Electrical Interference on Underground Structures

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1.0 Introduction

Interference can be defined as any electrical disturbance on a structure caused by a stray current. In this context, 'stray' refers to a current in an unintended path, although it is recognized that current will take all available paths in inverse proportion to the relative resistance of each available path.

Corrosion as a result of interference from a DC transit system was first reported by Stone & Forbes[1] in 1894, just six years after the transit system began operation. Their paper was entitled 'Electrolysis of Water Pipes' and the term 'electrolysis' has persisted ever since[2,3,4] to denote the corrosion attack on an underground structure caused by a stray current. Regional committees of underground utility representatives that were formed to discuss mutual electrical interference problems are called Electrolysis Committees.

Sources of stray current are any AC or DC systems that are grounded to the earth or use the earth as a current path. This includes both AC and DC power systems, cathodic protection systems, electrified transit systems, and telluric currents caused by the interaction of solar particles on the earth's magnetic field.

2.0 Detrimental Effects of Electrical Interference

2.1 AC Interference

Interference caused by AC transmission lines arises from three different modes of interaction, namely; electromagnetic induction, electrostatic induction and resistive coupling. These modes of interaction are particularly applicable to steel pipelines located on or near AC transmission lines.

Electromagnetic induction causes a voltage to appear on the paralleling structure, since the structure intercepts the electromagnetic field of the current carrying transmission lines. The magnitude of induced voltage (V_{EM}) is a function of the transmission line phase currents and their relative imbalance, the geometrical arrangement and distance between phase conductors and pipe and the length of parallelism. In this case the piping is functioning as the secondary of a single turn, air core transformer as illustrated in Figure 1.

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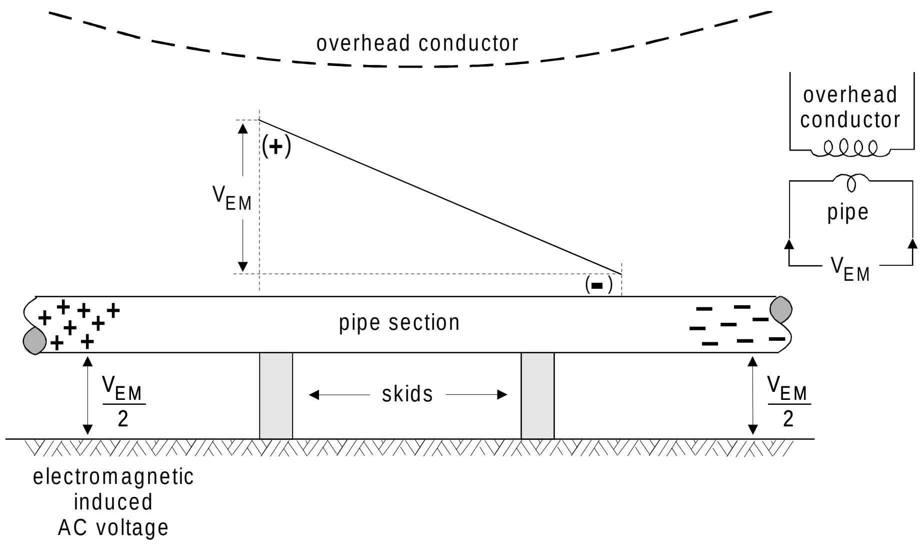

Figure 1 – Electromagnetic Induced AC Voltages

Electrostatic induction arises from the electrostatic field of the conductors interacting with the piping where the piping acts as one plate of a capacitor having an air dielectric as illustrated in Figure 2. The magnitude of the electrostatically induced voltage (V_{ES}) is a function of the phase conductor voltage, the distance from the phase conductors, and the length of parallelism.

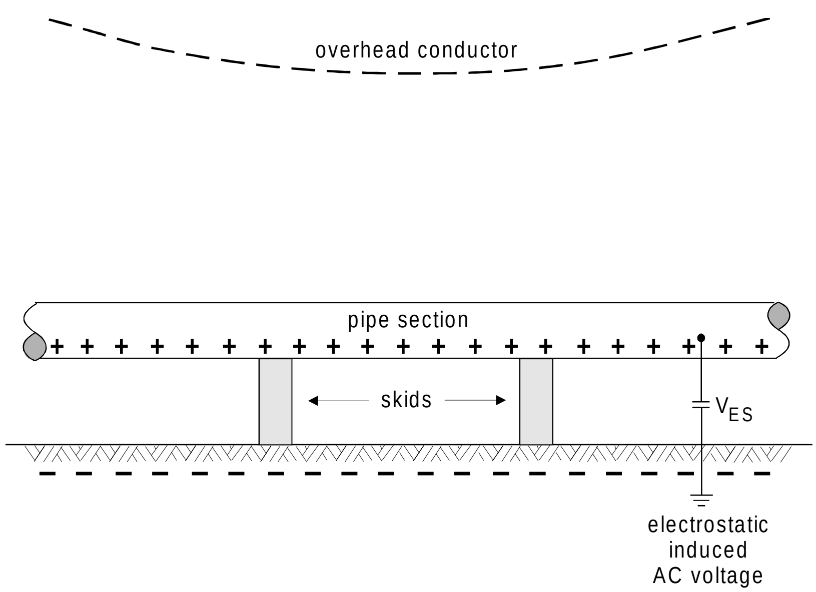

Figure 2 – Electrostatic Induced AC Voltages

Resistive coupling occurs as a result of the proximity of pipe to the transmission line during a power line fault to ground. Since the metal electrical resistivity of the pipe is several orders of magnitude less than the electrical resistivity of soil, the piping carries a large proportion of any fault current.

Electrical AC interference on steel can cause corrosion[5] although the amount of corrosion is a very small percentage of a DC current of equivalent magnitude. Nevertheless, there have been numerous reports[6,7,8,9,10,11] of corrosion on steel pipelines attributed to AC current, in most cases where the piping was otherwise considered adequately protected from corrosion with cathodic protection. Despite adequate levels of cathodic protection, corrosion attack can occur when the AC current density exceeds 2 mA/cm^2 and is to be expected when the AC current density is greater than 10 mA/cm^2. Although it is difficult to determine the actual AC current density, it is possible to estimate it at a 1 cm^2 circular holiday on a coated pipe if the AC induced voltage and soil resistivity is known. Typically where the induced AC voltage expressed in millivolts exceeds the soil resistivity expressed in ohm-cm, then AC corrosion is anticipated. In addition, it has been reported[12] that AC interference can cause a positive potential shift on a pipeline protected with sacrificial zinc anodes.

Another serious detrimental effect of induced AC interference is the personnel or public safety hazard presented by the induced voltage on a pipeline as illustrated in Figure 3. Voltages as high as 750V have been reported[13] from electromagnetic induction and over 1000V from electrostatic induction. Voltages at moments of power line faults can rise to 10 and 20 times steady-state values. Steady-state induced voltages in excess of 15 volts to ground normally require mitigative action.[14]

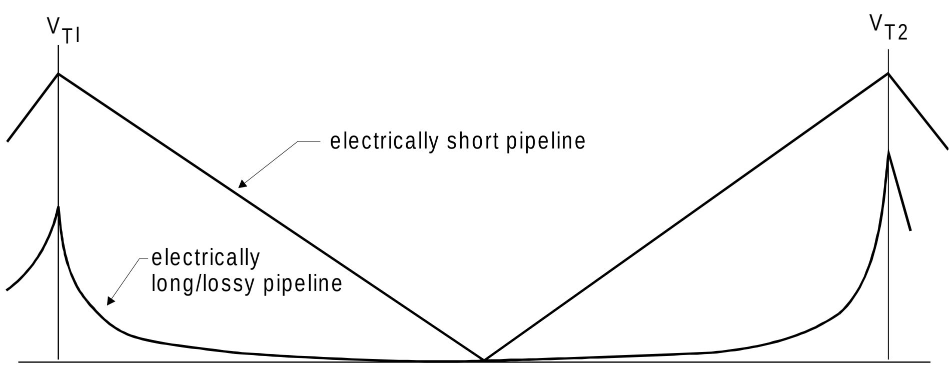

Figure 3 – Typical Induced Voltage Profile on a Steel Pipeline that is Electrically Short and Electrically Lossy

It is virtually impossible to reduce voltages arising from power line faults to a 15 volt level since the voltage and current levels are so high. A report[15] concluded that AC interference caused by resistive coupling can not only over-stress the damaged pipe coating but also melt the pipe through to perforation. In instances where the piping is not melted to perforation failure, partial melting can produce a heat affected zone around the melted point resulting in a hard spot and subsequent cracking and failure. The interference effects during power line faults are of critical importance since catastrophic failure of the piping would seem possible under certain circumstances.

2.2 DC Interference

Electrical DC interference is possible where either the positive or negative feed of a DC source is grounded. Typical sources of DC interference are cathodic protection rectifiers, DC welding machines, HVDC transmission lines, etc.

If the structure is made of an amphoteric metal such as aluminum, zinc or lead, additional corrosion, rather than additional cathodic protection, is likely to result at the stray current pick-up site.

Metallic structures in the earth provide a relatively low resistance current path, depending on their size and extent, compared with the earth. When a DC stray current (I_S) as shown in Figure 4 is picked up on a steel structure, the structure actually receives a cathodic protection benefit. Where the stray current discharges however, corrosion attack can occur at the rate of 10kg per year for every ampere of stray current.

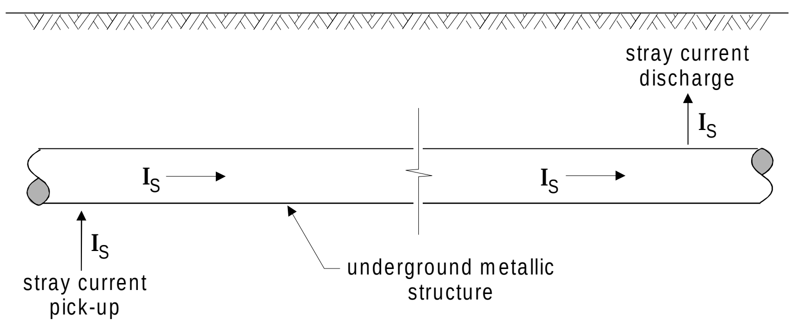

Figure 4 – DC Stray Current Pick-Up & Discharge on an Underground Metallic Structure

Increased structure potentials in the negative direction can also cause coating disbondment[16] and hydrogen embrittlement,[17] however, these latter effects have only been demonstrated in the laboratory. Hydrogen permeation of steel requires very high current densities (in the order of amperes square foot).[18] Cathodic protection rectifiers have also been reported to have caused noise on telephone circuits.[19]

Corrosion as a result of discharge of DC interference current is the most common detrimental effect of electrical interference. The discharge of current is usually detected by observing a shift of the structure solution potential in the positive direction. There is considerable controversy as to the magnitude of positive potential shift which must occur before corrosion commences. A structure solution potential shift in the positive direction does not always cause corrosion. For instance, where the structure experiencing the electrical interference is cathodically protected and the structure potential under interference conditions is not more positive than the valid protection criterion, then corrosion does not result.

Many practitioners have argued that on structures, in the absence of cathodic protection, a specific potential shift must be obtained before significant corrosion occurs. As an example, the British Standards Institution[20] allows a maximum of 20mV positive structure/electrolyte potential charge. Seifert[21] suggests that where positive structure/ electrolyte shifts are less than 10 millivolts, "negligible interference exists". Lennox and Peterson[22] have reported that in some laboratory tests considerable corrosion occurred on a test sample without a detectable IR drop at the anode sites. It can be concluded therefore that any detectable positive potential shift, assuming the measurements are IR drop free, warrants mitigative action.

3.0 Detection of Electrical Interference

The principal method of detecting electrical interference is by measurement of structure/electrolyte potentials, both AC and DC. Where the electrical interference current is static in magnitude and continuous in operation as in the case of an interfering cathodic protection system, comparative potentials at each test location suffices to indicate a negative or positive potential shift. However, the magnitude of electrical interference is best determined by interrupting the source.

Where the electrical interference is dynamic in amplitude and variable in geography, such as with a DC traction system or is static in amplitude but doesn't continuously occur such as with HVDC systems then structure/electrolyte potentials must be recorded over a typical operating period in order to fully define the extent of electrical interference.

The second method of detection of electrical interference is by current flow changes in the structure. Because of the general difficulty in taking current flow measurements and lack of facilities, this detection method is not widely used. Perhaps the best function of this technique is in the verification of electrical interference as detected by the structure/electrolyte potential change method.

4.0 Mitigation of Electrical Interference Effects

The corrosion literature is full of methods and calculations to provide a basis for mitigating the detrimental effects of electrical interference. This mass of literature can be simplified to a few general methods.

4.1 Mitigation of Induced AC Voltages

Mitigation of AC electrical interference is generally accomplished by electrically grounding the structure. Although straight forward in concept, the electrical grounding often must be accomplished while simultaneously maintaining the effectiveness and integrity of the cathodic protection system.

Studies[23] on electromagnetically induced AC indicate that where the pipeline has an exceptional coating it behaves as if it is electrically short such that the induced voltage profile is approximately linear. Conversely a poorly coated or bare pipeline behaves as if it is electrically long and lossy such that the voltage profile is exponential and peak voltages are less than for the well coated situation. Both cases are shown in Figure 3. Therefore, from an AC voltage mitigation viewpoint it is advantageous to have a pipeline with a high leakage conductance to earth. However, from a cathodic protection point of view, it is desirable to have a low leakage conductance so as to minimize the amount of cathodic protection current required.

Between these apparently opposing requirements there is a reasonably ideal solution. That is, the pipeline should be well coated to optimize cathodic protection current distribution so that sacrificial anodes can be connected at periodic intervals as illustrated in Figure 5. The galvanic anodes in effect make the piping electrically lossy to AC and hence reduce the magnitude of induced voltage. Also, it is usual for the electric power transmission authority to stipulate that impressed cathodic protection groundbeds not be located on the transmission line right-of-way in order to avoid interference on metal tower legs from the cathodic protection system. Thus the magnesium anode system complies with this requirement. The galvanic anodes also act as current receptors during power transmission line ground faults, therefore lessening the possibility for pinhole melting and stress cracking of the pipeline.

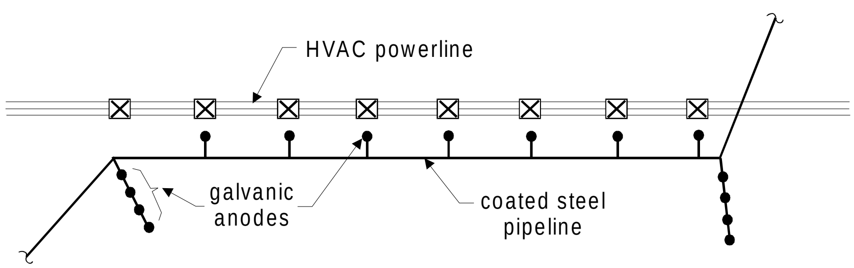

Figure 5 – Mitigation of Induced AC Voltages on a Coated Steel Pipeline Using Galvanic Anodes

In conjunction with the galvanic anodes, the voltage peak at such points as an electric field discontinuity must be treated separately. The grounding facility at these points must be substantially lower in resistance than the characteristic impedance of the pipeline in order for significant mitigation to result. Accordingly, multiple galvanic anodes or long lengths of zinc ribbon are often installed adjacent to the piping.

Changing the phase relationship on double circuited towers to a center point symmetrical arrangement can also substantially reduce the induced AC voltage although electric power companies are reluctant to do this. Use of polarization cells, having stainless steel plates, to ground steady state induced voltage should be avoided[24] as the plates tend to fail by accelerated corrosion.

4.2 Mitigation of DC Interference

Mitigation of DC electrical interference is usually limited to metallic inter-connection of the structures involved, installation of cathodic protection compensation, or shielding of the interfered-with structure in the pick-up area. Mitigation measures should attempt to return the interfered-with structure to its natural potential.[25]

For cathodically protected structures, the structure potential should be returned to the interfered-with company's protective criterion providing the criterion is in agreement with one of the industry standards such as in NACE Recommended Practice RP0169-96 Section 6.0.

The most used method of lessening DC interference is by metallic bonding of the structures involved in the interference. Such bonds can be bidirectional, unidirectional, have positive resistance, or be force drained (negative resistance). Generally bonding is the least expensive method of ameliorating electrical interference effects, and is applicable to both static and dynamic DC interference currents.

Bonding has a limitation in that the interfered with structure must be relatively close to the interfering system to minimize bond costs and resistance. Hence, in the case of two pipelines bonding is most convenient at mutual crossings. Accordingly, a standard arrangement of test equipment, as in Figure 6, should be installed at all mutual crossings to facilitate interference mitigation. There are many advantages of this arrangement. Besides the immediate availability of bond cables in the event of interference, the permanent positioning of the zinc reference electrode allows for precise and repeatable monitoring of the structure/electrolyte potentials at the crossing by all interested parties. This avoids errors between survey teams owing to differing reference electrode locations and it also eliminates the time required to accurately locate the crossing before conducting interference tests.

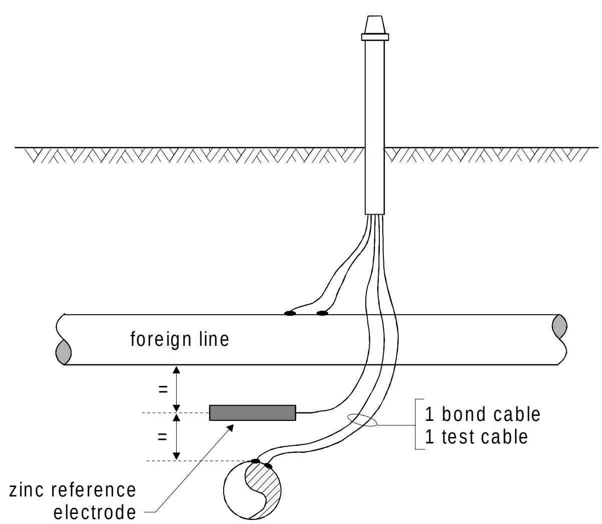

Figure 6 – Typical Cathodic Protection Facilities at a Crossing with a Foreign Line

Bonds, perhaps because of their convenience, are often overused. Bonds have several disadvantages and Morgan[26] has stated that 'any bond is undesirable'. Firstly, bidirectional bonds sacrifice the cathodic protection operating independence of all parties involved in the interference, since cathodic protection system outage on one structure can affect the protection level on another. Moreover, bonds have a high maintenance factor, since they require more frequent monitoring than other areas of the structure. Bonds are also subject to outages because of lightning, AC power fallout, etc.

Where the interference current is reasonably small (e.g. less than 2 amps) the use of galvanic anodes can be used to mitigate electrical interference effects as shown in Figure 7. Here the anodes are placed close to the structure whose system is causing the interference. This close anode placement lowers the resistance of the electrolytic path which previously existed between the two pipes. It also has the advantage that some compensating cathodic protection current is produced by the anodes thus improving the structure/electrolyte potential of the interfered-with structure. The galvanic anode mitigation method allows each party to maintain mutually independent cathodic protection systems.

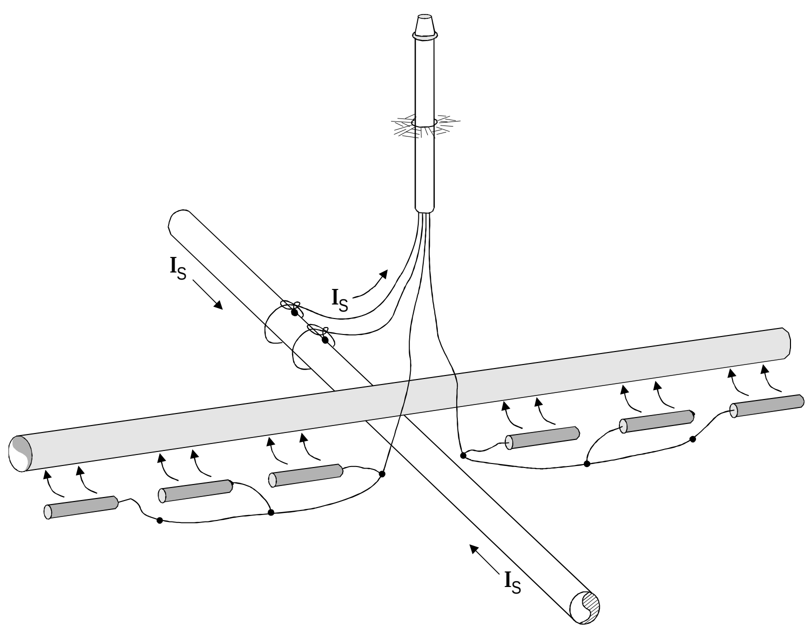

Figure 7 – Typical Interference Mitigation using Sacrificial Anodes

Large interference currents, either static or dynamic, such as one might expect from DC traction systems can not be mitigated with sacrificial anodes. Transit system stray current must be drained using a unidirectional bond to ensure that stray current only enters the source. So called 'electrolysis' switches have been used for this purpose but have several distinct disadvantages. Firstly, they have significant forward resistance, so that a considerable voltage drop exists between the structure and the source when the interference currents are large.

Electrolysis switches are almost as expensive as automatic potential controlled rectifiers, but the rectifier can be inserted in series with the bond to make it a negative resistance bond as in Figure 8. The rectifier is set on the normal structure/electrolyte potential so that it operates only to remove the interference current. A forced drainage bond using a potential controlled rectifier is by far the most successful method of mitigating DC electrical interference arising from traction systems. Further, when all other maintenance factors are taken into account, it is usually the most cost-effective method as well.

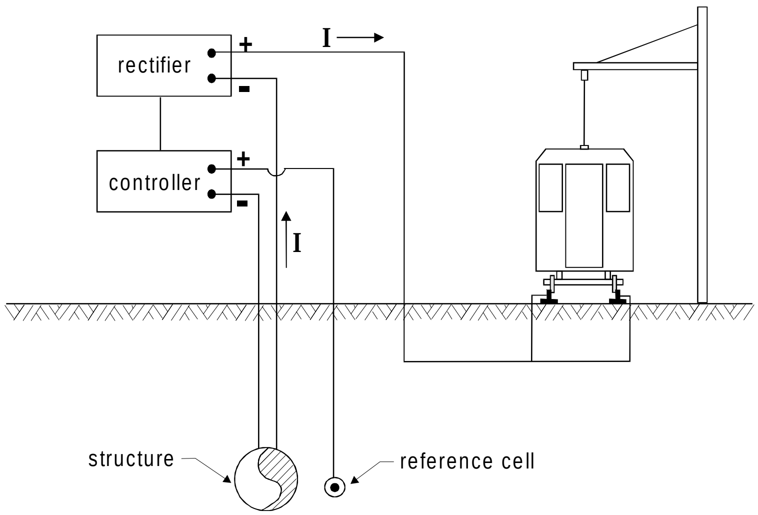

Figure 8 – Stray Current Drainage Automatic Potential Control

Where the separation of the structures is large and a bond is impractical, the potential controlled rectifier can be used to power an impressed current groundbed. This method is used successfully in the mitigation of DC electrical interference, from transit systems. The rectifier has a dual role, which is to supply cathodic protection current during non-interference periods and to compensate for interference effects during periods of electrical disturbance.

In conclusion there are three principal methods of DC electrical interference mitigation, namely metallic bonding, cathodic protection compensation, or shielding of pick-up areas.

5.0 Prevention of Electrical Interference

The first step in prevention of electrical interference is acquiring an awareness of the sources of electrical interference and participating in all local electrical interference committees.

Subsequent steps in minimizing electrical interference involve careful design of the structure and power sources. All DC electrical interference arises from a voltage gradient created by the flow of DC current through an electrolyte. The larger the voltage gradient is, then the larger will be the interference current, everything else being equal. Figure 9 is a typical voltage profile between an impressed current groundbed and the pipeline it serves. The slope of the voltage versus distance curve is the voltage gradient which, in turn, is the product of the soil resistivity and current density at any point. Accordingly, the optimum method for reducing the possibility of DC electrical interference is by reducing the current density. This can be accomplished by using longer impressed current groundbeds in the case of cathodic protection systems or moving the groundbed so that the voltage gradient doesn't influence surface structures.

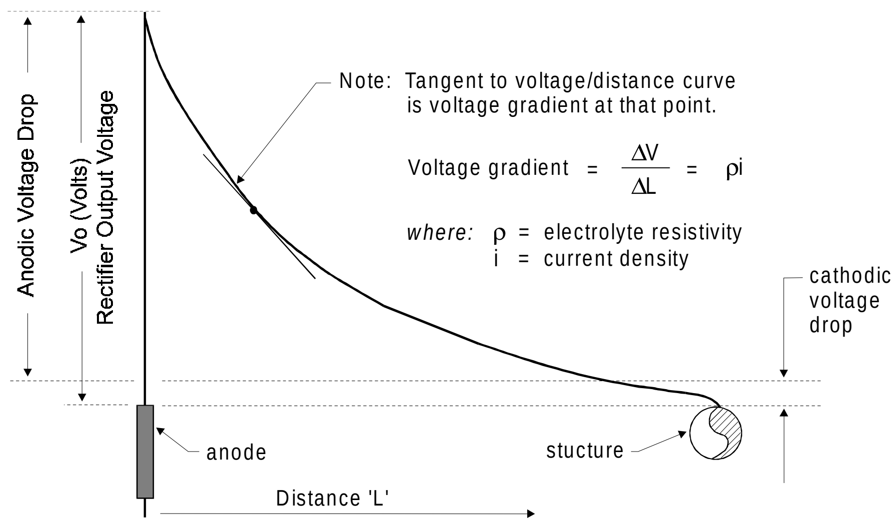

Figure 9 – Typical Voltage Profile Between Anode and Structure

A second major method of reducing the magnitude of electrical interference current is by the application of a protective coating which will provide the structure with a high electrical structure-to-electrolyte resistance. All anticipated current pick-up areas on the structure should receive extra attention. A well coated pipeline will pick-up only a small interference current, the effect of which can usually be mitigated inexpensively using sacrificial anodes.

Transit systems can be designed to produce negligible interference by simply isolating both positive and negative circuits from ground and from other structures.[27,28] Despite the success of such a fundamental approach many transit authorities have refused to take the necessary steps at the design stage. This situation is not likely to change dramatically until transit system designers are found negligent as was done with a consulting engineer for failure to provide adequate electrical interference facilities on a pipeline.[29]

Electrical interference from AC transmission lines can be prevented simply by locating the structure outside of the power transmission line right-of-way but owing to land availability constraints, this is not always possible. A practical but expensive prevention method would be to run the power transmission lines in a pipe-type conduit. Here the steel conduit would intercept the electromagnetic and electrostatic field. Hence power transmission lines and pipelines could co-exist on the same right-of-way without significant interference and the need for interference mitigation.

6.0 Telluric Currents

Telluric currents in the earth are caused primarily by the changes in the earth's magnetic field arising from its interaction with the solar wind. Telluric current effects are most noticeable in long pipelines located in the northern and southern hemispheres at latitudes close to the magnetic poles. These induced currents, which cause fluctuations in the pipe-to-earth potential, were considered to be merely a nuisance by most pipeline operators because they made the accurate measurement of cathodic protection levels more difficult. Recent reports[30,31] however have indicated that corrosion attack on cathodically protected piping caused by telluric current can occur and because of this, mitigation is warranted where telluric activity is significant. Impressed current cathodic protection systems operating in potential control mode, as illustrated in Figure 10, have been used successfully[32,33,34] to ameliorate the effects of telluric currents. The current output of these impressed current systems vary in response to the pipe potential as monitored by the reference electrode.

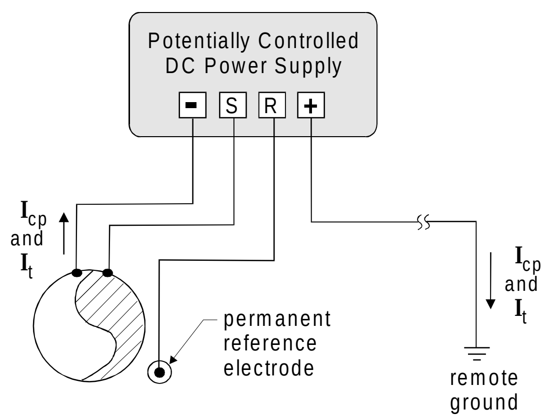

Figure 10 – Schematic of Potentially Controlled Cathodic Protection System Used to Mitigate Telluric Current Effects

When the pipe-to-soil potential attempts to shift electro-positively due to telluric current activity, the control unit increases its current output in order to maintain its set potential. During telluric current pick-up periods, the potential shifts electro-negatively and the current output goes to zero. This mitigation response is shown on Figure 11.

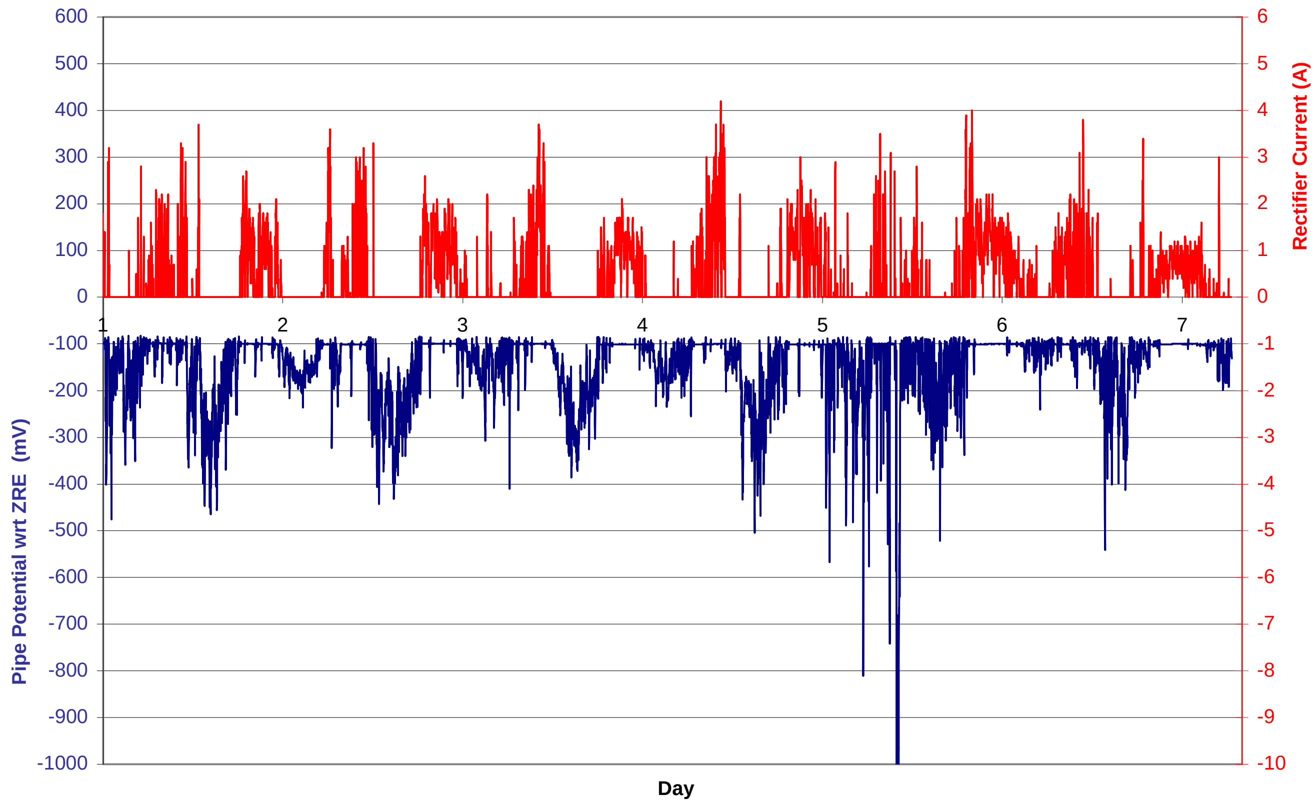

Figure 11 – Pipe Potential and Rectifier Current Output versus Time for An Impressed Current System Operating in Potential Control

7.0 Summary

Electrical interference on underground structures is, in many cases, unavoidable, but there are proven methods of ameliorating the deleterious effects of this interference. Participation in local electrolysis committees by owners of underground facilities is a cost-effective way of becoming aware of interference situations and of gaining insight into the methods of mitigating electrical interference.

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