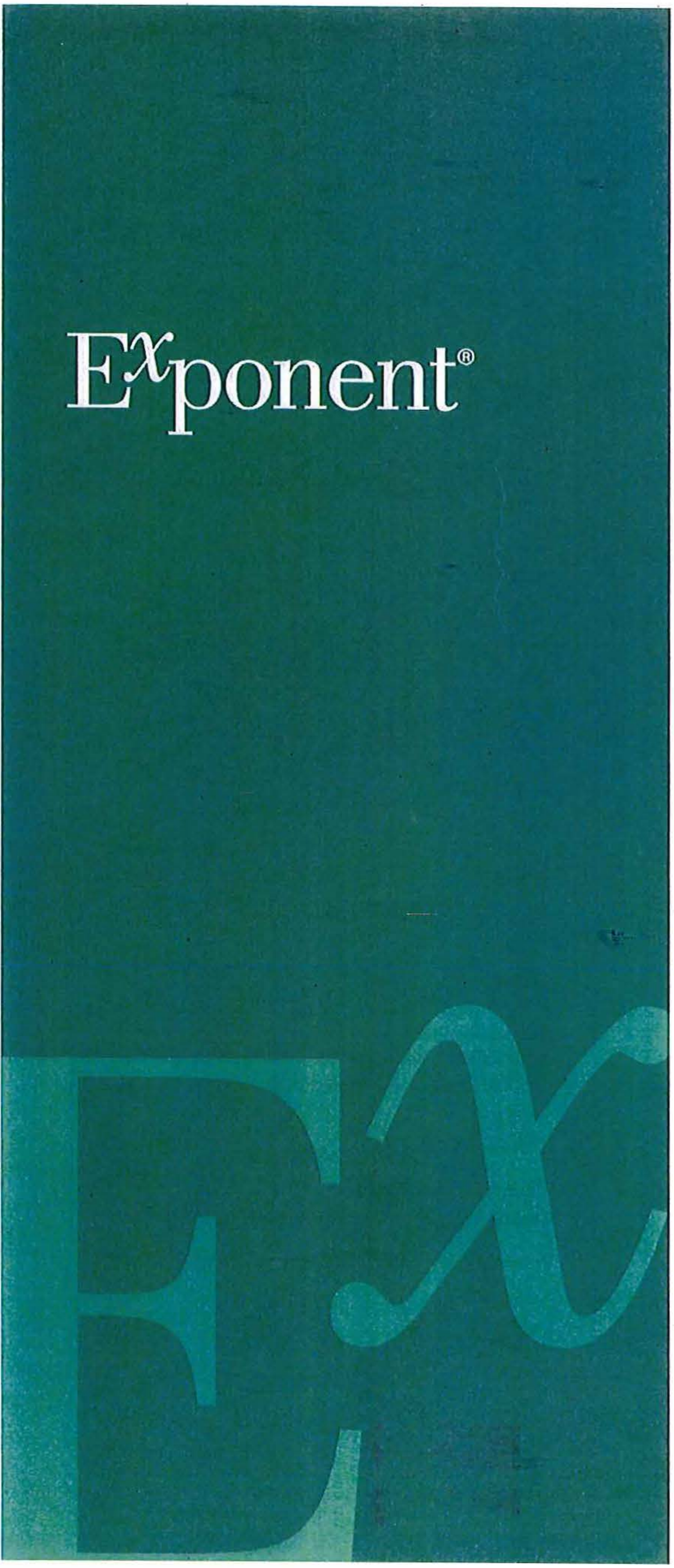

Exponent Engineering P.C.

FILED
December 5, 2014
Data Center
Missouri Public
Service Commission

New York Regional Interconnection Study: Regional Pipeline Compatibility

REP Exhibit No. 628
Date 11-12-14 Reporter KF
File No. EA-2014-0207

628

New York Regional Interconnection Study: Regional Pipeline Compatibility

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November 2007

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Acronyms and Abbreviations

A	Ampere
AC, ac	Alternating Current
dB	Decibel
dB(A)	Decibel A-weighted
DC, dc	Direct Current
EMI	Electromagnetic Interference
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
GE	General Electric
H	Henry, unit of inductance
Hz	Hertz, cycles per second
IEEE	Institute of Electrical and Electronics Engineers
kHz	kilo-Hertz, 1,000 Hertz
km	kilometer
kV	kilo-volt, 1,000 Volt
MFL	Magnetic Flux Leakage
mho	unit of conductance, Ohm^{-1}
MHz	mega-Hertz, 10^6 Hz
mV	milli-volt, 0.001 Volt
MW	mega-watt, 10^6 Watt
NACE	National Association of Corrosion Engineers
ROW	Right of Way
RF	Radio Frequency
RMS	Root Mean Squared
S	unit of conductance, Ohm^{-1}
TIF	Telephone Influence Factor
V	Volt, Voltage
VHF	Very High Frequency
UHF	Ultra High Frequency
Ω	Ohm
W	Watt
WIN	Weighted Induced Noise

Executive Summary

Exponent Engineering P.C. (Exponent) evaluated the potential effects of the New York Regional Interconnect's (NYRI) proposed ~190 mile direct current (dc) transmission line for effects on the adjacent Millennium pipeline project and pipeline cathodic protection and integrity and monitoring systems. The potential effects of dc electric and magnetic fields and corona phenomena from the NYRI transmission line on the cathodic protection of pipelines and communication systems were also evaluated.

The dc magnetic field from the overhead section of the proposed dc transmission line was too weak to produce any detrimental effect on the pipeline protection and monitoring systems. The dc electric field was at or below limits set forth in relevant suggested and cited guidelines.

The design of the NYRI dc transmission system includes a metallic return conductor. This design results in any ground current being reduced to a negligible amount. The leakage current to ground through the insulator strings and the ion flux from conductor corona was determined also to be negligible. Inductive coupling between the dc transmission and pipeline was also considered in detail, using the mutual inductances between the dc transmission line conductors and the pipeline. The study indicated that the traverse-induced voltages along the pipeline were too weak to interfere with the operation of pipeline cathodic protection and monitoring systems. The interference magnitude was also shown to be a function of the ac and dc filter designs of the proposed dc system. These designs were not planned to be available until the final converter station design; however, the results shown in this report are based on projected design parameters and final results are not expected to be materially different.

Interference with the telephone system was also investigated and been shown to be of negligible magnitude.

Exemplar pipeline monitoring equipment was reviewed and in the unlikely event of interference, potential mitigation techniques will be presented.

1 Introduction

New York Regional Interconnect, Inc. (NYRI) has proposed to construct an approximately 190 mile, single circuit ± 400 kV dc transmission line between the town of Marcy, New York and the Town of New Windsor, New York. The line would parallel existing transmission lines or gas pipelines for approximately 75 miles (of which approximately 3.3 miles would be underground) and railroad lines for approximately 73 miles (of which approximately 16 miles would be underground). A new right-of-way (ROW) would be required for about 22% of the route (approximately 42 miles of which about 2.3 miles would be underground). The positive (+) and negative (–) conductors and shield wires would be suspended from steel pole or latticework structures except for about 21.6 miles where the line would be placed underground.

In New York State, the transmission system transports electricity as alternating current (ac) that oscillates at a frequency of 60 Hertz (Hz) on three phase conductors. For electricity transported as dc power it must converted from ac power to dc power at a converter station; carried over a two-conductor transmission line (three conductors for a bipolar system if a dedicated neutral conductor is included; or two conductors with earth ground return if ground electrodes are provided to handle neutral return current when necessary), and then converted back to ac power at the terminal end of the line. In conceptual terms the process as embodied in the proposed project is illustrated below in Figure 1.

The Northern Converter Station will receive ac power from National Grid's Edic Substation over a very short single circuit 345-kV tie line. After conversion to dc power, electricity will be carried for approximately 190 miles down to the Southern Converter Station. After converting dc power back to ac power, the power will flow over two very short 345kV tie lines to the adjacent Rock Tavern Substation operated by Central Hudson Gas & Electric[1].

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[1] While the predominate direction of power flow is expected to be from north to south, as described above, the dc link can be designed to enable power flow from south to north if needed.

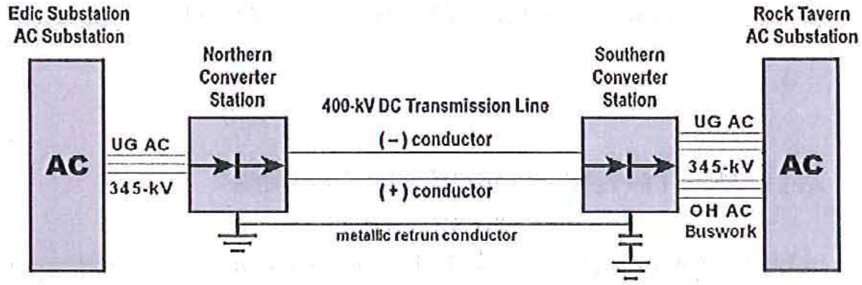

Figure 1. Schematic representation of the dc transmission line and ac/dc converter stations.

2 Relevant Aspects of DC Transmission Systems

2.1 DC Transmission Line Basics

In North America, electric power is primarily generated and transported as 60 Hz ac power but dc transmission lines are also utilized where ac transmission lines are not technically feasible or economical. DC transmission is a viable method for transporting a large quantity of power at high voltages or for connection between ac systems that are not operated synchronously. To do this, ac power must be converted to dc power at a source converter station, carried over a transmission line (typically two sets of conductors [called poles] instead of the three sets of conductors [called phases] needed for ac transmission), and then converted back to ac power at a terminal converter station. The simplest design is shown in Figure 2, diagram (a). This design is known as a monopolar link, with the earth being used as one of the conductors providing the ground return. A second design, known as a bipolar link, shown in Figure 2, diagram (b), has two sets of conductors – one positive, the other negative. In a bipolar link design, the current carrying path for any imbalance of the currents between the two poles (polarities) is typically the earth or, as shown in Figure 2, diagram (b) it can be a dedicated metallic return conductor[2]. As discussed later, NYRI has proposed a bipolar link with a metallic return conductor for both the overhead and the underground sections. In a bipolar link, each converter normally has the same power rating and is arranged such that the direct current in the neutral cancels so its current is normally close to zero. The neutral point between the two converters is typically connected to the ground via a grounding electrode at each end of the line. If a metallic neutral conductor were used, one end of the neutral conductor would be connected to the ground typically in or close to one of the two converter stations. By connecting the two neutral points, as shown in Figure 2, diagram (b), each converter station (positive and negative) can operate independently. If the two converters operate at equal current, then no current flows between the neutral points (or in the dedicated metallic return conductor). If either the positive or negative conductor is unable to provide service due to maintenance or a fault condition, or during

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[2] A metallic conductor is a conductor fabricated from a metal for the purpose of conducting electricity, i.e., not conducting through the earth (IEEE Standard Dictionary, 2000).

maintenance of one converter, the other converter can carry current up to the current limit of the converter and conductors using the remaining pole conductor and the dedicated neutral return conductor.

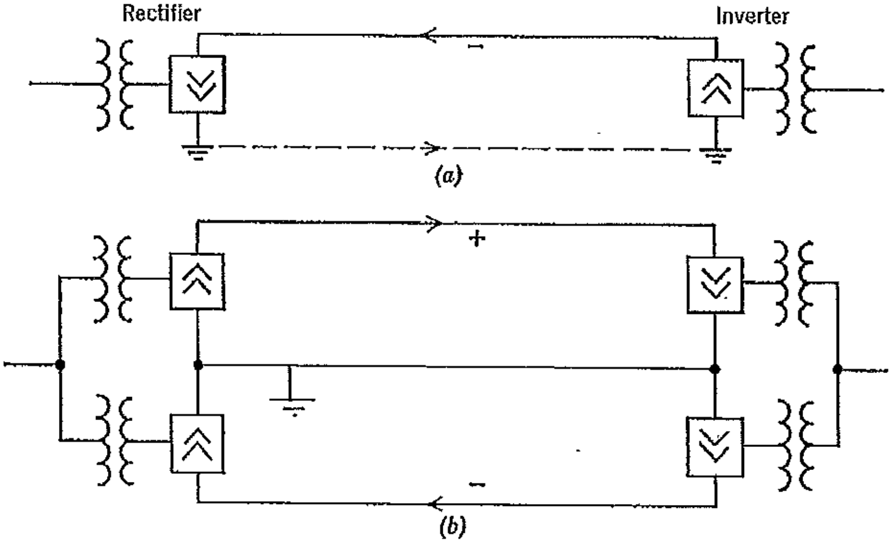

Figure 2. Monopolar and bipolar dc links

2.2 Equipment Interaction

The NYRI dc transmission design is a bipolar link with a dedicated metallic return conductor. The design includes two sets (poles) of dc conductors and one metallic return conductor, as shown in Figure 3. The metallic return conductor, if connected to a ground at only one point, provides a distinct path for return currents and prevents the dc return current from flowing through the earth. This thereby eliminates the possibility for the dc neutral current to be transferred through the earth into other systems such as pipeline protection and monitoring systems. In designs where the return current flows through the earth, the unbalanced neutral current potentially could interfere with the cathodic protection of buried objects reducing the effectiveness of installed cathodic protection systems. This is normally carefully studied in cases where such interference might pose a problem. With the design proposed by NYRI, the electrical isolation of the return current through the use of a dedicated metallic return conductor essentially eliminates the steady state ground return currents. The residual source of ground current is from leakage current through the suspension insulator strings and the ion flux from conductor corona. This leakage current is analyzed and discussed later in this report and was found to be of negligible magnitude.

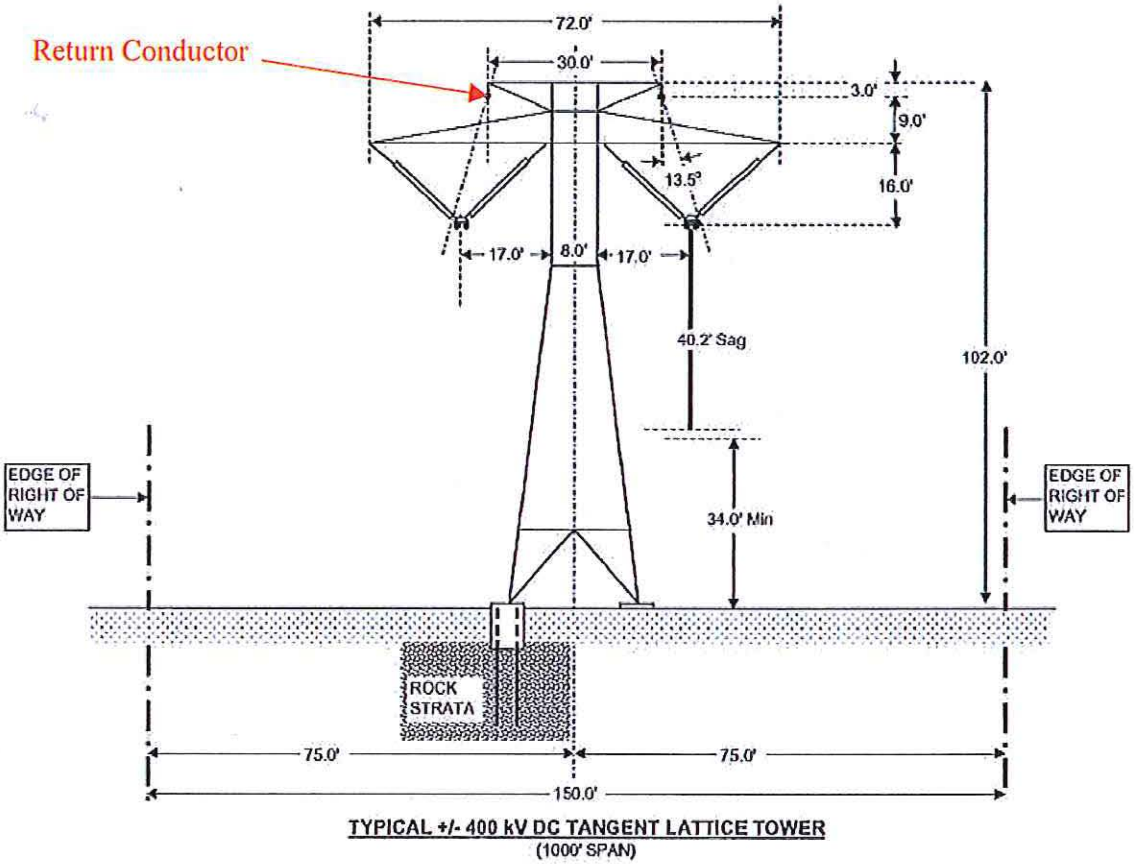

Figure 3. DC tower with metallic return conductor

The conversion process by which ac power is converted to dc power and vice versa can produce a byproduct of ac voltages and currents at multiples (orders) of the fundamental frequency, 60 Hz, which are termed harmonics. Harmonic voltages and currents are generated on both the ac and dc sides of the converters. A 12-pulse converter typically used in each pole of a bipolar link generates harmonics principally of orders 12*q* on the dc side of the converters and 12*q*±1 on the ac side of the converters, where *q* is an integer[3]. These are called the characteristic harmonics.

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[3] Kimbark 1971.

Small amounts of non-characteristic harmonics (typically odd harmonics of the ac fundamental frequency on the ac side and even harmonics of the fundamental frequency on the dc side) can also be present. The magnitudes of the harmonic voltages and currents are not constant and vary with the converter's operating conditions. These are a function of the load on the line and electric system conditions. Filters are installed to reduce the harmonics injected into the ac transmission lines connected to the ac side of the converters. AC filters serve the dual purpose of reducing ac harmonics and supplying reactive power to the interconnected transmission grid at the fundamental frequency. On the dc side of the converter, a dc reactor combined with a dc filter, connected between the poles and the ground or the dedicated neutral conductor, reduces to an acceptable level the harmonics that might otherwise be carried on the dc transmission line. The NYRI converter station design, as described in Exhibit E-2 of the Application, specifies that both ac and dc filters will be installed. A harmonic study will be performed during the final design to establish the design values criteria for the ac and dc filters.

The dominant harmonic voltage on the dc side of the converter is typically the 12th order harmonic at 720 Hz. Figure 4 illustrates the relative magnitude of the 12th order harmonic present at the output of a 12-pulse converter before the smoothing reactor and the dc filter for different operating conditions assuming a perfectly smooth dc current. The harmonic voltages generated by operating the converters, result in harmonic currents being injected into the dc transmission line conductors, but the harmonic currents are typically effectively reduced to a negligible magnitude by means of the smoothing reactor and the dc filter. The residual harmonic currents are superimposed on the main dc current, and establish an ac magnetic field around the dc conductors. This ac magnetic field, if of sufficient magnitude, may interact with adjacent objects and circuits such as a pipeline or its monitoring or cathodic protection systems. The inductive coupling between the dc transmission system and the pipeline system could induce harmonic voltages, which might interfere with the pipeline's monitoring and cathodic protection systems if the harmonic filtering is inadequate. Therefore it is important that an in-depth study to determine the extent of the potential interference as a result of dc transmission line be conducted when system details such as converter design, ac/dc filter specifications, surge capacitor, ac system specification, and communication system details are finalized.

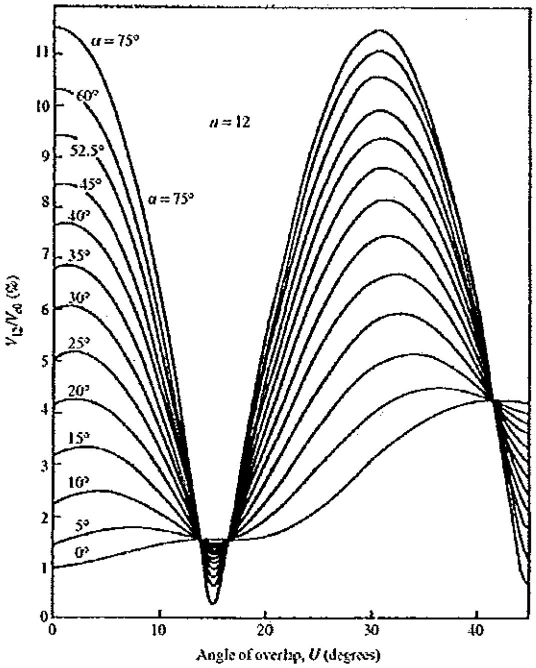

Figure 4. Harmonic spectrum of the voltage at the output of a 12-pulse converter[4]

The static electric and magnetic fields and corona-related radio-frequency fields associated with the proposed dc transmission line discussed in the companion report[5] were also considered in the present evaluation of potential effects on the pipeline system, including monitoring and cathodic protection systems in this context.

2.3 Monopolar and Fault Operations

In this section, the effect of rare events that might trigger the proposed dc transmission line to operate in emergency and fault operating conditions are discussed. The NYRI dc transmission line is a bipolar link design as presented in Figure 2. As stated earlier, the bipolar link transmission design can operate as a monopolar link during converter maintenance or fault on one of the conductors used for the dc transmission line. Monopolar link operation is typically

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[4] V_{co} is the maximum average dc voltage, α is the converter firing angle.

[5] Exponent "New York Regional Interconnection – Electric and Magnetic Fields, Ions, Audible Noise, and Radio Noise," November, 2007.

associated with higher uncompensated harmonics on the dc transmission line and increased noise interference in the audible telephone frequency range of 100-3,000 Hz. The effect of increased harmonics during monopolar link operation is studied in this context. Since a detailed harmonic spectrum of the NYRI dc transmission line as a monopolar link (i.e., bipolar link under monopolar link fault or contingency conditions) or bipolar link will not be available until the detailed final design phase of the project, this study was conducted using published data on comparable dc transmission designs in operation.

A fault on the dc transmission line results in flow of dc current through the ground and back to the converters. In the proposed NYRI system, the fault currents would flow back to the grounded neutral before flowing back through the converters. Unlike ac current, dc current has no zero crossing for protective equipment such as a circuit breaker to clear the fault current. The controls on the converter limit the magnitude of the fault current through the phase control of the converters and clear the dc transmission line fault currents by reversing the rectifier converter voltage. This stops the current flow from the rectifier into the line. Since dc transmission line fault clearing does not involve any mechanical action, it can be significantly faster than clearing ac transmission line faults. Although, the dc fault current is quickly interrupted, its impact on any adjacent circuits and systems such as pipeline systems needs to be closely investigated. The fault currents associated with a dc line to a ground fault are typically significantly lower than for ac systems and the interactions are not expected to cause any adverse effects.

Broken conductors are very rare, but are a known failure mode of transmission lines. In this case, the Millennium pipeline is buried and the NYRI dc transmission line is proposed to be located 100 feet away from the pipeline.[6] Therefore, any adverse effect from a broken conductor will probably not be any different than a short circuit from a pole to a ground. Similar fault studies would also be conducted for ac transmission systems, though dc systems are inherently benign compared to ac systems. Figure 5 depicts a simplified conduction of the

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[6] Based on email from NYRI, 10/10/2007, the Millennium pipeline is a 30-inch diameter coated pipeline. It will be located 100 feet away from the dc transmission centerline, and 36 inches below the ground surface. A second looping pipeline may be installed in the future and may be located at the edge of the pipeline ROW or about 75 feet from the tower centerline shown in Figure 3.

fault current through the earth and the pipeline. When a gas pipeline is provided with cathodic protection, the pipeline cathodic protection design team is required[7] to consider the need for lightning and fault current protection and isolating devices should also be considered. Cable connections from isolating devices to arresters should be short, direct, and of a size suitable for short term high current loading.

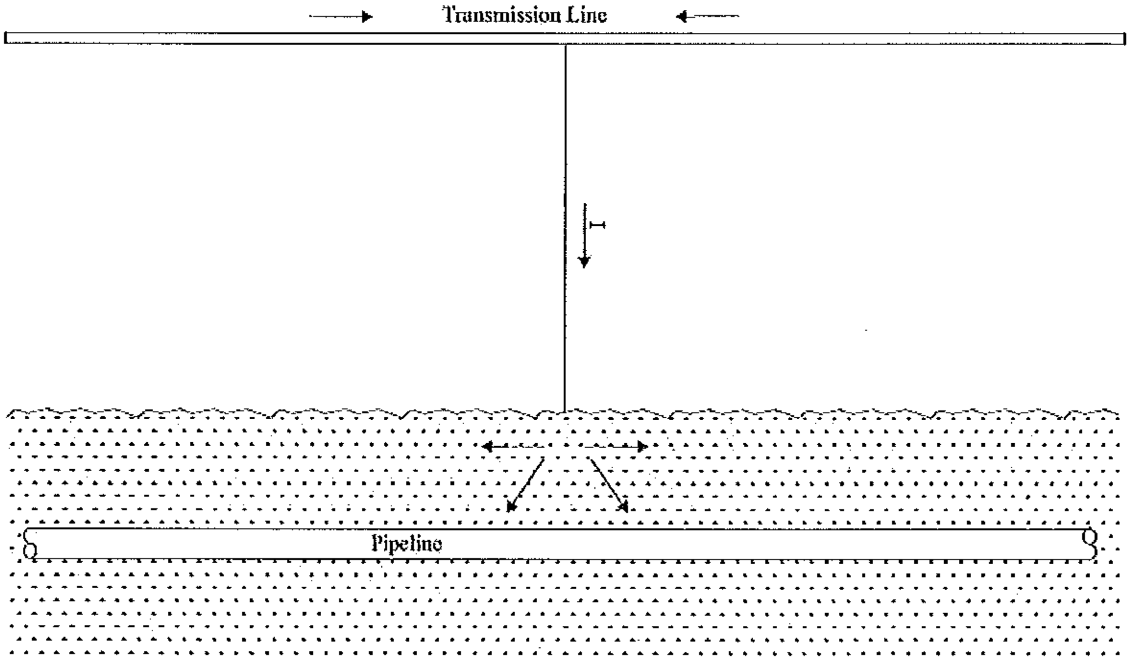

Figure 5. Conductive coupling during fault

2.4 Metallic Return Failure Mode Analysis

In a dc system with electrode lines or with neutral conductors grounded at one end of the line, loss of the neutral/electrode line by having a broken conductor or a ground fault on the neutral/electrode line has to be considered. First, in the bipolar mode, there is almost no unbalance of the current flowing in the neutral, so there is no voltage drop between the two ends of the conductor. In this case, it is very difficult to detect a broken conductor or a failed neutral

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[7] NACE Standard RP0169-2002.

conductor insulator. If the neutral current is assumed to be measurable, however, there might be a detectable effect on the voltage balance between the two poles if the neutral conductor is broken. If it is grounded, the current will be split between the neutral and the ground but the current in the grounding conductor might be less than the leakage current flowing back from insulator leakage and corona currents. So, a ground fault might not be detectable by just measuring the current flow at the ground point.

In monopolar operation with one pole out of service, a broken neutral conductor would result in failure of the pole to operate if the neutral conductor is not connected to the ground in such a way that the circuit is closed. This would be detectable by monitoring the current in the grounding conductor or by seeing an unbalance between the pole and neutral conductor currents. A failed insulator making contact with a tower might be detectable in a similar way if the grounding point is close to the end of the neutral that is farthest away from the grounded terminal. If however, the failed insulator is close to the grounded end, the current flowing through the fault is not easily detectable because most of the current would flow in the neutral conductor and very little would flow in the ground. There is probably a point at which the fault will not be detectable. This should be studied to ensure that insulator failures would be detected and not lead to permanent ground faults on the neutral conductor.

Lightning surges or ground faults on one pole of the line will cause over-voltages that will lead to flashover of the neutral conductor's insulators. In a bipolar operation, this is probably not a real problem because the voltage from the neutral conductor to the ground at the point of the flashover should be low and will not sustain the arc. In monopolar operation without the use of the second dc conductor, however, the voltage drop from the neutral conductor to the ground can be substantial at higher dc current levels. In this case, if lighting hits the line, the neutral insulator can be expected to flash over and an arc between the neutral and the tower will be struck. The voltage from the neutral to the ground will be highest at the terminal away from the grounded terminal. Magnetic forces acting on the arc will make the arc grow longer and eventually, the voltage of the arc will be such that the current probably will have commutated back into the neutral. If the insulator (the gap length) is sufficient, this should be the end of the arcing. If the arc path is too short, however, the arc may re-strike or not be extinguished. The way to assure then that the arc will self extinguish is to have insulator strings that are sufficiently long to facilitate commutation of the current back into the neutral conductor. The insulator design parameters will be established during the final design phase of the dc transmission line to ensure a neutral conductor path.

3 Review of Cathodic Protection

This section covers a brief review of several types of pipeline cathodic protection circuits and its operating principles[8]. This background is important for the understanding of potential interactions of the proposed dc transmission line with cathodic protection systems.

3.1 Cathodic Protection[9]

Cathodic protection is a method that is used to minimize the amount of corrosion on a metal object, such as a pipeline buried underground. Cathodic protection is an electrochemical means of corrosion control similar to what happens to the cathode in a battery. In cathodic protection the pipeline is made to be the cathode (negative terminal) in this electrochemical cell. The soil is the electrolyte and the anode (positive terminal) is either a less noble metal such as zinc or magnesium (sacrificial anode) or corrosion resistant materials (impressed current anode)[10]. Sir Humphrey Davy first suggested cathodic protection in the 1820s as a means of controlling corrosion on British naval ships. Three alternative methods are mainly used to protect underground structures that may be subjected to corrosion:

1. The impressed current method of cathodic protection uses a dc source, such as a battery, dc generator, or rectifier. The most common power source for impressed current protection is the transformer rectifier. There are also solid-state rectifiers that perform similar functions, without the use of transformers. Rectifiers can be provided with constant voltage, constant current, or structure-to-electrolyte potential control[11]. The structure to be protected is connected to the negative terminal of the dc power source. In areas where electrical power is not readily available, solar power and wind driven generators coupled with storage batteries are used. Common uses of impressed current include long transmission pipelines. For long pipelines, many kilometers in length, the

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[8] This section is reproduced from AREMA (2003).

[9] Kimbark 1971, p. 434-437.

[10] NACE Standard RP0169-2002.

[11] Fitzgerald 2000.

attenuation or reduction of protection falls off with distance from the anode bed. On larger-diameter (30- to 36-inch diameter) pipelines the corrosion can be controlled on 33 to 66 km (20 to 40 miles) of pipeline, assuming a reasonably satisfactory dielectric coating is in place[12].

2. In galvanic-anode drainage, anodes are made of zinc, aluminum, or magnesium, which are more chemically active with respect to buried metal objects, normally iron. The soil with its salts and moisture forms the electrolyte (conductive path), which is between the protected object (cathode) and the more active material (the anode), and provides the electrical contact between cathode and anode. No external power supply is required. The protection current from the anode through the soil to the pipeline comes from the electrochemical cell created by the connection of the anode material to the more noble or electropositive material in the structure, i.e. the pipeline.

3. In bus drainage, used principally to protect pipes near electric railways, the pipe is bonded to the most negative point available, which may be the ground bus at the rectifier substation or the negative terminal of a negative feeder booster.

Impressed current or forced drainage is the only method used for protecting long[13] pipelines. Rectifiers usually provide the necessary electro-motive force if ac power is available.

Three arrangements of anodes are shown in Figure 6.

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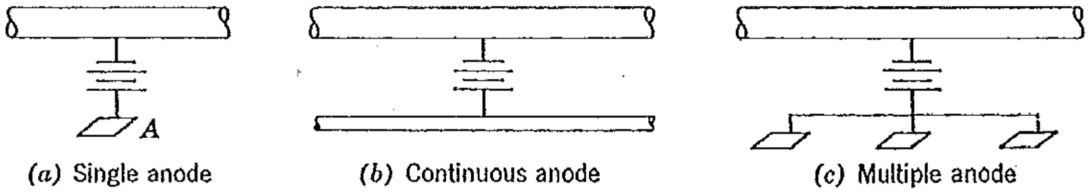
[12] Sigfried, Corrosion of Pipelines.

[13] For a typical soil resistivity of 1000 Ω.m, long pipeline is considered to be longer than one mile.



(a) Single anode (b) Continuous anode (c) Multiple anode

Figure 6. Three arrangements of anodes for cathodic protection

The single anode is applicable only to compact structures. Multiple anodes or continuous anodes are suitable to extended objects, such as cables or pipelines. Continuous anodes are made of old rails or abandoned pipelines buried parallel to the pipeline to be protected. Multiple anodes are generally more practical than continuous ones. The spacing between elements of the anode can be increased if their distance from the protected pipeline is increased. The greater the distance, however, the higher the resistance between the anode system and the protected pipe and the greater the possibility of damage to other structures, especially in congested areas. Practically, anodes are placed in order to get a reasonably uniform leakage current entering the protected pipe per unit of length. Sometimes the anodes are buried deep below the pipeline, principally for reducing ROW requirements.

3.2 Pipeline Coating

Pipelines with anodic protection are usually coated with insulating materials. The best coatings are made of polyvinyl chloride tapes. Other coatings used are concrete, cement mortar, and bituminous materials such as asphalt, coal-tar enamel, and mastic. Coatings significantly decrease the amount of current needed to protect a given surface of pipeline. A coating's performance depends on high resistivity, low permeability to water, good bonding between the coating and the metal, and absence of holes and cracks. Coating defects are normally called *holidays*. Uncoated portions of pipelines are most likely to cause corrosion and are known as *hot spots*[14]. Most coatings deteriorate with age but still have considerable value. The spacing

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[14] Parker 1999.

between rectifiers may be as low as 500 feet on bare or poorly coated pipes and as great as 50 miles on pipes with good thermoplastic coatings. Typical values of leakage conductance of a 12-inch pipe are given in Table 1.

Table 1- Typical values of leakage conductance of buried 12-inch pipe[15]

	G/l	
	mho/1,000 ft	**mho/km**
Bare pipe in water (ρ=1.4 Ω.m)	100	300
Bare pipe in soil of low resistivity (ρ=14 Ω.m)	10	30
Bare pipe in soil of medium resistivity (ρ=140 Ω.m)	1	3
Bare pipe in soil of high resistivity (ρ=1,400 Ω.m) or Pipe with normal coating	0.1	0.3
Pipe with very good coating	0.01	0.03

Assuming the average potential of the pipe with respect to the soil to be –1.0 V, the leakage current in amperes per unit length is numerically equal to the conductance in mhos per unit length. With the passage of time, polarization effects reduce the leakage conductance, especially on coated pipes.

The National Association of Corrosion Engineers (NACE) guidelines for fault conditions state that limiting the coating stress voltage should be a mitigation objective. Expected threshold values for coatings differ with type and are generally considered to be in the range of up to 2 kV for tape wraps and coal tar enamels and 3 to 5 kV for fusion-bonded epoxy (FBE) and polyethylene coatings for a short duration fault[16].

3.2.1 Permissible Range of Potential Difference Between Coated Pipe and Soil[17]

The potential of a pipeline with respect to the adjacent soil, for the avoidance of corrosion, should be negative by at least 0.85 V as measured with a copper-copper sulfate half-cell. Good

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[15] Uhlig 1948, p. 1188.

[16] NACE SP0177-2007.

[17] Kimbark 1971, p. 436.

insulating coatings can stand up to 10 V or more with no adverse effect on the pipe or coating. Inferior coatings that are perforated, are permeable to water, or have high leakage conductance should not be subjected to such high voltages. High voltages tend to form hydrogen on the surface of the iron at holes in the coating, degrading the bond between the pipe and the coating. Electro-osmosis[18] drives water into permeable coatings, thereby increasing the leakage conductance.

For gas pipeline in the United States, 49 Code of Federal Regulations (CFR) Part 192 regulates the minimum federal safety standards with respect to cathodic protection of pipelines[19]. Paragraph § 192.463 "External corrosion control: Cathodic protection" warns operators that:

> (c) The amount of cathodic protection must be controlled so as not to damage the protective coating or the pipe.

In appendix D to Part 192—Criteria for Cathodic Protection and Determination of Measurements, the following warning about over protection is included:

> A voltage in excess of 1.20 volts may not be used unless previous test results indicate no appreciable corrosion will occur in the particular environment. For oil pipeline in the United States, 49 CFR Part 195 regulates the minimum federal safety standards.

Paragraph § 195.571 requires:

> Cathodic protection required by this subpart must comply with one or more of the applicable criteria and other considerations for cathodic protection contained in paragraphs 6.2 and 6.3 of NACE Standard RP 0169 NACE Standard RP0169 applies to the DOT requirements for interstate gas transmission pipelines. This standard advises against using polarized potentials less negative than -850 mV for cathodic protection of pipelines when operating pressures and conditions are conducive to stress corrosion

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[18] The movement of fluids through diaphragms that is as a result of the application of an electric current (IEEE, Standard Dictionary 2000).

[19] Klechka 2007.

In addition RP0169 states that:

> Regardless of separation, consideration should always be given to lightning and fault current protection of pipeline(s) and personnel safety (see NACE Standard RP0177).

3.2.2 Transmission Line Interaction with Cathodic Protection

Pipelines with active cathodic protection deliver up to -50 V dc at the source to keep potentials of at least -1 V. The pipelines are normally insulated with various coatings, but these coatings will infrequently contain small holes, called holidays, that allow some fraction of the current to leak into the ground. With their overhead metallic shield wires, transmission lines tend to be the path of least resistance for cathodic protection dc currents. The NYRI dc metallic return conductor in the vertical configuration tower[20] is to be attached to the tower using a suspension insulator (rated for 25 kV to 50 kV) and thus does not provide a suitable path for the pipeline cathodic dc currents. If the shield wires are used on the dc line, however, they would provide a path of least resistance for the cathodic protection dc current. This effect can be minimized if needed by attaching the shield wire to the tower using an insulator (rated approximately 15 kV) where the dc transmission line is adjacent to the pipeline, which would prevent a suitable path for the pipeline cathodic dc currents.

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[20] Exhibit E-1.

4 Electromagnetic Interference (EMI) Study

There are four categories of electromagnetic coupling paths between systems: conduction, electric induction, magnetic induction and radiation of electromagnetic energy. Radio-frequency (RF) interaction is radiated energy, which is also discussed in this report.

- Conduction may occur when conducting paths, whether deliberate through wires, or through the earth or poor insulation, allow current to flow between the source and the receptor.
- Induction results from the electric and magnetic fields associated with the source coupling receptor objects that are in close physical proximity.
- Propagation of RF fields (arising from corona activity on conductors) to receptors is a far-field effect and occurs for more widely spaced objects.

4.1 Conduction

There are many possible conduction paths between the power system and the ground, where current can enter the earth and find its way into nearby pipelines and associated systems. These provide paths for earth currents from a power system to enter a pipeline. When power and pipeline facilities share a ROW, there can be numerous grounds in close proximity, providing a number of possible conducting paths for current between systems. It is important to consider conductive interference that may occur both during normal operation of the dc system and during faults when large currents can enter the earth. It is essential to preserve proper operation of pipeline facilities during normal power system operation. It is also essential to prevent damage to equipment or injury to personnel as a result of elevated voltages and currents during power system faults. It should be emphasized that worker injury cannot be entirely prevented by taking precautionary measures solely on the dc line. Protection of workers has to be a part of work procedures when working on the pipeline. The specific designs of both the power system and the pipeline greatly affect the potential for, and level of, any interference. A discussion for conductive interference between the NYRI dc transmission line and the adjoining pipelines can be found in sections 3.1 and 4.8.

4.2 Electric Field Induction

Electric field capacitive coupling between a source circuit and a receptor circuit can result in voltages on the receptor circuit. The receptor circuit may include objects such as motor vehicles, people, sheds, long trains or pole mounted communication wires. The magnitude of the coupled voltage depends on geometrical characteristics of the source and the receptor. Capacitive coupling occurs as a result of a change in the voltage over time (*dV/dt*) or by having a change in the capacitance over time (*dC/dt*). No net charge will result from the presence of the static charge on the dc line. Because of the small capacitance between the transmission line and pipeline object, and the location of the pipeline underground, electric field coupling between the NYRI dc transmission line, and pipelines will be negligible and thus interference is not expected.

4.3 Magnetic Field Induction

Magnetic field inductive coupling is significant for conductive objects that are located parallel to a power line for a significant distance, such as pipelines. Magnetic field induced voltage is expressed in volts per unit length along the parallel conductor, and is called the longitudinal electromotive force. It is important to consider magnetic field induction under normal operation of the power system and during power system faults, where the dc line current is significantly above rated values. It is also necessary to give special attention to harmonic currents when dealing with magnetic field induction. Because magnetic induction is proportional to frequency, one ampere current at 180 Hz induces three times the voltage that it would induce at 60 Hz. Commutation processes within the dc converters and operation-dependent harmonics generate harmonics typically in the range below the 50th harmonic but some radio frequency interference from corona sources must also be considered. The use of filters and reactors as planned by

NYRI will reduce harmonics on connecting ac and dc transmission lines to industry acceptable levels.

4.4 Radio-Frequency Field Interactions

Commutation processes within dc transmission converters generate harmonics in the kilo-Hertz (kHz) to mega-Hertz (MHz) ranges of the RF spectrum. Because of the short RF wavelength, they interact with distant objects at many multiples of their wavelengths, i.e., in the far field, but there are also near field interactions that must be considered. It is essential to distinguish between radiation and electric and magnetic field coupling. Figure 7 illustrates the types of interference that may occur at different frequencies. For example, ac harmonics can result in telephone interference, while corona results in ionic flux and radio interference.

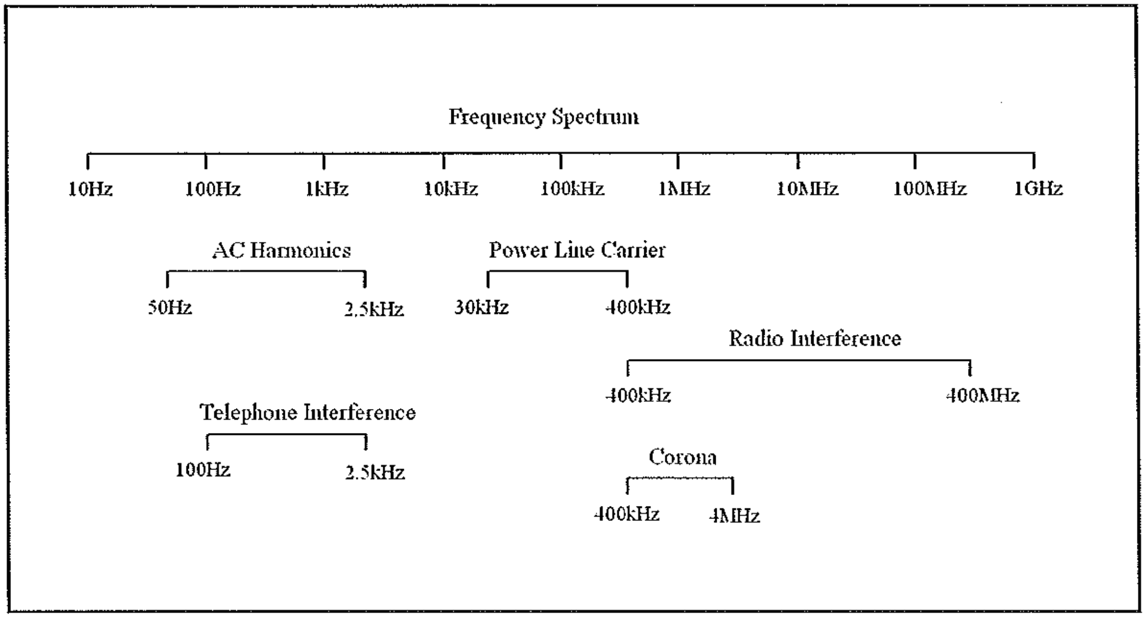

Figure 7. Various interference band

In order to investigate dc transmission interference into the pipeline's communication and signaling systems two general categories, radio interference and telephone interference, are studied as follows.

4.5 Radio Interference

Radio interference sources inject parasitic currents into the overhead conductors, causing radio noise fields. The electromagnetic field associated with such injected electric power in the transmission lines occurs predominately at frequencies less than 30 MHz. At frequencies above 30 MHz the line attenuation is so great that the noise fields produced as a result of direct (aerial) radiation from the interference source predominate.

Current commutation and voltage jumps in the dc converter operation generate parasitic electromagnetic emission. The metallic converter station building is designed to attenuate the RF generated inside the converter's valve hall.[21] RF fields measured outside the converter hall are found to be less than 40 dB (μV/m) across the broadcast frequency range of 400 kHz to 400 MHz[22]. Consequently, no or insignificant radio or TV interference originates from inside the converter's valve hall; however, interference can be coupled through the ac and dc conductors that penetrate the walls of the valve hall, so this has to be considered in the design of the converter stations. The interference field strength decreases monotonically with increasing frequency,[23] and this is the reason why there have been no reports of interference in the television frequency range. Such interference is of concern especially for pipeline diagnostic equipment, such as smart pigs, where video equipment might be used for inspection purposes.

Corona effects on the surface of high voltage overhead power transmission lines are the principal source of radiated noise. The conductor's corona process depends on the magnitude of the electric field strength at the surface of the conductors, the effective diameter of the

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[21] The building normally contains a conductive steel cage structure designed to act as a Faraday cage to reduce electromagnetic radiation (Arrillaga 1988, p. 142).

[22] Semidt 1996, p. 204-210.

[23] Uhlmann 1975, p. 352.

conductor or conductor bundle, their surface characteristics and weather conditions. Appropriate design measures can minimize corona. Corona effects similar to those around overhead conductors can be also observed in the proximity of a conductor's hardware fittings. Compared with the conductor corona, however, these hardware fittings produce little or no radiated noise. Another potential source of noise is the radio interference caused by discharges around insulators, which are mostly a result of corona discharges along the insulator's surface. The level of radiated noise depends to a large extent on the degree of pollution, e.g., dust, insects, etc. on the insulator and on the voltage gradient along the surface of the insulator.

RF noise levels for the dc transmission line configuration planned by NYRI for use along the pipeline, shown in Figure 3, are expected to be near ~65 dB (1 μV/m) at a frequency of 1 MHz at ground level under the conductors and attenuates as the distance from the conductors increases. Noise levels decrease for higher frequencies and also decrease with distance from the line. The levels of radio noise are below 1 μV/m within the dc line transmission ROW for frequencies above 500 MHz.

In order to provide a practical insight into this issue, test results from a similar system are presented. This system was not equipped with a dedicated metallic return conductor and therefore interference effects are higher than those expected for the proposed NYRI HVDC system. Nevertheless the results provide a point of reference to compare the results of this study. The result of field test studies conducted by National Research Council of Canada and Manitoba Hydro on the Nelson River dc bipolar link[24] indicated that the RF interference generated at the converter station and propagated along the dc transmission lines has the following characteristics.

a) It has a high level of line-to-ground mode radiated interference near the station but this mode attenuates rapidly and becomes negligible within 15 km.

b) It has a line-to-line mode, which propagates for hundreds of kilometers.

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[24] Morris et al. 1979, p. 1924-1946.

The Nelson River dc bipolar link studied above does not have a metallic return conductor (shield wire is not known to be continuous), and considering that line-to-ground mode radiated interference attenuates rapidly within 15 km of the converter stations, this mode does not pose any harm to pipeline system radio communication. The line-to-line mode is not expected to affect the pipeline systems because it is approximately 2 mV/m under the line at ground level and attenuates with increased distance from the line. It is below levels generated by other radiated sources such as from broadcast stations.

4.6 Telephone Interference

Telephone communication systems have been used in communication and signaling systems for pipelines. In addition, some electrical communication means used in the pipeline system closely resemble a basic telephone system. Therefore, a telephone interference study of the pipeline communication and signaling system is necessary.

A dc converter approximates a constant-voltage harmonic source on the dc side of the converter, and a constant-current harmonic source on the ac side of the converter. The harmonic currents flowing on both sides of a dc converter station are generated by the switching operations in the switching devices (thyristor or IGBT). These harmonic currents will induce potentials in neighboring parallel conducting objects as a result of magnetic induction. The magnetic coupling may be expressed as mutual impedance, i.e., as the voltage induced in the telephone circuit per ampere of current in the power circuit.

The magnetic coupling between the communication circuit and a high-voltage power line is a result of the ac magnetic flux linkage between the two systems. Therefore, harmonic current in a high-voltage dc transmission line induces a voltage in a wire running parallel to it with a magnitude that is determined by the mutual impedance. The coupling between parallel circuits is directly proportional to the common length, known as length of exposure. It is also dependent on the frequency and distance between the parallel circuits. The degree of coupling increases with frequency unless a dissipative media such as a ground is present between the two conductors in which case, the coupling is more complex and can be expected to be reduced for higher frequencies.

In order to assess the potential for telephone interference from ac harmonics, it is important to take into account the harmonic currents induced in the earth. The currents in the earth are modeled using an equivalent ground conductor.[25] The equivalent ground conductor substitutes the distributed currents through the earth and is modeled using an image conductor buried at an equivalent depth[26] below the earth's surface. Therefore a dc bipolar link with a metallic return conductor has significantly closer spacing between its conductors compared to the same bipolar link using an earth return. As a consequence of the distribution of current between a metallic return conductor and the earth, a metallic return conductor decreases the earth's currents and reduces the potential for interference accordingly.

The neutral current of a dc bipolar link, as stated earlier, is composed of a potential current mismatch, due to independent operation of the two converters, and their harmonic currents. In general this current, also known as residual current, is the primary contributor to telephone interference. Under monopolar operation, the harmonic currents on the neutral return conductor also contributed to the telephone interface.

The sensitivity of the human ear, the response of the telephone receiver, and the coupling between power and telephone circuits all vary with frequency. These variations are taken into account by appropriate weighting factors. Two systems of weighting factor are in wide use to determine the telephone interference in the U.S.: the Bell Telephone Systems (BTS) and Edison Electric Institute (EEI) weight factors. The weights in these systems have been revised from time to time to reflect increasing bandwidth and higher quality of telephone transmission. The weighting factors for each system, based on the sensitivity of the ear and the response of the telephone equipment, apply only to currents and voltages on the telephone circuit. This is called

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[25] Also known as Carson conductor.

[26] This depth is a function of ground resistivity. For a detailed derivation see Uhlmann 1975, p. 228-229.

C-message weighting. Kimbark[27] compiled a detailed description of these factors and outlined the interference calculation process.

The *I·T* product is defined as a root sum square of weighted harmonic currents as shown below.

$I \cdot T = \sqrt{\sum \{T_f I_f\}^2}$ where T_f is the *TIF* (Telephone Influence Factor) weighting factor.

The *I·T* product approximately relates to the effect of the harmonic currents flowing in the power circuit on the telephone lines. This is often defined on a station basis, i.e., for the total harmonic current flowing out of the converter bus into the ac system but not for the harmonic currents flowing in each line connected to the converter bus. This is an approximate measure of the amount of noise induced on a telephone circuit due to power-line currents.

To determine the noise induced in a communication circuit, the current in each power-line conductor is determined at each harmonic frequency. The current is then multiplied by the respective coupling impedance between each conductor and the communication circuit.[28] As a means of simplification, the concept of equivalent disturbing current (I_{eq}) is applied. I_{eq} is a weighted combination of harmonic currents in all conductors established to recognize existing and anticipated telephone circuits. Specifically, I_{eq} is a single-frequency current flowing in a theoretical single conductor located geometrically between the power conductors, which produces the same weighted noise in a nearby communication circuit. I_{eq} can be determined using the following equation,

$$I_{eq} = \sqrt{\sum \left[\{K_r(f) I_r(f)\}^2 + \{K_b(f) I_b(f)\}^2 + \{K_3(f) I_3(f)\}^2\right]}$$

where I_r is the residual component of current, I_b is the balanced component of current, and I_3 is the current in metallic return conductor or electrode line. K_r, K_b and K_3 are frequency dependent weightings.

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[27] Kimbark 1971, p. 327-331.

[28] Wilhelm 1994.

Interference from an alternating electric field can be suppressed by using shielded cables. The interference caused by harmonic currents can be reduced with the aid of ac and dc filter circuits and smoothing reactors. The filter circuits have to be custom-made according to the requirements of each specific system. Telecommunication systems can also be protected against interference by installing the appropriate protection such as isolation transformers or grounding reactors.

Based on the design proposed by NYRI, tuned dc filters at the 12th and 24th harmonics will limit the harmonic current superimposed on the dc side of the converter to 0.5 A-RMS under balanced bipolar link operation and to 1 A-RMS under monopolar link operation. The NYRI dc concept has not reached the analytical detailed design stage at this time, and these numbers are provided as the performance criteria.

The current harmonic level of 1 A-RMS is relatively low compared to similar dc transmission lines already in service. In order to provide a context for this value, the results of harmonic measurement of a comparable dc transmission line are presented.[29] Phase I of the New England dc bipolar inter-tie has a capacity of 690 MW with a nominal voltage of ±450 kV dc and is equipped with an overhead metallic return conductor. The accepted performance criterion under a bipolar link operation is 53 mV/km, and 260 mV/km. These performance measures were based on a one-kilometer line parallel to the dc transmission line with a one-kilometer separation. The dc transmission line current spectrum during bipolar link operation at rated power of 690 MW is shown in Figure 8. The RMS values for different harmonics are shown in Figure 8. The 6th and 12th harmonics have magnitudes of 0.9 A and 1.4 A respectively. The dominant harmonic appears to be the 3rd order harmonic for the New England Phase I dc bipolar inter-tie[30].

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[29] Garrity 1989, p. 779-786.

[30] The test results together with the fact that the 3-pulse harmonics are characteristic of a 3-pulse or half-bridge converter indicate that imbalances within the twelve-pulse converter are the cause of the 3-pulse harmonic. The conventional model described which was used to model the converter power circuits for this installation cannot reproduce the measured 3-pulse harmonics.

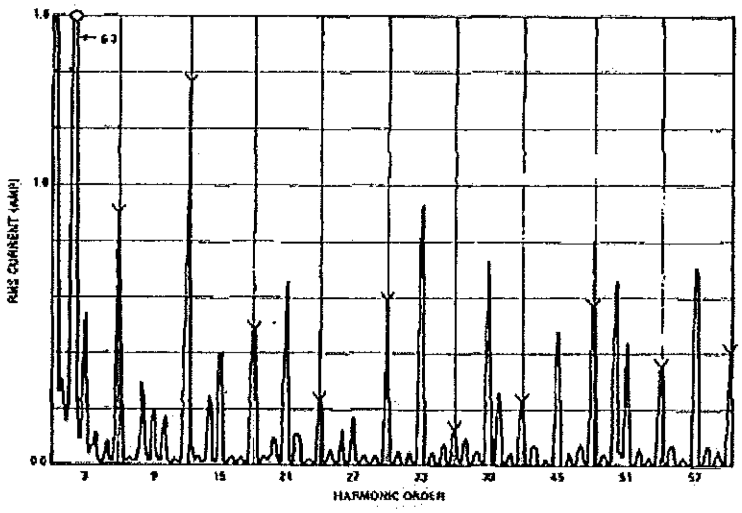

Figure 8. DC side current magnitude spectrum of rms current measured at harmonic frequencies

In order to provide an estimated value for the *I·T* factor based on the proposed performance criteria for the NYRI dc transmission line, it was assumed that the NYRI proposed dc side of the converter current spectrum resembles the New-England spectrum, except for the 3rd order harmonic which was unusually high in the New England system and later reduced[28]. Table 2 contains the harmonic current data used to calculate the *TIF* factor.

Table 2 - DC side current harmonics and *TIF* values[31]

h	TIF	I_{RMS} A	$(TIF.I)^2$	h	TIF	I_{RMS} A	$(TIF.I)^2$
3	30	0.00	0.00	39	9840	0.12	1,452,680
6	400	0.16	3,968	40	10090	0.04	194,826
12	2760	0.28	597,093	42	10480	0.04	210,178
15	4350	0.07	92,701	45	10480	0.09	840,710
18	5400	0.09	223,209	48	10210	0.10	1,149,047
21	6050	0.12	549,150	50	9670	0.11	1,209,660
24	6650	0.04	84,627	51	9230	0.08	528,217
27	6970	0.03	59,499	54	8410	0.06	265,285
30	7570	0.10	631,652	57	7470	0.12	837,184
33	8330	0.16	1,720,913	60	6460	0.07	204,441

$I{\cdot}T = 3{,}300$

The calculated $I{\cdot}T$ factor for the proposed NYRI dc transmission line based on the performance criterion $I_{RMS} = 0.5$ A is an order of magnitude smaller than the corresponding reported performance index values,[32] such as 25,000 for the Eel-River 230 kV, 320 MW Hydro-Quebec dc link. The calculated $I{\cdot}T$ factor would be approximately doubled under monopolar link operation with $I_{RMS} = 1$ A. It may therefore be prudent to reconsider the specified $I{\cdot}T$ factor to reduce the cost of harmonic filters for the NYRI system since these other systems operate without any known harmonic interference problems.

The measured values of harmonic currents were used to calculate the C-message-weighted induced noise (WIN) in a one-kilometer line parallel to the New England dc transmission line with a one-kilometer separation[33].

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[31] The harmonic current magnitudes are calculated based on $I_{RMS} = 0.5$ A. Current magnitudes are RMS ampere.

[32] Wilhelm 1994, table 13.2.3.

[33] Garrity 1989, p. 779-786.

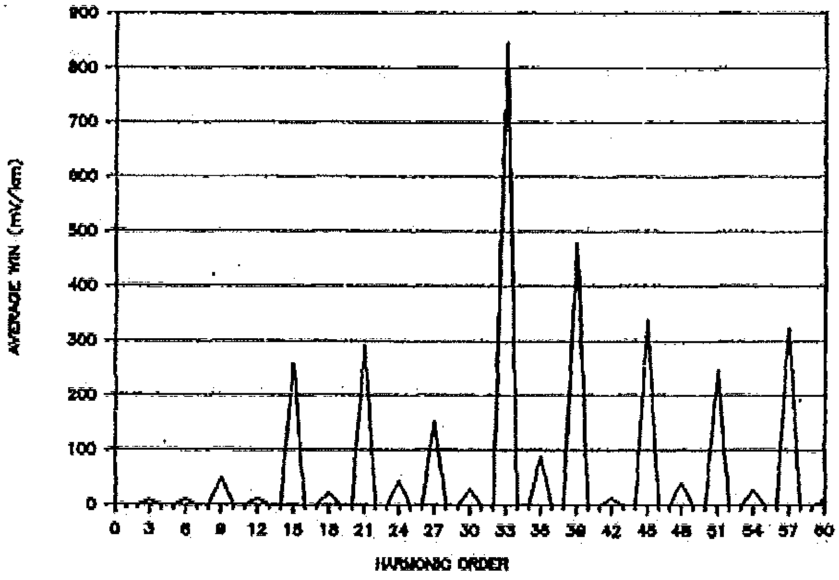

Figure 9. Average weighted induced noise spectrum

The WIN – using residual components of the measured harmonic currents – becomes 1,187 mV/km when the New England dc transmission line is operating at 690 MW. The test results indicated that the WIN values substantially exceeded the established performance levels. The results also indicated that the WIN was substantially reduced when the pole filters were disconnected, the neutral reactor bypassed, and the converter neutral points were grounded locally. As a result, the utilities agreed to permanently bypass the neutral reactor as an interim mitigating measure[34].

4.7 Inductive Interactions

Induction from ac harmonic currents on a high-voltage dc transmission line and a pipeline system results in voltages in the pipeline at harmonic frequencies that have been generated as a result of dc converter operation. In order to calculate the magnitude of the induced voltage in the pipeline, information on the dc transmission line harmonic magnitude and the mutual

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[34] Garrity 1989, p. 779-786.

inductance values between the dc transmission line conductors and the pipeline systems are needed. The calculation process closely resembles the telephone interference calculation as discussed in the previous section. The calculation process also requires information on the return current distribution between the metallic return conductor and the earth and the resistivity of the earth.

As discussed in this report, the proposed dc transmission line design includes a metallic return conductor. Although the metallic return conductor effectively isolates the dc return current from flowing through the earth, it is less effective in restraining harmonic current from flowing through the earth. Therefore, the effect of the earth return path is considered in order to determine the induced harmonic voltages.

The harmonic return current is divided between the equivalent metallic return conductor and the earth. The impedance of the metallic return conductor and earth paths determine the distribution of harmonic return current between the two. As shown in Figure 10 the harmonic return current, equal to the sum of the two harmonic currents I_1 and I_2, is divided between the metallic return conductor *n* and earth return path shown symbolically as *e*. The subscripts *1* and *2* stand for the high-voltage main dc conductors installed on the transmission tower, *n* stands for the equivalent metallic return conductor, and *P* stands for the pipeline. The transmission tower is not shown in this figure for simplicity.

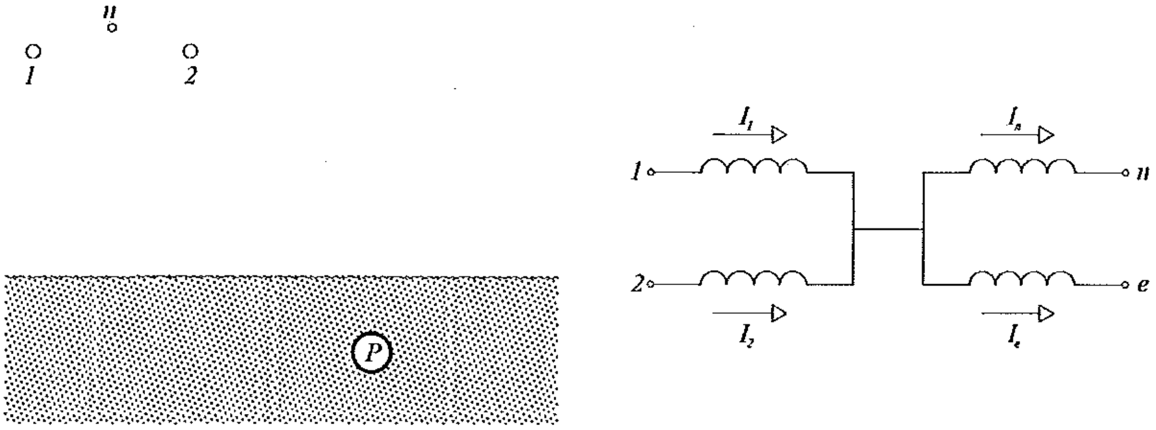

Figure 10. Simplified dc transmission conductors and return current inductances

As a first order calculation, the traverse induced noise in the pipeline caused by ac harmonics in a parallel power circuit can be approximated by using the mutual coupling between the pipeline and the dc transmission line conductors. Assuming the pipeline as conductor P, the mutual impedance, Z_{maP}, between conductor a and pipeline P with common earth return path can be determined using the following formula,[35] known as Carson's equation.

$$Z_{maP} = 0.00159f + j0.004657f \log\left(\frac{2160\sqrt{\rho/f}}{d_{aP}}\right) \frac{\Omega}{\text{mile}}$$

where ρ is the earth resistivity Ω.m, f is the frequency in Hz, and d_{aP} is the distance between conductor a and pipeline P. Carson's equation determines the induced voltage between the pipeline P and the earth for a unit current in a and earth return. The h^{th} order induced harmonic voltage in pipeline P can be determined from:[36]

$$V_{Ph} = \ell\left(I_{h1}Z_{m1P} + I_{h2}Z_{m2P} + I_{hn}Z_{mnP}\right)$$

where ℓ is the length of exposure and I_h is the harmonic current of order h in power line.

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[35] McMichael 1950.

[36] IEEE Std-1124-2003.

The following table summarizes the assumed the distances between the pipeline and the high-voltage conductors using the dimensions provided by Figure 3. Calculations assume the pipeline is located at the edge of the pipeline ROW and buried 36 inches below the ground level. The levels would be lower for larger distances between the dc transmission line and pipeline.

Table 3 - Pipeline distance from the dc transmission line conductors

$d_{P,1}$	102.883'	$d_{P,2}$	65.460'	$d_{P,n}$	129.034'

The harmonic current spectrum of the dc transmission line and its distribution between the metallic return conductor and the earth determines magnetic field intensity and therefore determines the induced voltage in a coupled circuit, including the pipeline. Similar to the approach adopted in the previous section, the harmonic current spectrum for the NYRI dc transmission line is assumed to be proportional to the New-England harmonic dc transmission line spectrum, which is produced in Table 2. The New-England residual current spectrum is also used for calculating the metallic return current, as exhibited in Table 4. These assumptions provide an initial approximation. More in-depth analysis requires further system details that will not be available until the final design.

Table 4 - Residual current harmonic content

h	9	15	21	27	33	39	45	51	57
I_{RMS} A	0.1	0.2	0.2	0.1	0.5	0.3	0.3	0.2	0.2

The induced voltage per mile for the pipeline is calculated assuming uniform ground conductivity (including the pipeline coating) of 1,000 Ω.m, which includes the pipeline coating. The mutual impedance between the pipeline and the dc power line at various frequencies, per

Table 2 and Table 4, were calculated using Carson's formula. The screening effect of conductors is not considered at this stage. Table 2 provides the harmonic current amplitudes for dc conductors at different frequencies. Since the harmonic current in the metallic return conductor opposes the dc conductor harmonic direction, the amplitudes of these harmonics are assumed to be negative of the Table 4 entries. The induced voltage in pipeline P per mile; i.e. V_P, is calculated and tabulated in Table 5. All the voltages are calculated for one mile of the pipeline parallel to the transmission line as illustrated in Figure 3.

Table 5 - Calculated induced voltages per mile in pipeline (NYRI case)

h	V_P V	h	V_P V
6	0.9	39	0.278
9	0.352	40	1.142
12	2.873	42	1.189
15	0.216	45	1.193
18	1.308	48	3.322
21	0.558	50	3.781
24	0.742	51	0.224
27	0.269	54	2.198
30	2.241	57	3.236
33	1.332	60	2.798

The calculated induced voltages are relatively small. Since the line height was considered at maximum sag (closest distance to the pipeline) instead of average line height along the span, the actual voltage levels will be less than listed. The maximum induced voltages occur at frequencies 720, 1,080, 1,800, 1,980, 2,880 Hz. Table 5 provides the spectrum of the induced ac voltages along the pipeline at different frequencies. Since the effect of line attenuation and the earth surrounding the pipeline are not considered in the above calculation, the induced voltage effect rises at higher frequencies. More accurate results require system details that will not be available until the final design phase of the project.

A minimum dc potential of -2 volts needs to be maintained between the pipeline and the earth for cathodic protection purposes. The largest induced harmonic voltages in the pipeline have a magnitude of ~ 4 volts. An ac voltage of this magnitude has a direct impact on the cathodic protection voltage profile along the pipeline, by forcing the pipeline to earth dc potential to drop below the minimum required amount. The effect of the dc transmission induced ac harmonic voltages into the pipeline is to annul the protection provided by the pipeline cathodic protection system. A practical remedy to this issue is to raise the cathodic protection source voltage to the effect that the attenuated voltage along the pipeline remains above 2 volts.

The above analysis assumes steady state (fixed loading) operation. While an analysis of dynamic conditions suggests potentially greater induction, the impact was determined to be negligible.

4.8 Conducted DC Current

The NYRI dc metallic return conductor minimizes the dc current flow through the earth, and thus reduces the dc transmission line interference into pipeline cathodic protection to a negligible level.

A source of residual dc current is the leakage current through contaminated dc suspension insulators. The suspension insulators are typically a string of insulator disks that meet the mechanical and the electrical insulation design requirements. A proposed insulator design for one of the towers is reproduced in Figure 11.

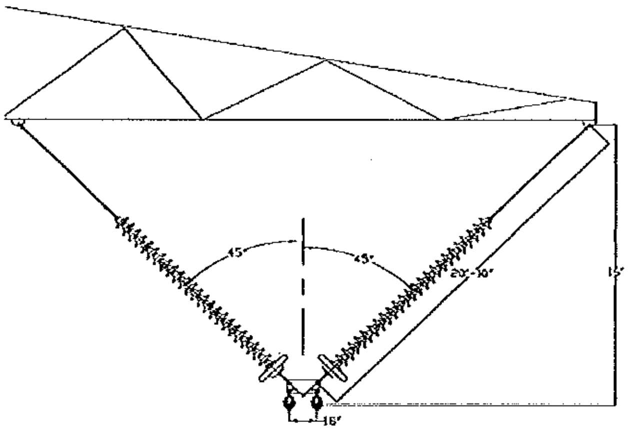

Figure 11. Suspension assembly detail

The distance between two consecutive dc transmission towers along the pipeline segments will vary from approximately 700 to 1,100 feet. Assuming a worst-case scenario with eight towers per mile and 660 feet between two towers, there are a total of 32 insulator strings for each mile of the dc transmission line. The maximum leakage current for a dc insulator with no arcing is below 0.5 mA[37]. The same number has also been suggested as the maximum value for the insulator strings by Washington Group.[38] Therefore, the maximum stray dc leakage current per mile per polarity (pole) would be + or - 16 mA. These leakage currents would tend to neutralize at the towers and any other adjacent towers joined by a bonded shield wire and only a small portion would flow back to the converter station. The portion of the leakage current flowing to the converter station would thus partially flow through the earth and partially through the pipeline. Coated pipeline is typically insulated from the earth, except for the hotspots along the pipeline. Thus a negligible portion of the leakage current would actually flow through the pipeline. The stray dc current from insulator leakage is in the milli-ampere per mile range under even worst-case conditions and therefore is negligible.

The result of the Pipeline Research Council International indicated that the ground-return currents from a dc system might have some effect on a pipeline even if the line is separated 100

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[37] Sörqvist and Vlastós 1997, p.1041-1048.

[38] Email correspondence from NYRI 9/20/07.

miles or more from the nearest electrode for a dc system with an earth return[39]. Currents induced in the ground and currents from adjacent cathodic protection systems will also have some effect on pipelines. The NYRI dc metallic return conductor practically isolates the dc transmission line from the earth and does not effect the pipeline

4.9 Pipeline Shielding

Varying magnetic fields induce current flows in conductive materials. This current, called eddy current,[40] tends to oppose the external magnetic field inside the conducting object producing a lower net field.[41] The eddy currents tend to stay on the surface of the conducting object. This occurs because the reactance at the conductor surface is smaller than the reactance of other possible paths within the conducting object. The skin depth, δ, measures exponential damping of the electromagnetic interference as it travels through the conducting object.[42] The skin depth for a flat conducting plate is:

$$\delta = \left(\sqrt{\pi f \mu \sigma}\right)^{-1} \approx 503\left(\sqrt{f \mu_r \sigma}\right)^{-1} \text{ meter}$$

where f is the frequency, μ and σ are the permeability and conductivity of the conductor respectively. This equation shows that the skin depth decreases as the frequency increases. Figure 13 depicts the comparative values for the skin depth for common metals.

Pipelines are typically made of iron, which is a conductive material. The skin depth for a flat iron plate at 60 Hz ($\sigma = 1.02e7\ (\Omega.\text{m})^{-1}$, $\mu_r \sim 1000$, $\mu \sim 1.26e\text{-}3$ H/m) is 0.64 mm. The shielding effectiveness of solid conduit, in this case pipeline, is the same as that of a solid sheet of the same thickness and material.[43] Therefore the pipeline interior is effectively shielded from

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[39] PRCI 1970, p. 91.

[40] Current that circulates in a metallic material as a result of electromotive forces induced by a variation of magnetic flux (IEEE Dictionary, 2000).

[41] Kipp 1969, p. 315.

[42] The external electromagnetic field drops to 5 percent of its magnitude at the surface of conductor once it travels $3.\delta$ into the conductor (Kipp, 1969, p. 612).

[43] MIL-HDBK-419A, p. 8-60.

external electromagnetic fields. Thus the dc transmission line's ac electromagnetic field does not interfere with the pipeline monitoring and internal integrity inspection tools of the system such as smart pigs.

Magnetic flux leakage (MFL) tools, such as smart pigs, apply the principles of flux leakage inside a pressurized, flowing gas-transmission pipeline. A magnetizing system applies a magnetic field along a length of pipe as the tool moves through the line. Defects distort this applied field, producing flux leakage. Sensors measure flux leakage, and a recording system stores the measurements. Finally, the measurements are analyzed to estimate the defect geometry and severity[44]. MFL tools use energy density magnetic fields for accuracy, which are significantly larger than the dc transmission system EMI. Thus the dc transmission system EMI does not affect inspection accuracy of the MFL tools.

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[44] Nestleroth and Bubenik 1999.

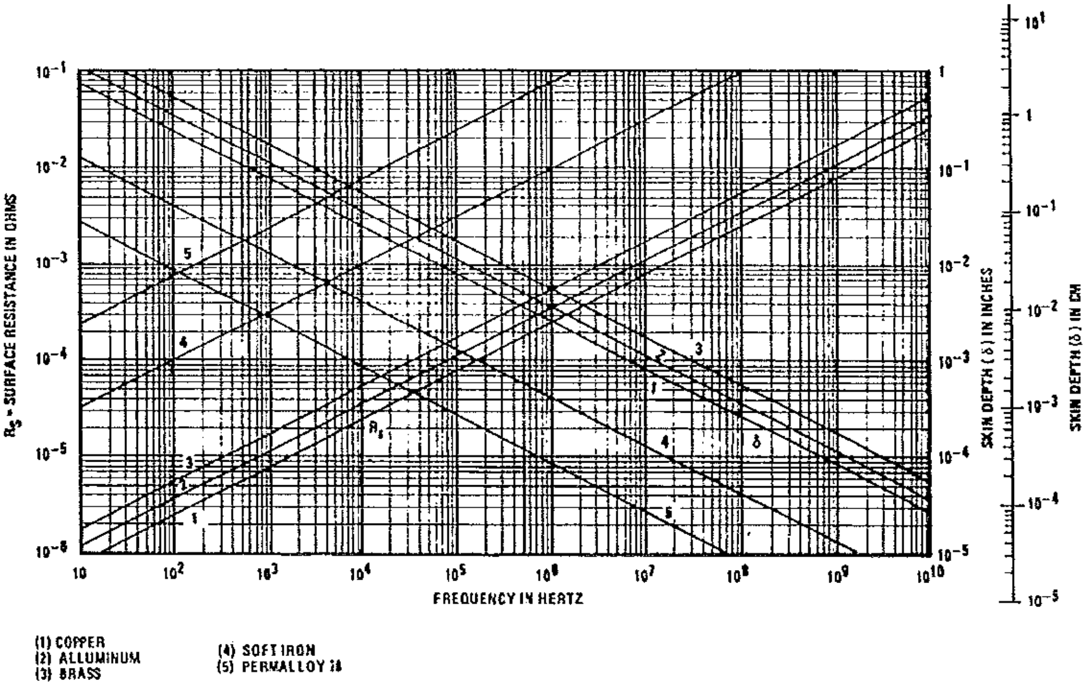

Figure 12. Skin depth for common metals

4.10 Conclusion

The effects of the conductive and inductive voltages and currents have been investigated. It has been shown that the conductive currents in the earth are normally negligible except during system transients such as faults. The associated fault voltages and currents for a dc line are less than for a comparable ac line or for lightning strikes. The normal conductive currents are of negligible magnitude and are too weak to affect the pipeline cathodic protection and control and monitoring systems. DC transmission ground fault can raise the momentary ground potential along the pipeline, which can overwhelm the pipeline cathodic protection, and communication and monitoring circuits but these effects will be less severe than for a typical ac line. Pipeline systems, including cathodic protection, should be inspected periodically especially in proximity to a fault location. This inspection can be based on the recommended procedure or maintenance guideline enforced for a lightning strike to the pipeline.

The effects of the EMI on the radio and telephone communication systems have also been investigated, and it was shown that the EMI effect is within industry acceptable limits. More detailed analysis, however, is required once further system design parameters are determined.

The harmonic induced voltages into the pipeline could have magnitudes in the range of the electric potential required for pipeline cathodic protection. The effect of these induced voltages depends on the ac impedance of the cathodic protection systems. If the ac output impedance of the cathodic protection systems is low, the voltages will be essentially short-circuited to the ground and should then not have any effect.

5 Exemplar Pipeline Equipment

The data on causes of gas transmission pipeline accidents (i.e., threats to the pipeline) show that between 1990 and 1999, there were a total of 777 reported accidents. The data indicates that the two greatest threats to a pipeline are from outside force damage (41%), and corrosion (22%)[45]. Pipelines are guarded against corrosion by coating and cathodic protection. It has been established that the NYRI dc transmission line with a dedicated metallic return conductor will have a negligible effect on the pipeline's cathodic protection systems. The pipeline is typically protected against outside forces by structural barriers or an impact monitoring system. No exemplar protection or monitoring system for the pipeline is identified at this time; however, a cursory review of commercially available equipment indicates that such equipment, such as GE ThreatScan,[46] is acoustic equipment. Such systems provide acoustic monitoring for accurate location and immediate risk assessment of impact events to pipelines, both underground and above ground. Considering that the audible noise of the NYRI dc transmission line is below common environmental noise levels,[47] the dc transmission line audible noise is not expected to interfere with such a monitoring system.

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[45] Federal Register / Vol. 68, No. 18 / Tuesday, January 28, 2003 / Proposed Rules, page 2486.

[46] GE Gas & Oil, 2007.

[47] The NYRI dc transmission audible noise is 10 dB(A) below the EPA guideline (Exponent, 2007).

6 Mitigation Techniques

6.1 Review

Potential interference issues can be minimized or obviated, by routing transmission lines as far away as possible from other facilities[48]. Prevailing regulatory and environmental factors, however, often force the electric and other utilities to share common corridors rather than follow separate routes. Hence, there is not much regulatory flexibility for achieving separate ROWs. This can be mitigated in part by installing filters at dc converter stations of appropriate design and size to attenuate sources of harmonic interference to acceptable levels. Despite the great care and effort expended during planning, design, construction, and commissioning of dc projects, many factors contribute to uncertainty that could potentially result in interference conditions between the power system and the pipeline system. Thus, consideration of mitigation is a logical and economic course of action to resolve localized interference issues, if they occur.

The following four general steps can be followed to achieve successful mitigation, if necessary:

1. Characterize the type and level of potential interference and the level of mitigation required.
2. Identify the locations of potential interference.
3. Identify the type of mitigation device to be used at each location.
4. Schedule the implementation of mitigation devices.

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[48] IEEE Std. 1124-2003.

Although it is the conversion of an ac electromagnetic field from a transmission line into conducted interference (in the pipeline) that usually results in operational issues, the level of conducted interference that such a field could normally produce is still far below the level needed to cause permanent damage to the equipment.[49] The only significant exception to this generalization is, of course, that of a short circuit of a dc pole to the ground; however, even in this case the impact of the fault would be less than that associated with an ac line.

6.2 Interference Mitigation

Once harmonic interference issues have been identified, there are many different techniques available to electric utilities and pipeline companies to mitigate circuit interference. Several mitigation techniques are also discussed in IEEE Standard 1137. Some applicable techniques are as follows:

- Modify dc filters,
- Active dc filters,
- Improve loop balance,
- Replace open-wire circuits with cables,
- Improve cable shield grounding,
- Verify cable shield continuity,
- Apply noise chokes,
- Apply induction neutralizing transformers, and
- Use optical fibers.

While the application and benefits of most of the above items are obvious and self evident, the dc filters and loop balance are less obvious and are discussed below.

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[49] Cramer 2004, p. 6-3.

6.2.1 DC Filter Modification

Earlier in this report, it was shown that harmonics on the dc side of the converters could be a potential source of telephone noise[50]. The analysis indicated that these harmonic effects are negligible; however the results were based on limited system details and assumptions based on existing dc transmission lines. Additional calculations should be conducted once further system detail becomes available. With detailed models based on final system design for calculating harmonic generation, it will be possible to compute higher order non-characteristic harmonics more accurately. This should determine the degree of filtering required on the dc side of the converter. Hence, any unpredicted interference due to higher order non-characteristic harmonics is less likely and so is the need to modify the dc filter later. If such calculations indicate a greater potential for interference than indicated by this analysis, then the design of the dc filters can be updated to eliminate the noise. An example of modification of a 12th order harmonic filter to provide 12th order and high-pass filtering and their filtering characteristics are shown in Figure 13. This modification reduced noise-metallic voltage by about 10 dB.[51]

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[50] Telephone noise is considered as a general term for noise into pipeline communication and signaling systems.

[51] Hancock et al. 1979.

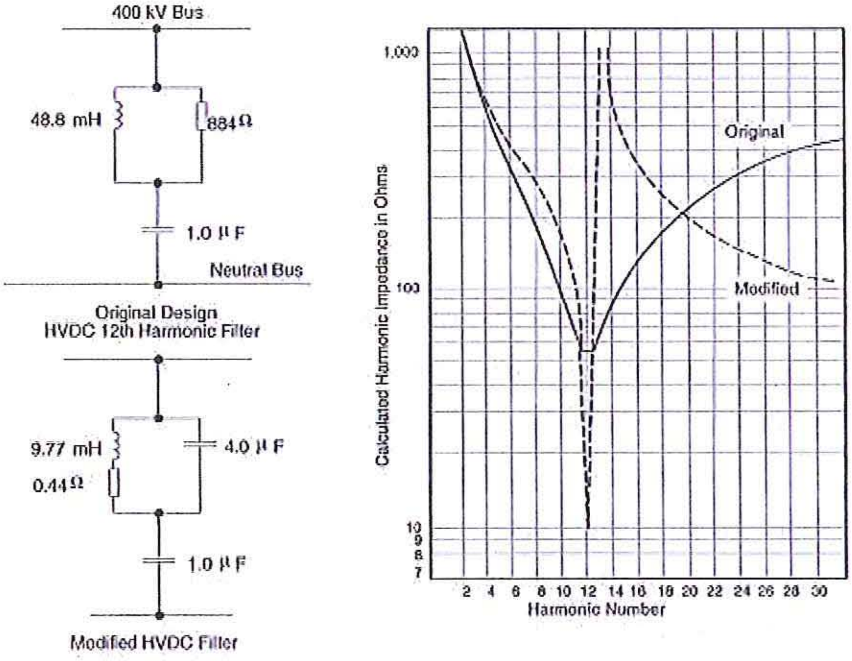

Figure 13. DC filter modification

6.2.2 Balance of Loops and Equipment

The induced voltage is of noise to ground type, whereas actual noise perceived by a circuit is metallic noise[52] or circuit noise. The difference is called balance voltage, similar to rail-to-rail induced voltage. Improvement in balance of loops results in reduction of metallic noise. The improvement will not only result in a reduction of induced noise but also will improve the overall quality of signaling service. Monopolar operation needs also to be considered in this study.

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[52] Metallic noise is the weighted noise current in a metallic circuit at a given point when the circuit is terminated at that point in the nominal characteristic impedance of the circuit (IEEE, 2000).

7 Findings and Conclusions

The effect of the NYRI dc transmission line on a parallel pipeline, and the pipeline protection and monitoring systems have been evaluated in this report. The following are the findings and conclusions:

1. The flow of dc current in the earth and interference to any adjoining facilities, including those of pipelines, is essentially eliminated by the provision of the metallic return conductor. The dc leakage current, through the suspension insulators is negligible and will not be a source of interference. Only a dc fault current that arises from infrequent, short circuits from one pole to the ground would be large enough to potentially interfere with the pipeline. The fault current and any interference produced, however, are of extremely short duration.

2. The proposed dc transmission line will be designed to reduce harmonic currents. In addition, the inductive coupling between these harmonics on the dc transmission line and the pipeline should not result in interference into pipeline cathodic protection. The induced ac voltage into the pipeline might be in range of cathodic protection drainage potential.

3. Internal monitoring devices, such as smart pigs, are shielded by the pipeline metallic structure from fields of the dc transmission line. DC transmission line audible noise would not have any impact on typical acoustic based monitoring equipment.

4. Because the proposed dc transmission line will be designed to minimize harmonic currents, magnetic field coupling to the pipeline signal and communication systems and circuits should not be an issue.

5. Shield wires could provide a low resistance path for the pipeline protective dc current.

This report was based, in part, on certain design assumptions and industry guidelines. As part of the final design, the design team will study system harmonics. That study will build on and amplify the analyses provided in this report and support additional design criteria, if necessary.

8 Limitations

Exponent investigated specific issues relevant to the objectives of this stage of the project. Therefore, the scope of services performed during this investigation may not adequately address the needs of other users, and any reuse of this report or the findings, conclusions, or recommendations presented herein is at the sole risk of the user.

Preliminary conceptual designs were evaluated to assess the potential likelihood and severity of the operation of the proposed transmission line and to identify the need for mitigation of electrical effects that might adversely affect adjacent pipeline functions. During the final design stage of the project these issues will be reviewed again and addressed in the converter design, ac/dc filter specifications, surge capacitor, ac system specification, and communication system details.

The conclusions and recommendations presented herein are based on the work performed as described in this report. Exponent reserves the right to revise these conclusions and recommendations if and when additional information becomes available.

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