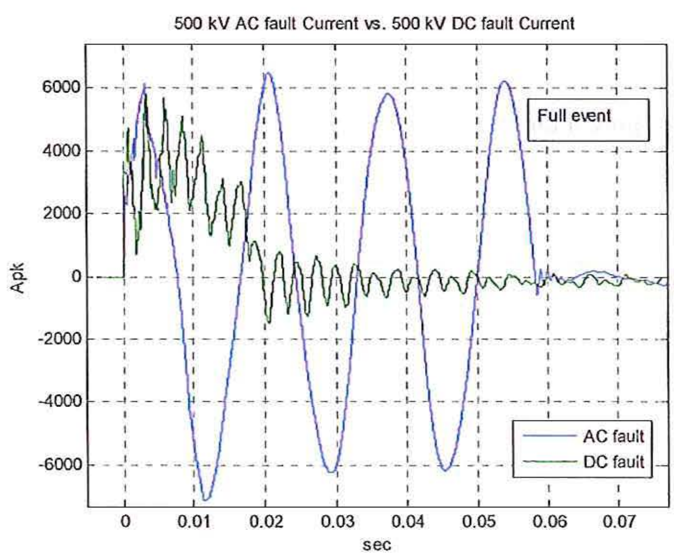

Figure 4 AC/DC Fault Current Comparison

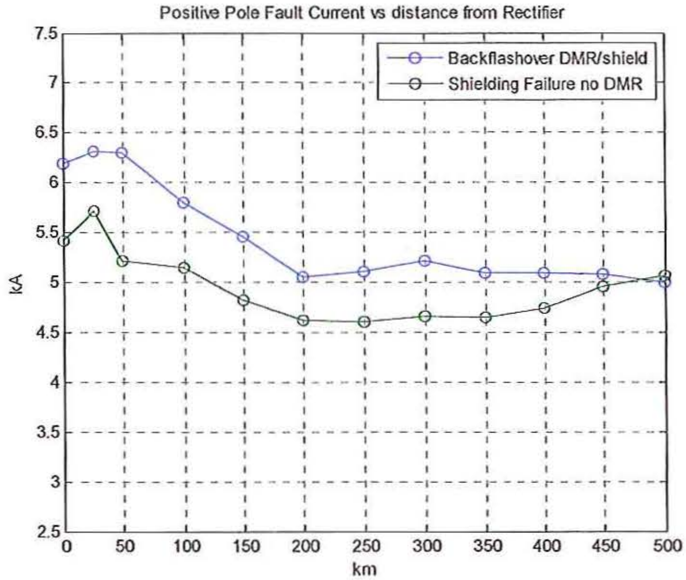

Figure 6 Peak Fault Current versus Fault Distance for BF and SF Faults

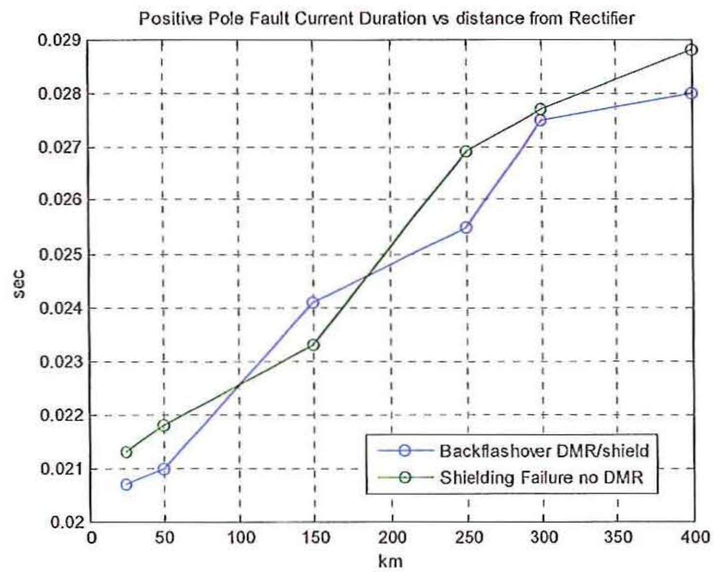

Figure 7 Fault Duration versus Fault Distance for BF and SF faults

2.3.2 Response to Back Flashover Faults

Any stroke of sufficient magnitude to the tower top/shield wires will lead to a back flashover of the DMR well before a potential pole conductor flashover. A sustainable DMR only flashover will introduce an additional ground point causing some DC current flow to earth for a short time till the DMR fault is detected, leading to a link shutdown and restart. The DC current injection is low due to the unfaulted negative pole conductor path. A much larger stroke would lead to both DMR and positive pole conductor back flashovers (Figure 55). The current paths are shown in Figure 9 for both monopole and bipole operation. Though the currents in the vicinity of the faulted tower are depicted, the conductor connections at the line end points are highlighted. The shield wires are continuously grounded at each tower.

In Figure 9(a), unlike an AC fault, the ground path is not necessarily the main path. In the HVDC case, a large fraction of current can return to the rectifier station via the DMR causing a decrease in the ground current. This has two important consequences:

- The ground current is reduced leading to a lower GPR
- The return current conductors act to limit the inductive coupling to the pipeline due their screening effect.

Also since the DMR and negative pole conductors are paralleled, the loop current becomes a superposition of the fault current with the negative pole current. In the bipole case Figure 9(b) the situation is similar. The negative return current commutates to the DMR. The DMR current back to the rectifier is the vectoral sum of the negative return current, and the portion of fault current not going to ground. It should be noted that the magnitude of the positive pole fault current is the same as the monopole case, but the induction to the pipeline will be different due to the screening effect of the negative pole circuit.

In Figure 4 the only source is the rectifier, upon shorting out the rectifier, there is no infeed from the inverter terminal. The location of the HVDC tower fault relative to the parallel pipeline becomes important; i.e. a tower fault point before the parallel (closer to the rectifier) will have a lower inductive coupling to the pipeline as opposed to a point at the end (or downline) of the parallel (further away from the rectifier). Of course, if the rectifier and inverter operations are interchanged, the reverse would be true. Fault points in the middle of the parallel will tend to have the maximum instantaneous coating stress voltage values.

returning via the DMR as a function of fault distance from the rectifier terminal is shown in Figure 10 where a uniform soil resistivity of 100 ohm-m is assumed.

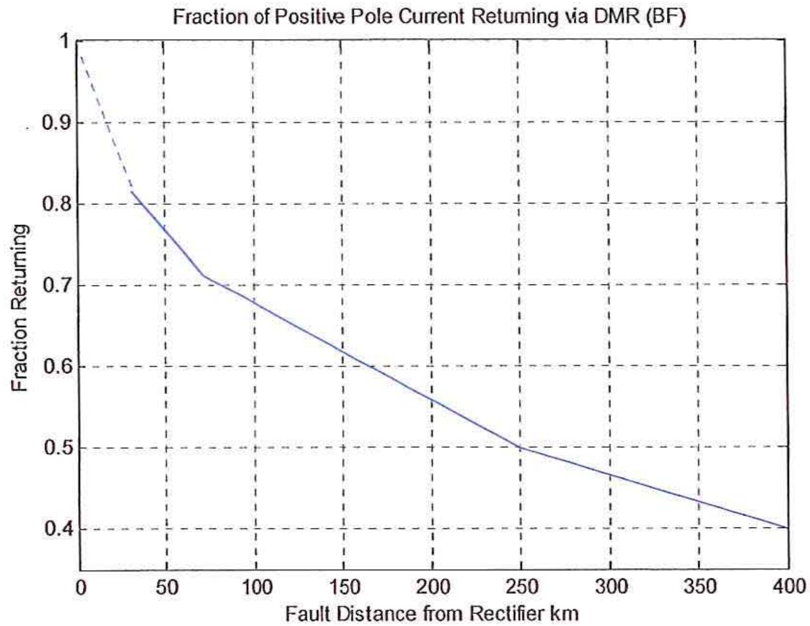

Figure 10 Fraction of fault current returning to Rectifier via DMR

In Figure 10, for a fault 75 km from the rectifier terminal 70% of the fault current will return via the DMR conductor. By contrast, for an AC fault >80% of the fault current returns via ground at a distance of several km from the source terminal, and with two sources, there is division of ground current between the two sources. For DC faults close to the rectifier, the GPR will be low, and for faults close to the inverter end, a significant fraction of current still returns via the DMR relative to the AC line case. In both the AC and DC cases, low tower footing impedance(s) will assist in minimizing the GPR at the faulted tower.

It is important that the software used in the analysis of HVDC faults be able to properly represent the ground return current. The results in Figure 10 were derived in EMTPRV[9].

2.3.4 Shielding Failures

A shielding failure occurs when a low intensity lightning[10] stroke bypasses the shield wire and terminates upon the pole conductor (Figure 55). With AC lines, shielding failure rates can be computed using EGM (Electro Geometric Model(s)) as detailed in [5]. The EGM has been refined over the years with recommended approaches given in both IEEE[11] and CIGRE. In reference [6] an attempt is made

[9] EMTPRV – Electromagnetic Transients Program Restructured Version – EPRI DCG (Electric Power Research Institute's Development and Coordination Group)

[10] A stroke typically in the 3 – 20 kA range

[11] IEEE – Institute of Electrical and Electronic Engineers

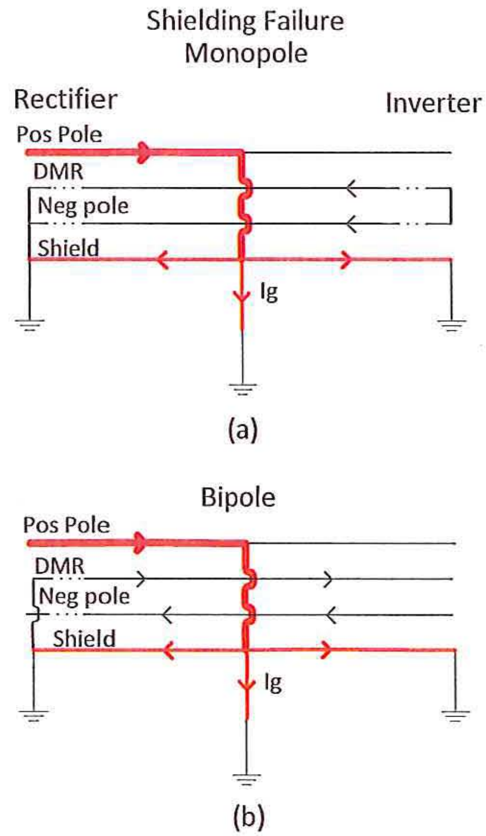

Figure 11 Current Paths - Shielding Failure

In the shielding failure mode, most of the fault current goes to earth. When considering shielding failures at a specific location, the utility must be consulted to provide the typical tower footing impedances and the DC pole fault current associated with a shielding failure at that location.

2.3.5 Ground Current Distribution Factors for Shielding Failures

As discussed in Section 2.3.4, the ground fault current at the stricken tower will equal the pole fault current less the currents being shunted to the adjacent towers via the shield wires. Inductive coupling is also affected since under monopole conditions only the currents in the shield wires will provide any screening.

2.3.6 DMR out of Service

Though the DMR is expected to be in service under monopole transmission, there may be times where it might be advantageous to have it disconnected at each end, and run the link with only the negative return conductor. In this situation the back flashover scenario becomes identical to the shielding failure scenario under fault conditions. It is more likely however that one end of the DMR would be grounded. If grounded at the invertor end, the backflashover scenario remains identical to the shielding failure scenario. If grounded at the rectifier end, the

Under line fault conditions, the natural frequencies of the HVDC line are excited which tend to be in the 300 Hz range. In Figure 12, at 1 km, the coupling strength at 300 Hz has become asymptotic at less than 5% of its initial value. Existing AC standards suggest any parallel further away than 300 meters need not be considered. Figure 12 suggests at 300 Hz, the limit would be 200 meters to have the same effect all other factors being equal.

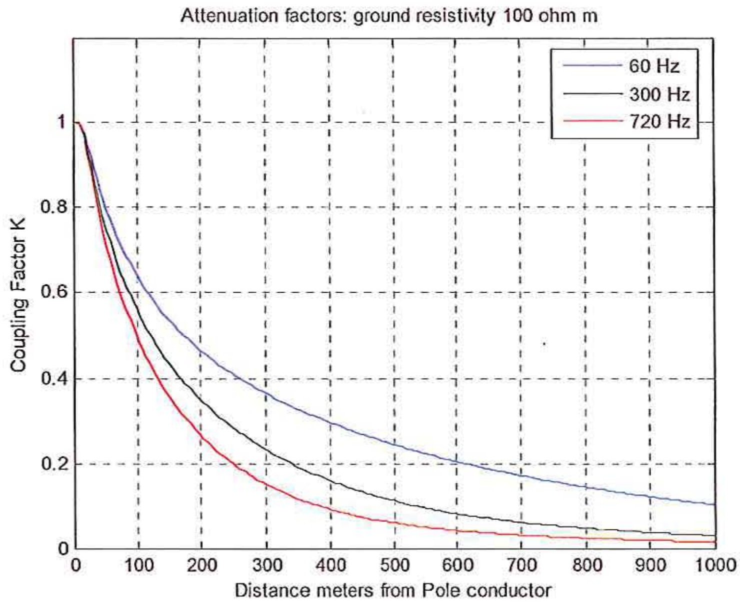

Figure 12 Decrease in magnetic coupling factor with pipeline distance

3.3 Exposure Length

For pipeline parallels, the induced voltage tends to increase linearly with exposure length up to a few kilometers depending upon pipeline coating. Beyond a few kilometers, the conductance of the coating causes the voltage to increase at a less than linear rate [2]. The higher the quality of the coating resistance, more linear the rise will be. The induced voltage due to HVDC line faults will follow a similar pattern.

At the transfer point, $R_{coating}$ goes to zero and the pipe voltage is limited by R_e and Z_{pe}. In reality the soil structure is more complex and sophisticated grounding software is needed to evaluate the soil potential at the pipe. In addition, an induced voltage may also be present on the pipeline which typically adds to the stress level across the coating.

If R_e were zero, this would imply an arc due to soil ionization. This is considered unlikely since the spacing between the pipeline and tower footing would have to be very small for a power frequency discharge [2]. A lightning discharge has the ability to ionize the soil but the ionized zone has been found to only extend a few tens of cm from the tower electrode. It is further usually assumed the lightning discharge would have dissipated by the time the power frequency or DC pole current discharge commences. In this regard the 10 m spacing recommended in [1] should be more than adequate for the DC fault levels anticipated.

Ontario Hydro (now Hydro One) carried out staged faults in the early 1980s upon transmission towers in order to determine the surface voltage gradients that would occur in practice. Reference [7] discusses a sequence of measurements made upon some 765 kV and 500 kV AC towers along with comparison to SES's MALT program. The findings were the type of tower foundation greatly impacts the GPR as one moves away from the tower leg. Some of the results from [7] are reproduced in Figure 14. Pertinent information when considering the results:

- To approximate the measured result, the analytical study used a two layer soil model for the AEP tower: top layer 20 meters with 40 ohm-m resistivity, bottom layer 200 ohm-m. Similarly for the Klienburg tower, a two layer model with top layer 15 m thick with 30 ohm-m resistivity and bottom layer resistivity of 100 ohm-m. The measured footing impedances for the Ontario Hydro and AEP towers are shown in Table 2.
- In Figure 14 the distances were measured radially from the tower footings which were either bonded to ground rods or to rebar in concrete caissons.
- Though the percent drop with rebar is less with distance compared to rods, the actual GPR is less for the same distance compared to having only rods due to the lower footing resistance (Table 2). As an example if the ground current were 3 kA and the GPR at 25 meters is to be estimated for the Klienburg tower:

  GPR with rebar (3 kA) (1.41 ohms) (.250) = 1.057 kV

  GPR with rods (3 kA) (2.77 ohms) (.18) = 1.495 kV
- The Klienburg tower had the most uniform soil conditions but was only measured out to 10 meters. The AEP tower with poorer soil conditions was measured out to 30 meters. Extrapolation is based upon slope of AEP data.
- AEP data based upon rods.

Calculation is based upon procedures presented in reference [8]. The H pile (mutuals) curve represents the effect of calculating each corner electrode resistance individually and then using a mutual correction term [5]. The other curves treat the 4 electrodes as a single entity. Figure 15 shows footing resistance difference between installing caissons or H piles is small provided they penetrate the same depth.

Part of the HVDC line commissioning procedure is measuring of the footing resistance at each tower with a target value of less than or equal to 10 ohms[15]. Early results indicate values in the 1.0 to 9.0 ohm range with median value of 5 ohms. Based upon Figure 15, it would appear the median soil resistivity lies within a range of 200 to 300 ohm-m, however given the lengths of the HVDC lines, the line commissioning measured footing resistances (seasonally adjusted) in the vicinity of a crossing or parallel should be utilized in any simulations.

Figure 14 highlights that the soil voltage gradient drops very quickly with distance from the tower footing. Since the footing impedance is mainly resistive, a similar variation with higher frequency current components is expected. This resistance is also constant for the frequency range applicable to the HVDC fault condition. As an example, if the footing resistance is 3.5 ohms and the ground fault current is 4 kA pk, then the GPR at 25 meters (edge of the ROW) would be (0.25)(3.5)(4) = 3.5 kV pk. The low NACE[16] voltage RMS coating limit is 3 kV RMS or 4.25 kV pk (see Section 6.2). This result suggests pipelines passing as close as 25 meters to the tower footing are not at risk as far as coating stress is concerned due solely to the transferred GPR, however induced voltage effects would still have to be factored into the assessment.

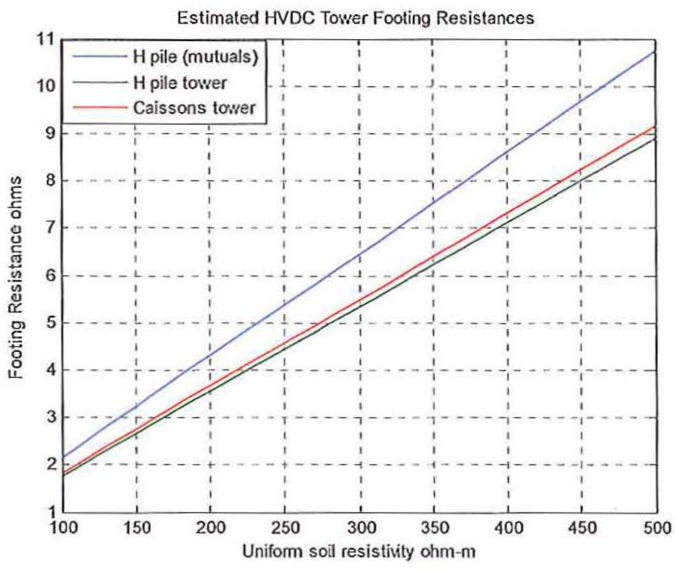

Figure 15 Estimated HVDC Tower Footing Resistance

[15] If greater than 10 ohms, mitigation is applied to reduce the resistance
[16] NACE – National Association of Corrosion Engineers

Parametric studies of pipeline coating thickness, pipeline diameter, and coating resistivities suggest smaller diameter pipelines with highly resistive coatings present the least electrical loading to the power line, which lead to the highest induced voltages. In Figure 16, tower 1 is closest to the rectifier terminal.

The worst case overvoltages occur when the tower fault occurs at the mid parallel point (tower 3 or 4) or at tower 7.

In Figure 17, a comparison of the EMTPRV output and the output from SES's Multi Fields program is displayed (induction only).

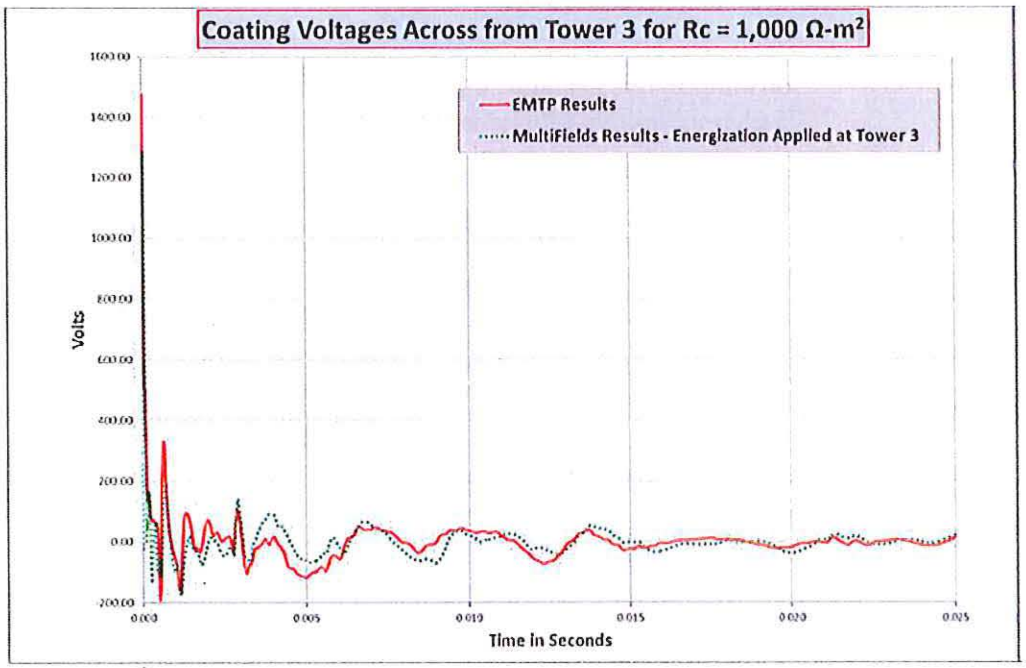

Figure 17 SES CDEGS output compared to EMTPRV output

The two results are very similar but there are some differences. Of note:

1. The initial spike is due to the step change in current at the beginning of the fault. As discussed, this initial transient would be common to either an AC or DC fault. In terms of magnitude it is the dominant feature.
2. Beyond the initial spike, a lower but albeit relatively high frequency component due to wave reflections on the line manifest.
3. The low frequency ripple which makes up the bulk of the wave form reflects the natural frequency of the line transient.
4. Beyond the initial spike, the voltage doesn't exceed 330 Vpk
5. The entire event lasts only 20 msec.

6 Result Interpretation

The simulated results from the last section must be interpreted in the context of pipeline impacts discussed in Section 1.2. The first two aspects: safety and damage to the pipeline coating will be considered in detail.

6.1 Safety

6.1.1 IEEE Standard 80

IEEE Standard 80 [9] deals mainly with safety within energized substations but by necessity presents a criterion for evaluating personnel safety in the presence of electric shocks. The criterion was developed by Charles Dalziel over a period of 25 years of empirical research on both humans and animals.

The human shock hazard associated with a person touching a pipeline appurtenance (being exposed to the induced/conducted pipeline voltage, V_{cs} in Figure 13) can be estimated by using Dalziel's energy relationship for impulse shocks [10]:

$$E_{body} = \int_0^{\infty} \frac{V_{cs}^2}{R_b} dt < E_{fr}$$

Where R_b is the resistance of the human body and the minimum energy to cause heart fibrillation is given by E_{fr}. The total body resistance includes both the effects of skin impedance (which has a capacitive component) and internal resistance. The internal body resistance is 500 ohms at 60 Hz [11]. The total body resistance depends upon both contact voltage and frequency. The high frequency (> 2 kHz) approximation approaches 500 ohms.

What modern research has shown is that there is a vulnerable period during the heart cycle when disruption can lead to ventricular fibrillation (**Figure 17** in [11]). Timing of the impulse or oscillatory discharge becomes critical since the disruptive current while appearing similar in magnitude can have a shorter duration if it coincides with the heart's vulnerable period.

To simplify the shock hazard evaluation, the energy approach is approximated by equating the hazard with the RMS value of the shock current. This allows equations for step and touch potential to be derived per IEEE Standard 80 which provides two equations for tolerable body current (low risk of ventricular fibrillation (≤0.5%)):

$$I_b = \frac{0.116}{\sqrt{t_s}}$$

Dalziel for 50 kg Body Weight ($0.03<t_s<3.0$ seconds)

For unidirectional impulses, **Figure 20** in [12] applies. The *c1* and *c2* curves are continuous from **Figure 20** in [11] having the same meaning.

The two **Figure 20** curves in [11, 12] are combined and shown in Figure 19 in this guide, the IEEE 80 fibrillation thresholds have been added for reference. Note at 60 msec, the IEEE 50 kg curve becomes more stringent than the *c1* curve.

The vertical section in the IEC curve as suggested by Biegelmeier's Z curve no longer follows absorbed energy concepts but an energy relationship reappears for durations less than 4 msec.

The following procedure is recommended to estimate the shock hazard potential of body currents due to HVDC fault events:

1. The body resistance is set at 600 ohms if the highest frequency components are less than 2 kHz. For faults very close to the rectifier station this frequency adjustment may have to be adjusted but cannot be less than 500 ohms. This is a conservative approximation since shock currents are maximized.
2. The event waveform is enclosed in an exponentially decaying envelope. According to IEC 60479-2 [12] when the decay value of the envelope has reached 5% magnitude, the duration of the event waveform is defined.
3. The RMS value of the event waveform can be calculated for the decay duration defined in point (2) above, and compared to either the *c1* curve [11] or IEEE 80[9] (if duration is long enough).
4. The high initial current (within the first 4 msec) needs to be considered prior to the biphasic oscillations per IEC 60479-2[12]. The allowable charge transfer for initial duration of 4 msec per the *c1* curve is 2 mC. It is noted that an oscillatory component also exists in the waveform which further reduces the monophasic pulse when compared to IEC 60479-2. To calculate the charge transfer the instantaneous shock current $i_b(t)$ must be integrated as shown below:

$$C_{charge} = 1000 \int_0^{.004} |i_b(t)| dt \ < 2\, mC$$

If i_b is in units of amperes, the result will be in coulombs, C. To obtain mC the result is multiplied by 1000 as shown.

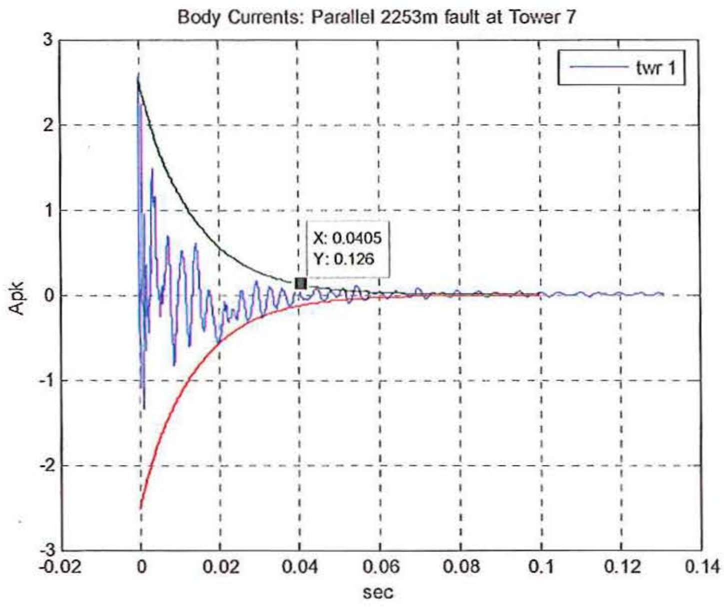

Figure 20 Induced Body Current at Tower 1 with BF at Tower 7

The first step is to determine the duration of the event using an exponential envelope as shown in Figure 20. The duration for this event is 40.5 msec (the envelope current has declined to 5% of its initial value); hence IEEE Standard 80 may be applied. The event charge transfer is shown in Figure 21.

The RMS value of the event waveform for the 40.5 msec duration is calculated along with other data and presented in Table 3. Despite the high initial peak current value, the initial charge transfer is not significant (< 2 mC). The shock hazard for this event is within acceptable limits.

Table 3 Event Summary Shock Current across from Tower 1

Event Waveform Duration (msec)	40.5
A RMS	0.414
Charge transfer initial (4 msec) mC	0.791
IEEE 80 limit Arms (for Duration) 50 kg	0.576
IEEE 80 limit Arms (for Duration) 70 kg	0.780

In Table 3 the event is safe in regard to both IEEE and IEC standards.

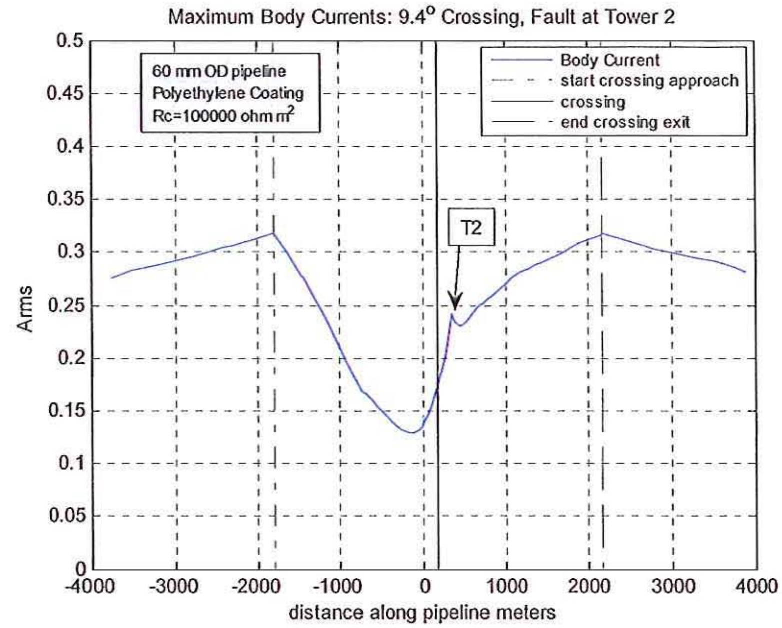

Figure 22 Estimated Induced Body Current Profile along Pipeline

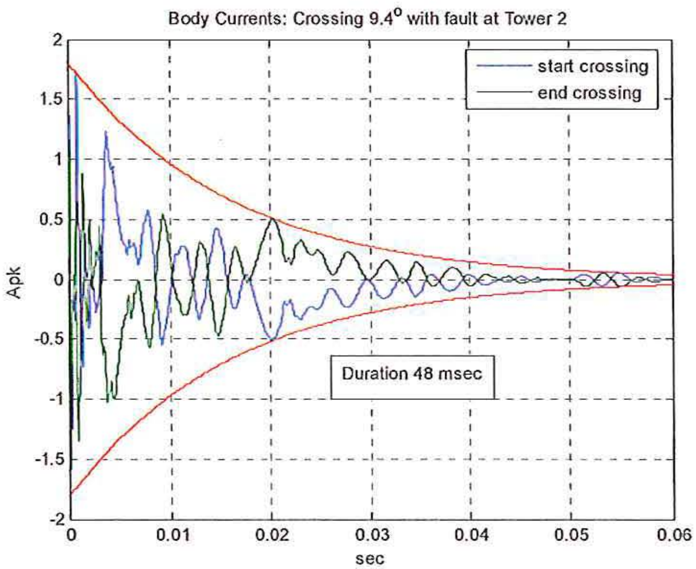

Figure 23 Induced Body Current with largest RMS value

6.2 Coating Stress

When voltage is applied to a dielectric material, the electric field applies a force on the bound electrons in the outer orbital of the atoms. At the breakdown electric field stress, a few electrons are lifted to the conduction band and quickly accelerated. Collisions with other atoms can release more electrons leading to an avalanche effect culminating in breakdown of the dielectric. Electrical breakdown is a complex phenomenon depending upon the electric field strength, geometry of the sample (thick or thin film), temperature and homogeneity (freedom from defects). When such materials are used in electrical devices, proof tests are needed to verify quality of the device. Both power frequency voltage withstand tests and impulse tests (both below the failure level) are required.

Impulse breakdown characteristic due to lightning induced transients lead to higher crest voltages being required. In general as the voltage duration is reduced, a higher voltage is needed to cause breakdown. This suggests a minimum energy requirement for breakdown to occur. The impulse ratio is the ratio between impulse voltage (Vpk) needed for breakdown over the AC voltage RMS breakdown value. This ratio can vary from 1.6 for air up to 2.5 for polyethylene.

6.2.1 Holiday Test on Pipelines

According to ASTM G62 [13] the continuous test voltage that may be applied to the pipe for holiday detection is (where T_d must be in mils):

$V_{test} = 1250\sqrt{T_d}$ Vdc $T_d > 41$ mils (1.04 mm)   (1)

Below this thickness, equation below applies:

$V_{test} = 525\sqrt{T_d}$ Vdc $T_d < 41$ mils (1.04 mm)   (2)

For a coating thickness of 30 mils (760 microns), the test voltage would be 2.87 kV DC, whereas for extruded polyethylene coatings (1.08 mm or 42.5 mils) the voltage withstand would be 8.15 kV DC.

Under DC voltage stress, the voltage grading for a composite coating will be based upon shunt resistance across each coating layer. With extruded polyethylene tending to have the highest apparent volume resistivity and thickness, nearly all the voltage drop is across this layer (>90% for high performance composite coatings).

The primary purpose of the DC test voltage in the ASTM standard is to detect voids, metal particles protruding through the coating, pinholes and thin spots. Clearly the level of detection voltage will determine the defect level of interest. A low level will only detect gross defects such as metal protrusions whereas a high test level will detect thin spots and large voids. The quality of the factory coating which was applied in a controlled environment should have withstands at least approaching the ideal AC test voltages, whereas field coating of welded joint sections will be lower.

layer were damaged are also included. Note the Paschen curve closely follows the Australian limit.

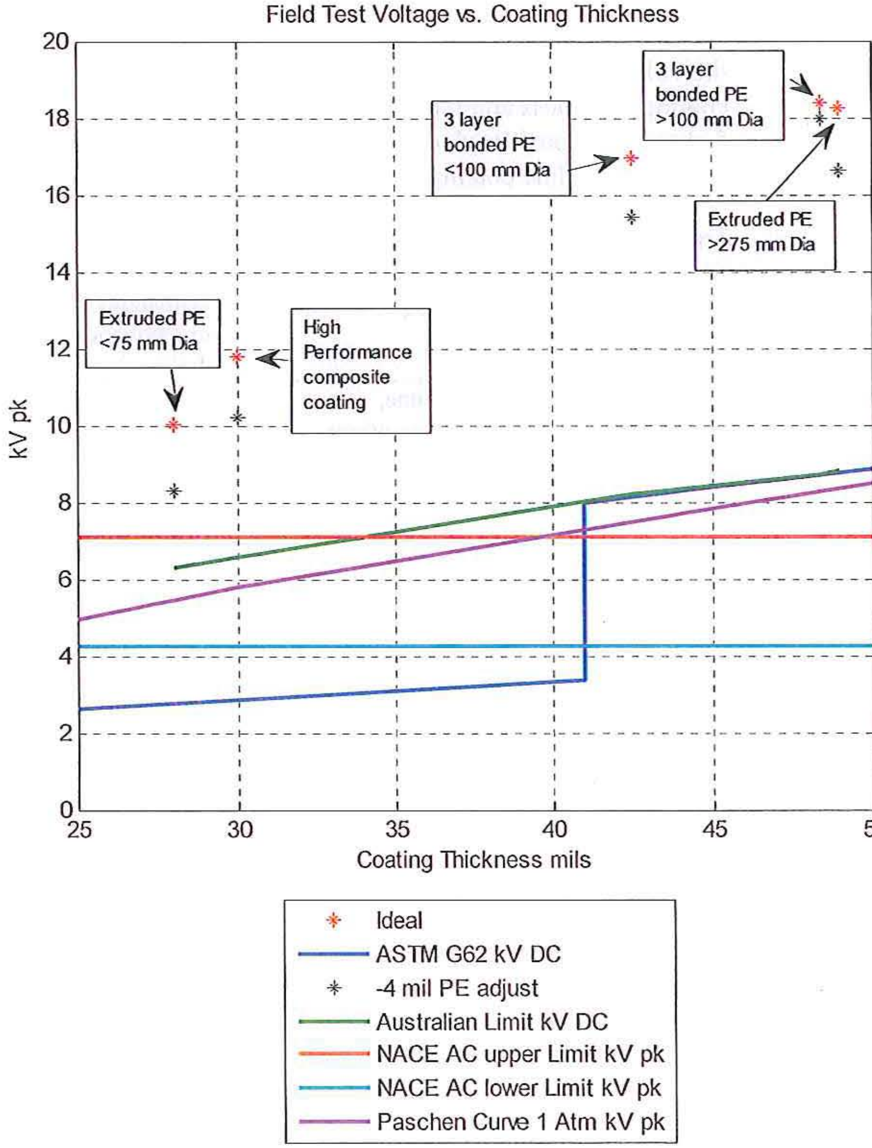

Figure 25 Comparison of NACE AC withstand limits with DC test voltages

The Australian limit exceeds the Paschen curve since any test voltage should exceed the breakdown strength of air for the coating thickness considered. Conversely, it is not clear why the lower ASTM curve (< 1 mm or 41 mils) is less than the breakdown strength of air. The upper and lower NACE AC fault limit curves appear to approximate the test voltages depending upon coating thickness.

7 Screening Guidelines

Buried pipelines behave like underground conductors in the presence of an HVDC line disturbance (fault). Buried pipelines have a certain voltage withstand limit, and in addition safety aspects arise at above-grade appurtenances. The interaction is geometry dependent, and this screening guideline differentiates between those crossing/parallel geometries requiring study from those that might be dismissed as posing no risk to the pipeline or personnel working in proximity to above-grade pipeline appurtenances.

Since the HVDC fault transient is composed of different frequencies, the magnitude of the induced voltage will display frequency dependence. In this section, these interdependencies are presented with the intent of answering how different pipe diameters, parallel lengths, crossing angles, coating qualities (thickness and resistivity) impact the induced voltage. It should be recalled that the conducted voltage tends to be a short range phenomena with GPR voltages dropping to low values at more than 50 meters from the tower footing with typical soil conditions about the fault point, whereas the induced voltage can extend over several km depending upon the relative paths of the HVDC line and pipeline. In this sense, any pipeline passing within 30 meters from a tower footing should be studied, but for induced voltages the situation is more complex, the effect of several parameters upon the induced voltage needs to be reviewed. It should be noted that any voltage constraints due to safety issues need to be more exact and stringent than those applied to coating stress evaluations.

It is impossible to cover all possible geometries and the guidelines presented are to be used with care. If in doubt, at study should be carried out. For example a dry area where tower footing resistance exceeds 10 ohms or resistivities exceed 100 ohm-m by a large margin, a study should be considered.

7.1 Parameter Sensitivities

7.1.1 Impact of Pipe Diameter

For underground pipelines the coating conductance and capacitance per unit length of pipe depend upon the surface area of the pipe which is directly proportional to the pipe diameter. The capacitance as a function of coating thickness and pipe diameter is shown in Figure 26. For pipe diameters greater than NPS 12 a FBE layer is assumed with increased permittivity relative to polyethylene (which is assumed for pipe diameters NPS 12 diameter and below). There is more than an order of magnitude difference between the smallest diameter pipe considered and the largest. If the volume resistivities for common coating materials are used, high coating resistances arise. Coating resistivities in practice appear much lower. For a given resistivity per m^2 the variation in coating resistance per meter for different pipe diameters is shown in Figure 27.

pipe coating reactance decreases with frequency, causing the higher frequency induced components to be more attenuated. An example of this is shown in Figure 28 where a NPS 24 OD pipe is compared to a NPS 2.5 OD pipe. For the larger diameter pipes, the lower natural frequencies of the HVDC line tend to be the dominant frequencies with the implication that larger diameter pipes will be insensitive to impulsive transient, leaving only the sensitivities to the lower natural frequency HVDC line transient (i.e. the tail of the waveform). This tends to explain why the initial transient is not considered in AC inductive coordination studies. In Figure 28, the coating resistivity is the same for both pipe diameters.

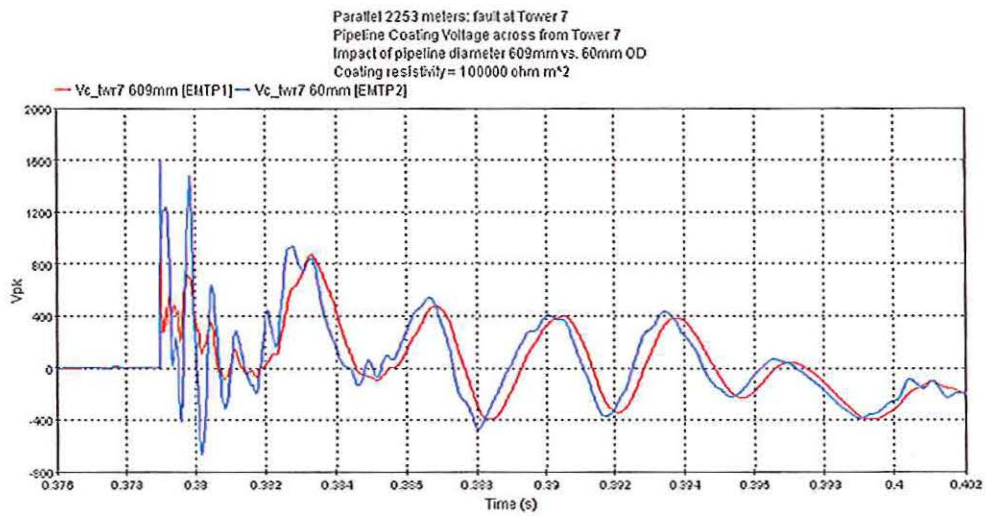

Figure 28 Impact of pipe diameter upon coating voltage (BF)

7.1.2 Impact of Coating Resistance

Lower coating resistances will have a greater impact on the damping of the induced voltage as shown in Figure 29 where the coating resistance is varied from 1000 to 100000 ohm m^2 for a NPS 2.5 OD pipe. The effect is most pronounced on the high frequency components especially the initial voltage spike.

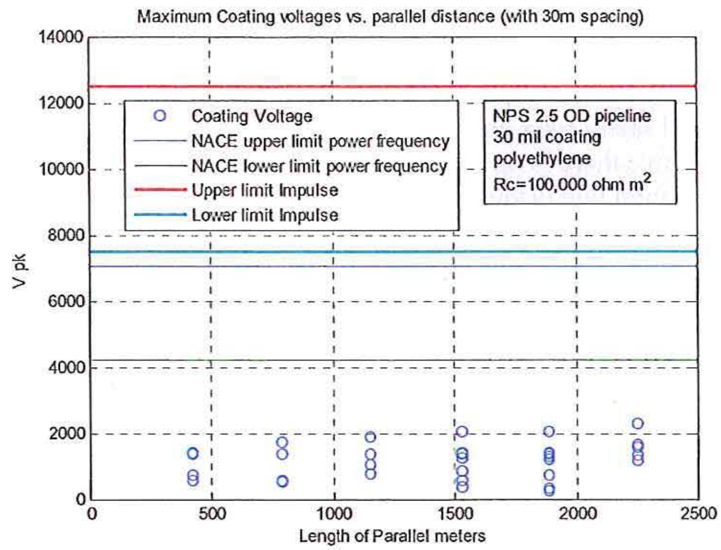

Figure 30 Peak Voltage Summary for Back Flashover Events

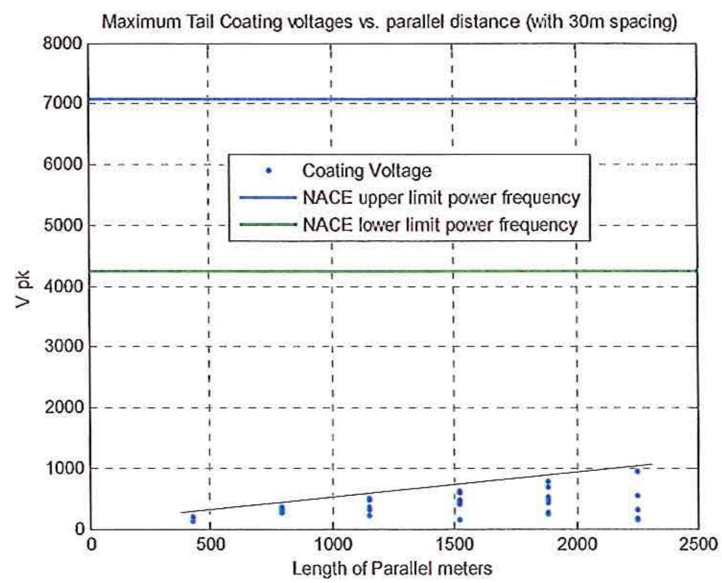

Figure 31 Tail Voltage Summary for Back Flashover Events

In Figure 31 the tail voltage tends to rise linearly with distance. Assuming linearity is maintained, the lower NACE AC fault limit would be reached in 10 km[19]. With larger pipe diameters, based upon Figure 28, the limit would be similar. For lower coating resistivities longer parallels are needed to reach the NACE limits. Similarly, a longer parallel with a larger spacing between the

[19] For the polyethylene coating assumed the upper NACE AC limit would be reached in 17 km

greater than 25° are unlikely to have coating stress or shock hazard problems except across from a faulted Tower 1 where conduction effects will dominate. As the pipe diameter increases, the transient peaks in Figure 33 would decline, becoming insignificant for NPS 24 OD pipelines and above.

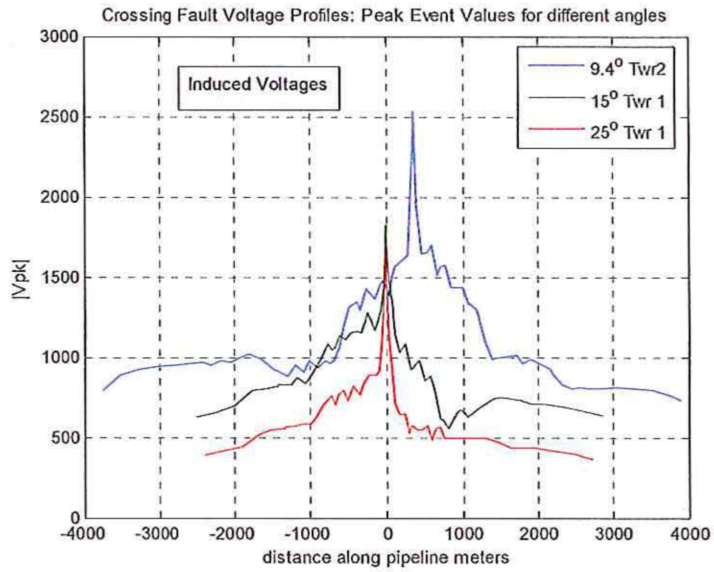

Figure 33 Peak induced Voltages NPS 2.5 OD pipeline with different crossing angles

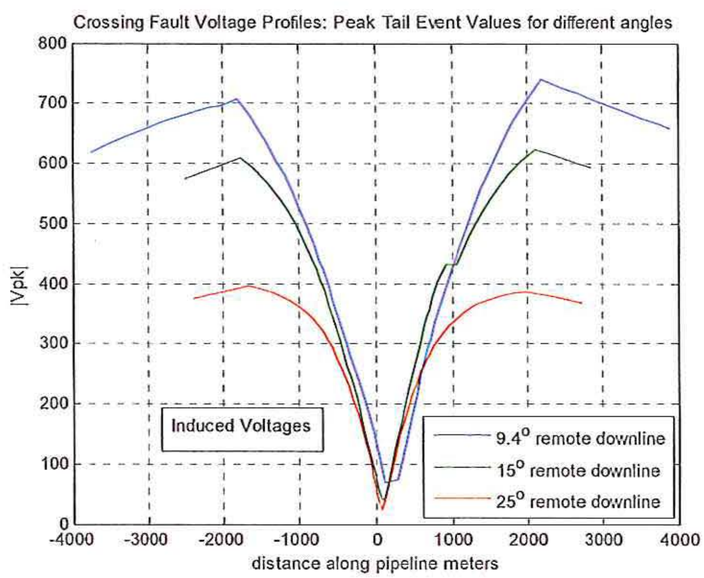

Figure 34 Peak tail voltages NPS 2.5 OD pipeline with different crossing angles

currents, assuming typical footing impedance of 5 ohms the different tower ground currents for the fault at Tower 7 are depicted in Figure 37.

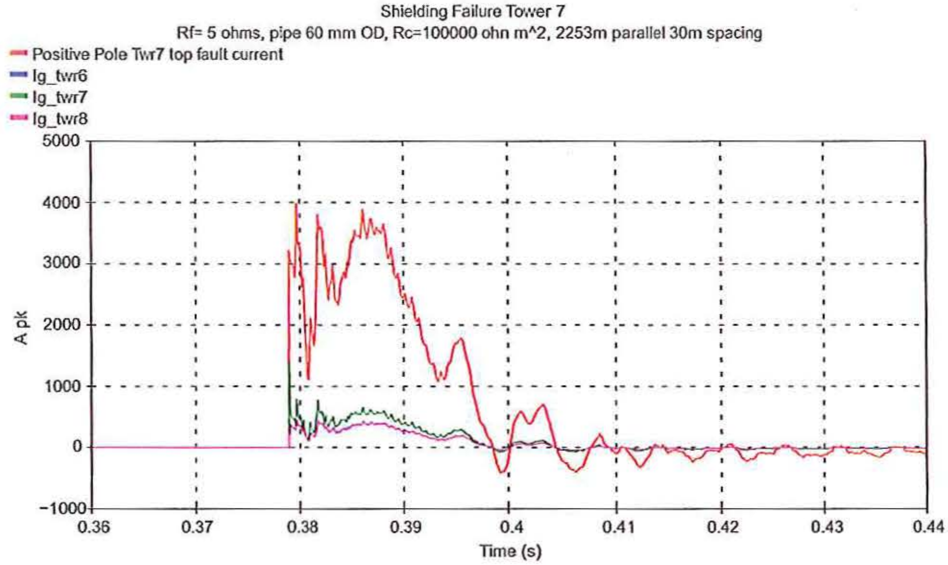

Figure 37 Tower Ground Currents - Shielding Failure

The low frequency component is discharged at multiple towers. Ignoring the initial current transient, shows only 17% if the fault current is discharged at the faulted tower with decreasing percentages at adjacent towers.

The worst case occurs when the fault is at the end of the parallel as shown in Figure 38.The lower NACE AC limit is also depicted.

The coating voltage across from Tower 1 is approximately the induced voltage. It depicts the geometric voltage rise as a function of parallel distance. Ignoring the transient voltages, there is a low frequency envelope that peaks at 940 Vpk.

The coating voltage across from tower 7 is an empirical estimate that assumes 25% of the GPR appears at the pipeline coating per the concrete caisson data provided by Figure 14. The coating stress, V_{cs}, becomes the difference between the conducted voltage, V_c and the induced voltage, V_p on the pipe as discussed in Section 4. The envelope voltage of V_{cs} is 1652 V pk which is less than the low NACE AC limit. The coating stress voltage across from the faulted tower as a function of parallel distance, x in km, where the faulted tower is at the end of the parallel, is given by:

$$V_{cs} = 0.451x + .636 \qquad \text{kV pk}$$

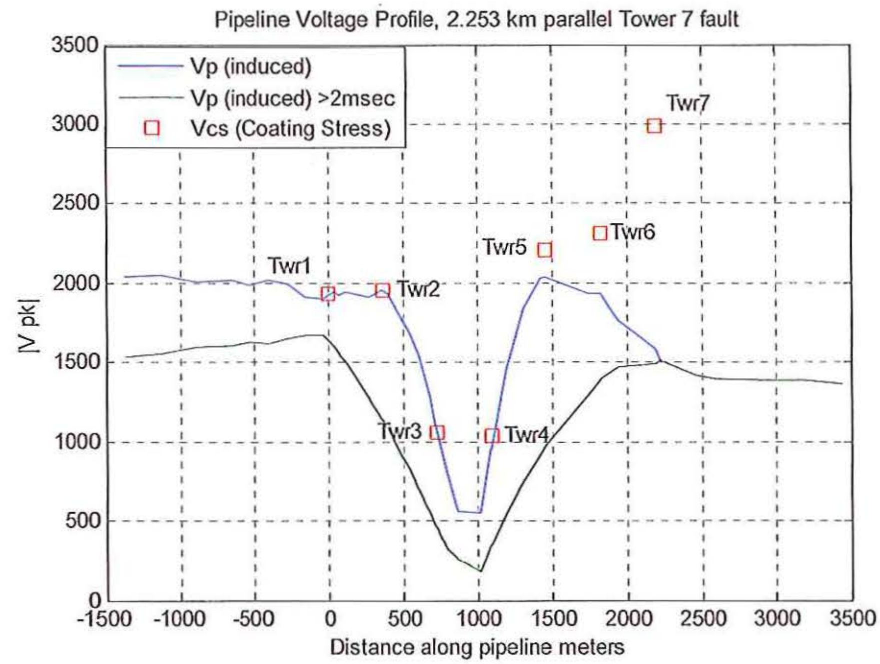

Figure 39 Pipeline voltage profile, Shielding Failure at Tower 7, 2253m parallel

In Figure 38 the initial impulse is less than the associated AC impulse limit (Table 5) of 7.5 kV pk, and beyond 1.5 cycles of the NACE AC withstand curve, the event is nearly over.

The worst initial transient voltage occurs on the pipeline directly across from Tower 3 if Tower 3 is the fault point as shown in Figure 40. The voltage peaks at 4.1 kV pk but is less than the low impulse withstand of 7.5 kV pk. For this location there is little induced voltage in the waveform i.e. $V_{cs} \sim V_c$.

The worst shock hazard tends to occur either at the start or end of the parallel as shown in Figure 41 where the measurement interval was standardized to 33 msec. For a ground fault at Tower 7, the shock current in RMS evaluated from the waveform is 0.634 Arms for a pipe location across from Tower 1, and 1.086 Arms across from the faulted Tower 7. Problems likely exist across from adjacent Tower 8 (not shown) due to symmetry with Tower 6. The IEEE 80 limit for this duration is 0.64 Arms suggesting the induced voltage exposure (since $V_{cs} \sim V_{p}$) for the 2.253 km parallel is at the safety limit across from Tower 1. The shock hazard across from the Towers 7, 6 and 8 exceed the safety limit but this result cannot be generalized since a specific hazard evaluation should entail using the SES CDEGS software. What can be generalized is that the induced voltages for any remote downline fault from the parallel will lead to induced voltages of similar magnitude.

In general, the safety criterion per IEEE 80 becomes:

$(V_{cs})/R_b < .116/\sqrt{t}$ Arms $0.03 < t < 3.0$ seconds

7.5 Minimum Crossing Angles for Shielding Failure Events

In Figure 32 four different crossing angles are displayed. The GPR effects will be the most pronounced opposite the tower closest to the pipeline. The pipeline voltage profile for the 25° crossing case is shown in Figure 42 for a SF fault at Tower 1 (30 m spacing from the pipeline). A NPS 2.5 OD pipe with a PE coating is assumed with the same characteristics as was used in the back flashover case.

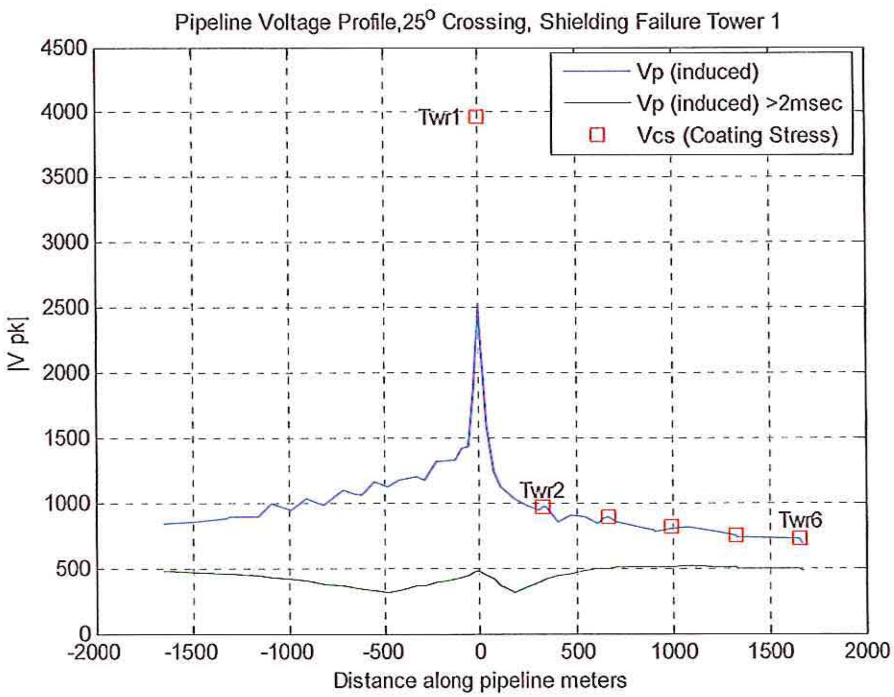

Figure 42 Voltage Profile along pipeline, fault at Tower 1 (origin), 25° crossing

The maximum instantaneous coating stress voltage V_{cs} occurs across from Tower 1 with a value of 4.0 kV pk similar to the parallel case but less than the low impulse withstand limit of 7.5 kV pk per Table 5. The coating stress voltages, V_{cs}, at the adjacent towers consist of only the induced voltage V_p. The induced tail voltage reaches its maximum value of 504 V pk near the start and end points of the crossing (at 1 km). The only location capable of supporting high instantaneous coating stress voltage is across from Tower 1. At other locations, instantaneous stresses are less than 1300 V pk and the envelope voltage is ≤504 V pk.

The coating stress waveform voltages at Towers 1 and 2 are shown in Figure 43. Ignoring the voltage transients, the envelope voltage has a peak value of 926 V pk for Tower 1 and 371 Vpk for Tower 2.

The inequality introduced in the last section is repeated below:

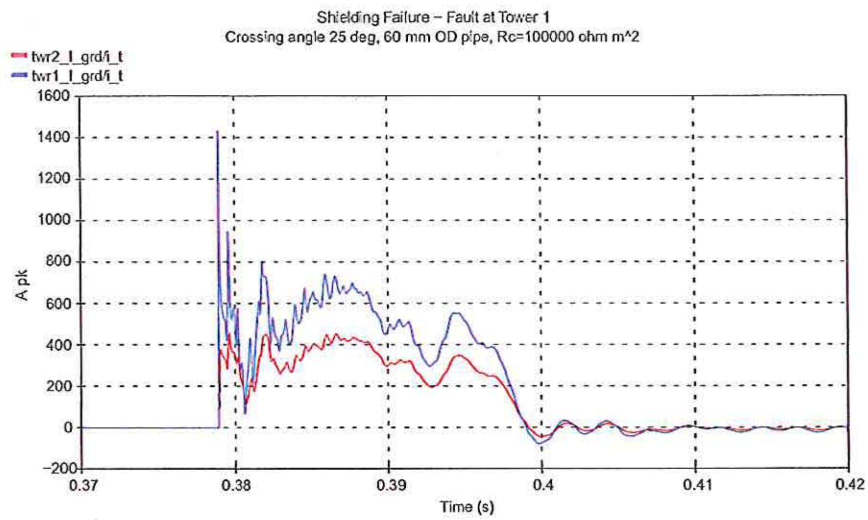

Figure 44 Tower Ground Currents Towers 1&2

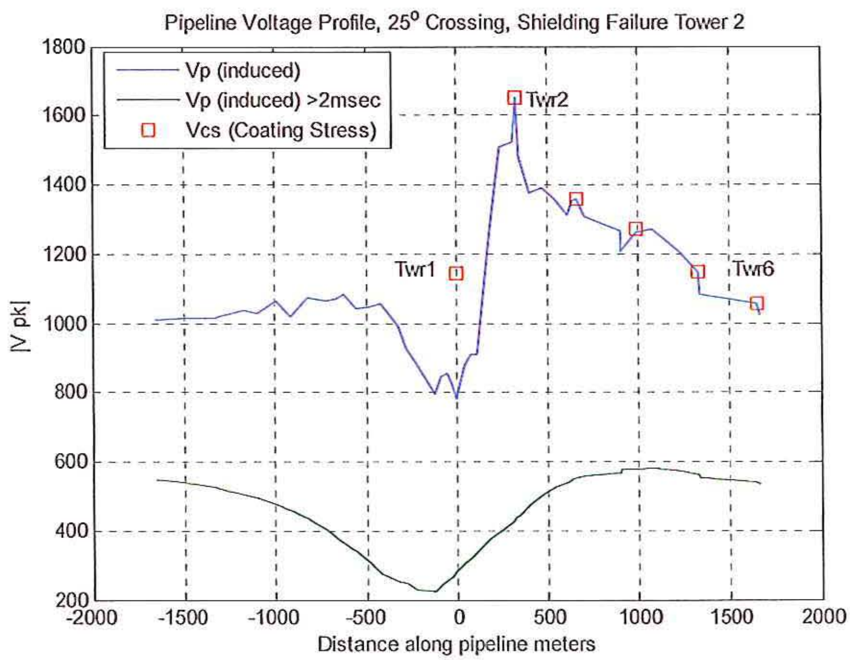

Figure 45 Voltage Profile along pipeline, fault at Tower 2, 25° crossing

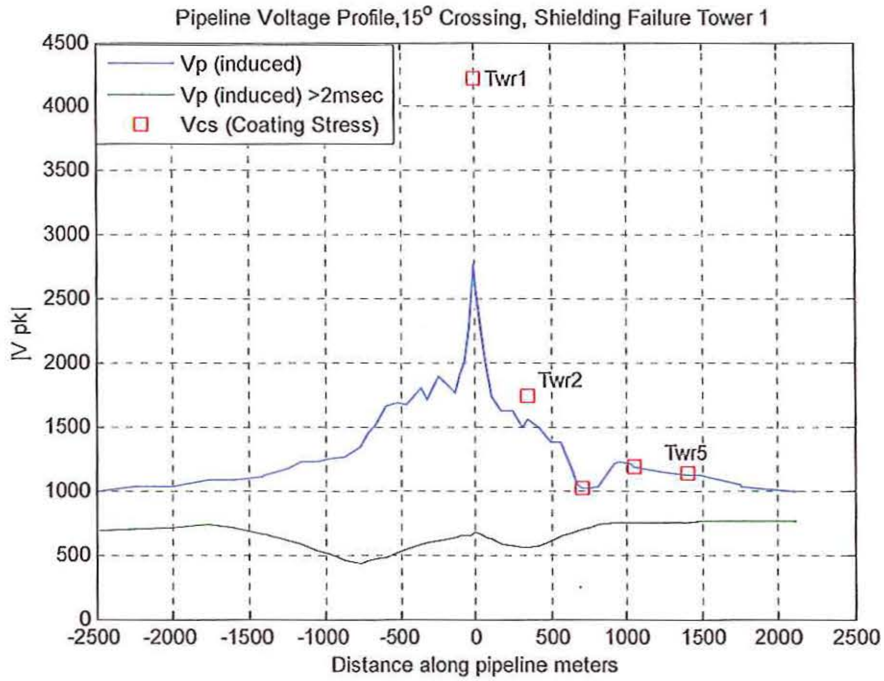

Figure 47 Voltage Profile along pipeline, fault at Tower 1, 15° crossing

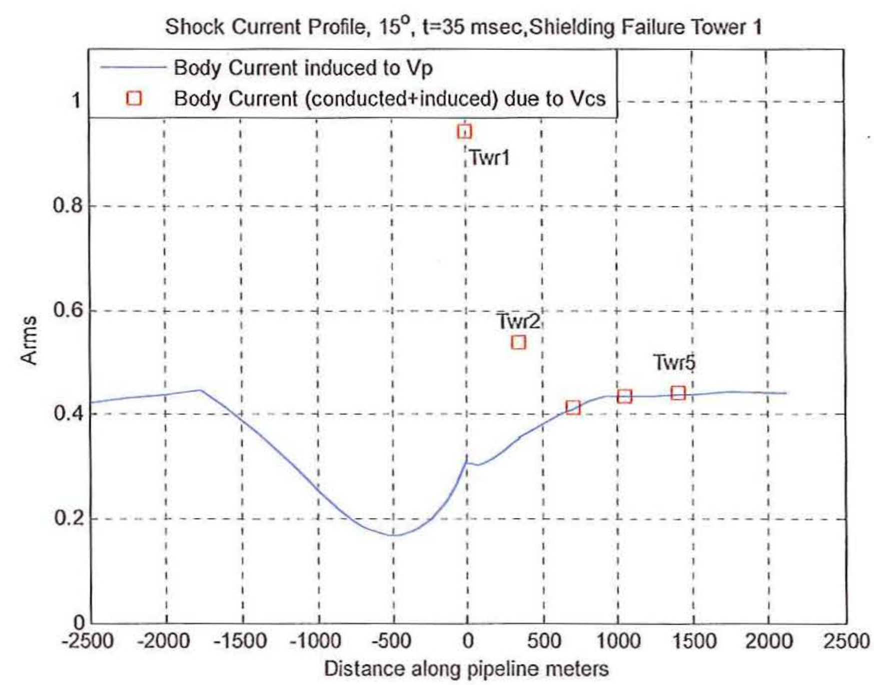

Figure 48 Shock Current at different pipeline points, SF fault Tower 1, 15° crossing

Table 6 Conditions leading to Coating Integrity Studies

Pipeline Spacing to closest towers	Less than 30 meters	Greater than 30 meters
Parallel with HVDC line (Figure 49)	any parallel length	Parallel> 8 km (at 30 meter spacing, allowable length increases with wider spacing)
Crossing the HVDC line (Figure 50)	any angle	Angle <15°

Assumptions:

1. 100 ohm-m soil resistivity (uniform), see Sections, 3.2 and 4 for further information on impact of soil resistivity
2. Shielding failure mode (DMR not involved), see Sections 2.3 and 7.4 for more information on fault impact
3. Tower footing resistance of 5 ohms, see Section 7.1.3
4. NPS 2.5 OD pipe, coating resistance of 100,000 ohm m². See Sections 7.1.1 and 7.1.2 for discussions regarding impact of pipe diameter and coating resistance.

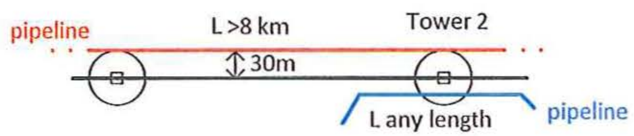

Figure 49 Parallel conditions leading to coating integrity studies

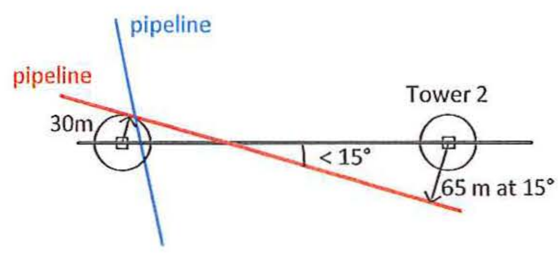

Figure 50 Crossing conditions leading to coating integrity studies

Table 7 Conditions Leading to Safety Studies

Appurtenance Spacing from closest tower leg	Less than 100 meters	Greater than or equal to 100 meters
Parallel with HVDC Line (Figure 51)	any parallel length	Parallel greater than 2 km (at 30 meter spacing to tower center line). A longer parallel length is needed if spacing increases
Crossing the HVDC Line (Figure 52)	any crossing angle	Crossing angle less than 25° and appurtenances within 2 km along pipeline, either side of crossing point.

Assumptions:

1. 100 ohm-m soil resistivity (uniform), see Sections, 3.2 and 4 for further information on impact of soil resistivity
2. Shielding failure mode (DMR not involved), see Sections 2.3 and 7.4 for more information on fault impact
3. Tower footing resistance of 4 ohms, see Section 7.1.3
4. NPS 2.5 OD pipe, coating resistance of 100,000 ohm m^2. See Sections 7.1.1 and 7.1.2 for discussions regarding impact of pipe diameter and coating resistance.

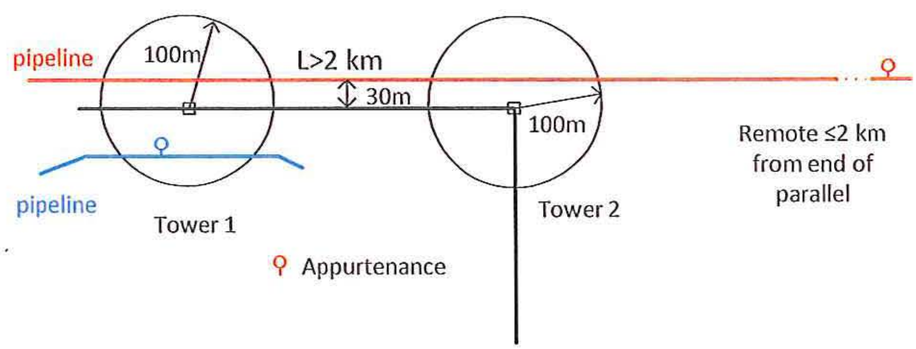

Figure 51 Parallel conditions leading to Safety Studies

Review of safety (shock hazard assessments):

In Figure 53(a) induction is not an issue but the 60 m spacing could be a problem if an appurtenance exists. Figure 53(b) would have similar issues

In Figure 53(c) there is both conduction and inductive effects near possibly both towers adjacent to the crossing point, and the last tower spacing to the pipeline. Figure 53(d) would pose similar concerns.

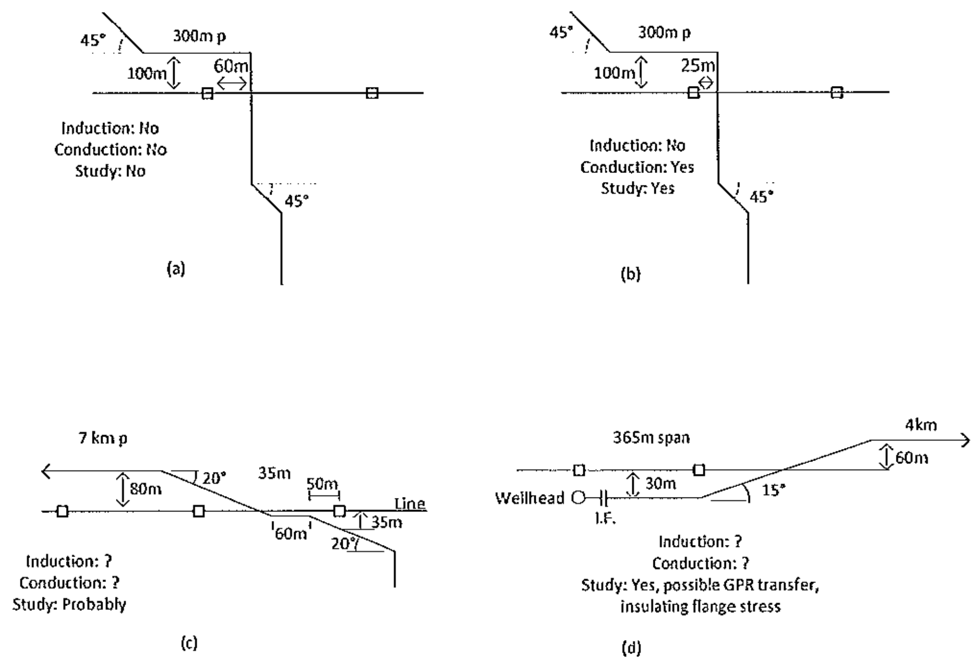

Figure 53 Possible pipeline/HVDC line geometries for considering coating integrity

9 Information Interchange

For a successful study and possible mitigation outcome key data have to be interchanged between the electrical utility, the pipeline owner and any consultant retained by either party for the work. The following is suggested in reference [1]'s Appendix and is modified slightly for HVDC line application and represents the minimum requirement.

9.1 Maps

A general location map of the area is required to establish the location accurately, plan and profile drawings showing construction details, including relative location of proposed facilities with respect to existing plant.

9.2 Technical Data Pipeline

1. Diameter of pipe
2. Wall thickness
3. Type of steel (or other metal i.e. aluminum if applicable)
4. Coating system (establish NACE fault withstand limits), thickness, type resistivity
5. Product transported
6. Pressure
7. Cathodic protection system
8. Location and type of appurtenances
9. Grounding facilities
10. Existing mitigation if any

9.3 HVDC line

1. Voltage is 500 kV dc monopole; ±500 kV dc bipole
2. Load current 2000A dc present and immediate future (the line is capable of higher currents but no foreseeable plan to increase link loading)
3. Fault current magnitude and duration (will be similar to Figures 6 -8)
4. Structure dimensions and conductor assignment
5. Conductor data, pole and DMR, maximum sag
6. Shield wire data
7. Ground facilities, footing impedance if available for structures in vicinity
8. Corrosion control data
9. Fault recovery practices

11 References

[1] CAN/CSA -22.3 No. 6 – M91 (2013) "Principles and Practices of Electrical Coordination between Pipelines and Electric Supply lines"

[2]CIGRE 95 "Guide on the Influence of High Voltage AC Power Systems on Metallic Pipelines" Working Group 36.02, 1995

[3] "Environmental Characteristics of HVDC Overhead Transmission lines" L.A. Koshcheev, HVDC Transmission Institute, St. Petersburg, for Third International Workshop on Grid interconnection in North Eastern Asia

[4] 2011 Annual Report "Forced Outage Performance of Transmission Equipment" Canadian Electricity Association - CEA

[5] "Insulation Coordination of Power Systems" – A.R. Hileman, Marcel Dekker Press 1999

[6] "Monte Carlo Simulation of Lightning strikes to the Nelson River HVDC Transmission lines" S.J. Shelmy, D.R. Swatek of Manitoba Hydro. Presented to IPST (International Conference on Power System Transients) 2001

[7] "Step and Touch Potentials at Faulted Transmission Towers" E.A. Cherney, K.G. Ringler, N. Kolcio, G.K. Bell, IEEE Transactions on Power Apparatus and Systems, Vol. PAS -100No. 7, July 1981

[8] "Lightning Surge Response of Ground Electrodes" William Chisholm, Wasyl Janischewsky, IEEE Transactions on Power Delivery, Vol. 4, No. 2 April 1989

[9] IEEE 80-2000 "IEEE Guide for Safety in AC Substation Grounding"

[10] "A Study of the Hazards of Impulse Currents" Charles F. Dalziel, AIEE October 1953

[11] IEC 60479-1 "Effects of current on human beings and livestock – Part 1: General Aspects"

[12] IEC 60479-2 "Effects of current on human beings and livestock – Part 2: Special Aspects"

[13] ASTM G62 Standard Test Methods for Holiday Detection in Pipeline Coatings

[14] "Pipeline AC Mitigation Misconceptions" R.A. Gummow, S.M. Segal, W. Fieltsch – Coreng Consulting Service Company Ltd. A subsidiary of Corrosion Service Company Limited – Presented to NACE Northern Area Conference Feb 15 -18, 2010, Calgary AB

[15] "Standard Handbook for Electrical Engineers – 10 Edition" Donald Fink, John Carroll – McGraw Hill 1969 Section 4 -301

A.1 HVDC Tower Shielding Angle

The shielding angle for the HVDC tower is illustrated in Figure 55 along with the different arc paths for an impinging lightning stroke depicting successful shielding (potential back flashover event still possible) and shielding failure (Section 2.3).

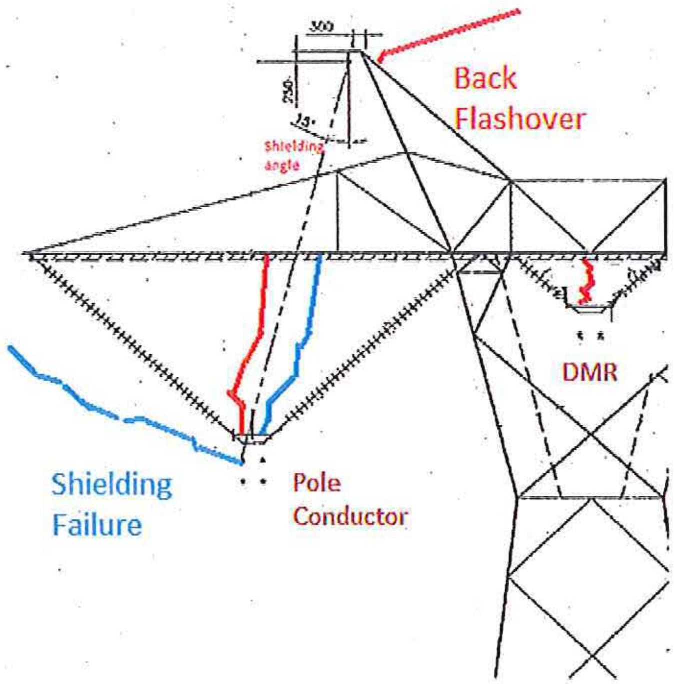

Figure 55 Shielding Angle HVDC Tower showing arc paths

Several electro-geometric theories have been developed by transmission line designers to estimate the minimum shielding angle needed to reduce the shielding failure rate to an acceptable level (including theoretically zero). Older more generally accepted theories are empirically based and tend to give reasonable results with AC lines.

To obtain perfect shielding (zero failures) the shielding angle for a particular line design will approach a certain minimum value depending upon the particular theory[21] adopted. The presence of trees along the ROW, being on top of hill or on its side, all affect the perfect shielding angle needed. In very exposed areas, a low angle of 10° may be suggested but both mechanical limitations and or line cost may become a limiting factor. Reference [5] may be consulted for more information on shielding design.

[21] Suggested by either IEEE or CIGRE