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Evaluation of Gradient Control Wire and Insulating Joints as Methods of Mitigating Induced Voltages in Gas Pipelines

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ABSTRACT

Significant voltage levels can be induced in the gas pipelines due to power transmission lines in the areas where they share the same corridor, especially during a fault. These voltages can affect the operating personnel, pipeline associated equipment, cathodic protection and the pipeline itself Quite often, mitigation is required to reduce these induced voltages to levels that are safe for personnel and integrity of the pipeline. This paper compares features of two mitigation methods: insulating joints and gradient control wire. An existing Agility pipeline is modelled using the specialized CDEGS software incorporating these two mitigation methods in order to compare the performance and costs. Results of this case study may be used as guidelines for designing the mitigation schemes for new pipelines.

1. INTRODUCTION

There has been a considerable amount of research into interference effects between AC power lines and pipelines [1, 2] including computer modelling of pipelines and power lines [3]. Induced AC voltages in gas pipelines located in shared corridors with power transmission lines may affect operating personnel, instrumentation and pipeline coating and steel. Mitigation system on the pipeline must be designed to reduce the induced voltages on the pipeline both during normal operation and fault conditions on the power lines. There are measures applied to power lines that reduce induced voltages on pipelines. These include increased physical separation of power line from the pipeline, type of power line towers, selection of phase sequence and the inclusion of shield wires. However, this research will focus on mitigation methods that are applied to the pipeline.

This paper will begin with an introduction to the four most commonly applied methods for mitigation of AC induced voltages on pipelines. A case study of a pipeline whose induced voltage mitigation system was based on insulating joints will be presented. The effect of the power line fault currents on pipeline coating stress voltage, and safety evaluation of test points along the pipeline will be examined. An alternative mitigation system using the gradient control wire method will be designed and examined. A comparison of the effectiveness of the two mitigation methods will be presented.

2. MITIGATION METHODS

2.1. LUMPED GROUNDING

The simplest method to lower AC interference levels in a pipeline is to connect it to earth electrode at certain locations. This method is known as lumped grounding or a "brute force method". The soil resistivity in the area can affect the size of the required electrode significantly. For example, 50 m vertical rod in a 100 Ωm soil achieves 3 Ω. 0.3 Ω can be achieved by six 100 m long vertical rods spaced 100 m apart and connected with a horizontal conductor. If soil resistivity increases to 1000 Ωm, these dimensions increase tenfold. While it can still work well for mitigation systems with low impedance requirements and in a very low soil resistivitity, in many practical cases this method is impractical and very expensive [4].

2.2. CANCELLATION WIRE

Cancellation wire as a method was developed in the late 1980's. It consists of a long buried wire parallel to the transmission line, often on the side of the transmission line opposite to the pipeline. With proper positioning, the voltages induced in the wire are out-of-phase with voltages induced into the pipeline. By connecting one end of the cancellation wire to the pipeline, these voltages cancel each other when the other end of the wire is left free [4]. The problem with this method is that it only cancels inductive component of the fault currents and it may transfer excessive voltages to its unconnected end. The method requires purchase of additional land for the placement of the wire.

2.3. INSULATING JOINTS

The use of insulating joints is illustrated by Figure 1. Insulating joints divide the pipeline into several electrically isolated parts so that induced voltage cannot reach high levels. Local ground is then connected to the pipeline at each side of the insulating joint. Each earthing electrode is connected to the pipeline through a surge diverter, which operates only when the voltage on the pipeline is higher than its breakdown level. With this method, the pipeline is protected from stray currents that can cause corrosion and cathodic protection currents are prevented from leaking out. The combination of insulating joints and permanent earths can be quite an effective way of mitigating AC voltages on the pipeline. But there are several drawbacks to this method, which will be discussed in Section 7.

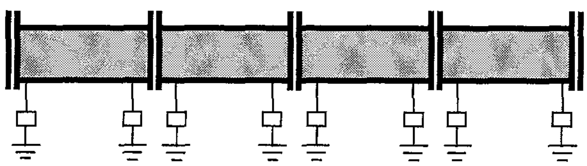

Figure 1: Use of insulating joints

2.4. GRADIENT CONTROL WIRE

The latest method for mitigating induced voltages on pipelines to emerge is the use of gradient control wire. It consists of one or two zinc wires buried in parallel with the pipeline, with regular electrical connections to the pipeline. An example with two wires is shown in Figure 2. The connections should be made through surge diverters, as in the case of insulating joints. Two insulating joints are also present at the start and at the end of the pipeline. It is compulsory to electrically isolate pipeline itself from the rest of the pipeline network if the rest of the network operates on different gas pressure level or belongs to a different pipeline owner.

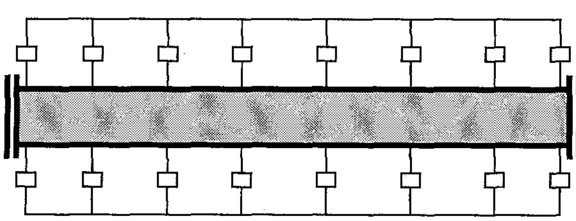

Figure 2: Use of gradient control wire

Gradient control wires provide grounding to the pipeline in relation to inductive interference. They also raise the potential of the local earth, reducing the touch and coating stress voltages. Similarly, in relation to conductive interference, these wires reduce the potential difference between the pipeline and local earth by allowing the current to flow between them [5].

3. OBJECTIVES

The prime objective of the work presented in this paper is to study the electrical interference taking place between power lines and two of the Agility owned natural gas pipelines.

Specific objectives:

- To analyse current pipeline mitigation design with insulating joints by examining the interference for both steady state and during fault conditions of the power lines and compare results with applicable Standards for compliance
- To develop alternative pipeline mitigation design employing gradient control wire method and examine the interference for steady state and during fault conditions of the power lines, and compare results with applicable Standards for compliance
- To analyse current cathodic protection systems on the pipeline and cathodic protection system design based on gradient control wire
- To compare performance and cost of pipeline mitigation systems based on insulating joints and gradient control wire

4. SOFTWARE

This study was performed using CDEGS, a well renowned software package used for analysis of electrical induction and conduction problems occurring in non-uniform three-dimensional lossy environment (air and soil) when time-harmonic currents are injected into various points of network of arbitrarily located conductors in that environment [6]. The package consists of several independent modules designed to solve different problems.

5. COMPUTER MODELLING

5.1. SHARED CORRIDOR

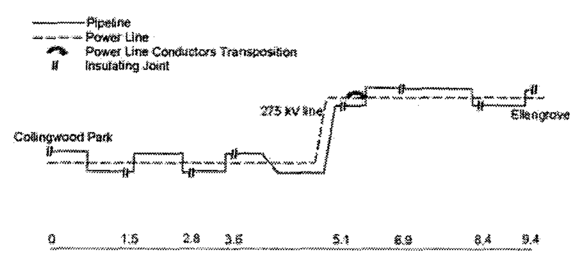

Figure 3: Physical layout of a Brisbane shared corridor

The part of the Brisbane to Roma pipeline between metering stations at Collingwood Park and Ellengrove is 9.3 km long which is illustrated in Figure 3. Along with this distance the pipeline shares the corridor with a double-circuit vertical steel tower power line. The separation between the pipeline and power line towers varies, but is generally around 30 m. Considering the length of the corridor and the fact that pipeline often changes the side it runs along the power transmission line, it is expected that significant amount of induced AC voltage would appear on the pipeline, especially during a fault on the power line.

5.2. PIPELINE

The pipeline is API 5L X60, a standard pipe grade specified in API (American Petroleum Institute) specification 5L. The pipeline is made of steel with a 406 mm outer diameter and 9.5 mm wall thickness.

Applied coating on the pipeline is high density polyethylene, known as yellow jacket. The coating resistance of yellow jacket is around 1000000 Ω/m². The average depth of the pipeline in the ground is around 1.5 m.

5.3. POWER TRANSMISSION LINE

The power transmission lines are owned by Powerlink in Queensland. Line ratings are 300 MVA at 275 kV (630 A per phase). Protection speed settings on the lines are 80 ms primary and 250 ms backup. The tower footing resistances of power lines are incorporated in the study.

5.4. SOIL RESISTIVITY

Soil Resistivity measurements were taken at several locations in the shared corridor. Based on these measurements and CDEGS software calculations, a two layers computer soil model resulted and was used in the study. Soil in the shared corridor was described in Agility earthing installation schematics as sandstone, sandy, clay or as a combination. In areas where sandy soil was in the top layer, a high soil resistivity was observed (e.g. 1300 Ωm). Much lower soil resistivity levels were observed in areas with sandstone of clay in the top layer (e.g. 200 Ωm). Shared corridor was divided into several regions based on different soil models.

6. CASE STUDY RESULTS

In the first stage, the complete pipeline interference study on the Brisbane pipeline was carried out by modelling the existing interference mitigation system. The steady state pipeline potentials, coating stress voltages during the faults (consisting of inductive and conductive component), test point touch voltages and cathodic protection analysis were established in order to compare results with results obtained by using the alternative mitigation system employing gradient control wires.

6.1. EXISTING MITIGATION SYSTEM WITH INSULATING JOINTS

6.1.1. STEADY STATE POTENTIALS

Steady state analysis revealed that maximum induced voltage on the pipeline is around 5 V. This value is well within the allowed levels in the Standards [7]. There is no need for any mitigation of steady state potentials on the pipeline.

6.1.2. FAULT INDUCTIVE COATING STRESS VOLTAGE

The first step in any fault interference analysis should be the calculation of induced voltage levels on pipeline with no mitigation applied. With this scenario, faults were modelled at each of the 22 power line towers in the shared corridor. Results of this study are shown as an envelope plot in Figure 4. Quite high and unacceptable voltage levels are seen to appear on the pipeline during the fault in this case. For example, over 7000 V is induced at one end of the pipeline. This clearly demonstrates the need for induced voltage mitigation on the pipeline.

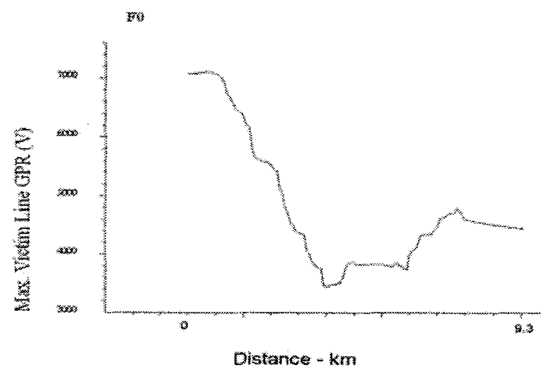

Figure 4: Inductive Coating Stress Voltage with no mitigation applied

In the next step, the mitigation system involving insulating joints and permanent earths on each side of the joint were modelled. According to the installation details sheet, these permanent earth electrodes must achieve impedances less then 10 Ω to earth. Once these levels are included in the computer model, inductive fault study revealed the envelope plot shown in Figure 5.

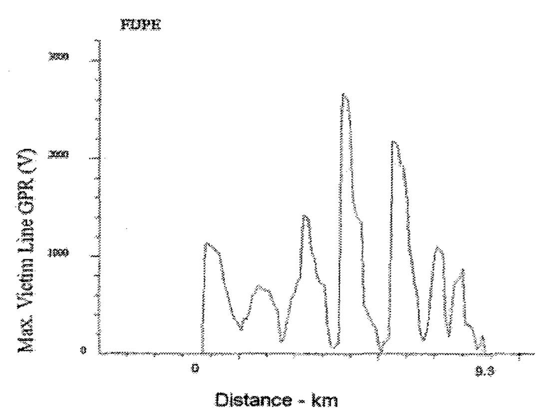

Figure 5: Coating Stress Voltage with insulating joints

It is interesting to note the appearance of the plot. At the locations of insulating joints and permanent earths, the fault levels are very low, the induced voltages being below 100 V. Half way between two insulating joints or two permanent earths these levels peak.

6.1.3. CONDUCTIVE COATING STRESS VOLTAGE AND TOTAL COATING STRESS VOLTAGE DURING FAULTS

To obtain the stress voltage to which pipeline coating would be subjected in the case of power lines fault, it is necessary to calculate conductive component and add it to inductive component. In reality, there is a small angle between the two components, so adding them arithmetically represents a conservative approximation. The fault study was repeated for faults on all towers in the shared corridor. Inductive and conductive components and total coating stress voltage are presented in the Table 1 in the Appendix. From this it is seen that the total coating stress voltages, appearing on the pipeline, are well below required 5 kV, level that corresponds to polyethylene, material used to make yellow jacket coating that was used on the pipeline. This means that pipeline is well protected against high coating stress voltages with the existing mitigation system.

6.1.4. TEST POINTS TOUCH VOLTAGES

Pipeline test points are located on the earth surface, on the top of each insulating joint. Gradient control grid, serving as test point mitigation, is made of galvanized steel and placed at a depth of 0.6 m into the ground. The grid has 1m x 1m square shape. Connection between the earth mat and the pipeline is made through a surge diverter, which means that it is active only during the fault. This arrangement is used to prevent interaction between pipeline cathodic protection system and the grid.

The maximum allowed touch voltages are calculated according to IEEE recommendations [8] taking a nominal human body weight of 50 kg. These touch voltages are very dependent on the soil resistivity of the top layer in the layered soil model. The results are shown in Table 2 in the Appendix. It can be seen from the Table that touch voltages at test points 3, 4 and 5 exceed the maximum allowed by IEEE recommendations.

Pipeline test points belong to Category B equipment according to Australian Standards [7]. This Category allows a touch voltage of 1000 V during faults lasting less than 1 sec. It can be seen from Table 2 that all test point touch voltages comply with this Standard.

6.1.5. CATHODIC PROTECTION

Between each two insulating joints a separate sacrificial anode cathodic protection system was modelled (7 systems between 8 joints). Calculations show that existing sacrificial anodes supply 0.9 μA/m² current density to the pipeline in pre polarized state and 0.6 μA/m² current density in polarized state. Pipeline coating was modelled with 1,000,000 Ω/m² coating resistance, which is a usual value for a polyethylene coating in a very good shape. Pipeline was built in 2001 and previous surveys show that coating is in excellent condition. According to these surveys, current densities of less than 1 μA/m² were required to polarize the pipeline to the required levels in the field. Exact value varies depending on the season and wetness of the soil. Calculations showed good matching with pipeline survey.

6.1.6. COSTS

The costs given below are rough estimates for the mitigation system on the pipeline. These include cost of materials and estimates of labor cost required for installation [9]:

- insulating joints $ 60,000
- permanent earth anodes $ 60,000
- installation of permanent earths $ 30,000
- total cost: $ 150,000

6.2. ALTERNATIVE MITIGATION DESIGN WITH GRADIENT CONTROL WIRE

In the second part of the study, the alternative mitigation system for Brisbane pipeline using gradient control wire was designed. One bare zinc wire was placed in the pipeline backfill at the same depth as the pipeline itself, at 1.5 m, 1.5 m horizontally away from the center of the pipeline. The connections between the pipeline and zinc wire were made approximately at the locations of the power line towers. In addition, two insulating joints were placed at the beginning and the end of the line to electrically isolate the pipeline from the rest of the pipeline network.

6.2.1. STEADY STATE POTENTIALS

Steady state analysis of AC interference between the power transmission line and the pipeline revealed very low induction levels, in the range 0 and 6 volts, which falls well within the levels allowed by Standards [7].

6.2.2. INDUCTIVE COATING STRESS VOLTAGE DURING FAULTS

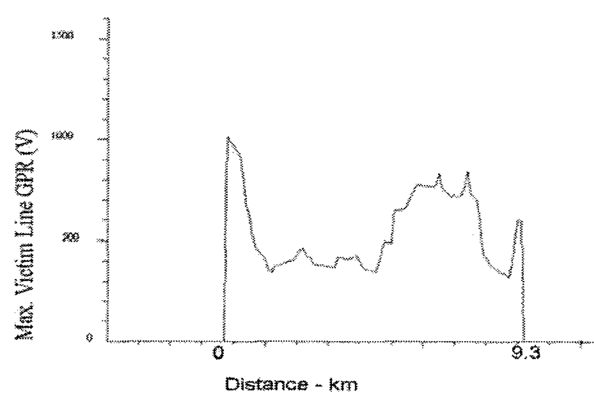

Figure 6: Inductive Coating Stress Voltage with gradient control wire

Faults were simulated at each single tower in the shared corridor. The maximum inductive coating stress voltages on the pipeline are shown in an envelope plot shown in Figure 6. It is seen that the maximum inductive coating stress voltage is around 1000 V.

6.2.3. CONDUCTIVE COATING STRESS VOLTAGE AND TOTAL COATING STRESS VOLTAGE DURING FAULTS

The conductive analysis has been carried out with faults applied at all towers in the corridor. The total coating stress voltage obtained by adding the inductive and conductive components are also given in Table 1 in Appendix. It can be seen from that total coating stress voltages on the pipeline are significantly below the recommended values [6]. In general total coating stress voltages obtained with use of gradient control wire mitigation are much lower than in the case of insulating joints mitigation.

6.2.4. TEST POINTS TOUCH VOLTAGES

With this alternative design, locations of test point could be arbitrary, but to enable comparison with insulating joints mitigation system, the test points were designed at exactly the same locations. The calculated test points touch voltages are given in Table 2 in the Appendix. As it can be seen only the calculated touch voltage at test point 5 is higher than maximum allowed touch voltage calculated by the IEEE methods taking into account body weight of 50 kg. All test points comply with Australian Standards [7].

6.2.5. CATHODIC PROTECTION

Zinc gradient control wire used for mitigation was modelled as anode material for cathodic protection of the pipeline. The calculation revealed that zinc wire can supply 0.6 $\mu A/m^2$ current density in pre polarized state and 0.3 $\mu A/m^2$ current density in polarized state. While these current densities can polarize the pipeline, it can be observed that the values are lower than in the case of insulating joints mitigation system. The reason is that magnesium anodes used in the system with insulating joints have higher natural electrochemical potential than zinc. This fact is in line with recent recommendations from the industry that independent cathodic protection systems should be installed in addition to gradient control wire mitigation system [10]. In this situation AC couplers/DC decouplers or surge diverters (see Figure 2) should be installed between the pipeline and the mitigation wire to protect pipeline from stray currents and prevent leakage of cathodic protection current.

6.2.6. COSTS

The rough cost estimate of a gradient control wire pipeline mitigation system is given below [11]:

- single gradient control wire 9.3 km: $123,668
- installation of gradient wire $180000
- total cost: $303668

7. COMPARISONS

7.1. COMPARISON OF COSTS OF THE TWO SYSTEMS

The basic cost analysis included cost of material and minimal estimated labour costs necessary for installation. The results revealed that basic cost for mitigation system using insulating joints would be around $150000 and corresponding basic cost for system with zinc gradient control wire would be around $300000. It should be noted once again that these cost are rough estimate and that they are particular to the pipeline and corridor considered. The results may differ for different corridor configurations. Most important aspect is that overall cost of a mitigation system is just a fraction of the total cost of the pipeline and its appurtenances, which runs into tens of millions of dollars. Therefore, consideration should be focused on adequate performance and possible costs of maintaining the mitigation system, considering the contingencies, and not just on the cost of mitigation itself.

7.2. COMPARISON OF ELCTRICAL AND PHYSICAL FEATURES

7.2.1. MITIGATION

The mitigation system with gradient control wire has superior performance compared to a system with insulating joints (Figure 6 versus Figure 5). The coating stress voltages on the pipeline are lower (1000 V maximum) than those in the case of insulating joints system (2600 V maximum). The induced voltage distribution curve is more uniform as mitigation is applied along the whole length of the pipeline, not only at certain locations (locations of insulating joints), as the case of the insulating joints system.

System with gradient control wire had one test point touch voltage higher than IEEE recommendations, compared to three test points on the system with insulating joints.

7.2.2. MAINTENANCE AND REPAIR OF GAS PIPELINES WITH INSULATING JOINTS AND GRADIENT CONTROL WIRE

Gas pipelines with insulating joints are more complicated in relation to maintenance. They can be shorted during operation (this case has already been reported in the field). Insulating joints are tested only in the laboratory, and thus, their performance in the field during faults or lightning can not be predicted. Sealing and installation of the joints maybe difficult and may lead to future leaks. Use of insulating joints appears to be an old technique for mitigation of induced voltages in pipelines [1].

While the repairs on a system with gradient control wire could be done without interrupting the flow of gas in the pipeline, for repairs on the insulating joints the flow of gas has to be interrupted through the pipeline, incurring high costs to the pipeline owners.

7.2.3. CATHODIC PROTECTION

Additional cathodic protection system in the case of insulating joints mitigation provided higher current densities to the pipeline than the zinc in the case of gradient control wire mitigation. Additional cathodic protection system is recommended in the case of gradient control wire mitigation. If surge diverters are used to contact the pipeline, the same system with sacrificial anodes installed on the pipeline can be applied.

7.2.4. CONTACT WITH PIPELINE

Quite often there is a requirement to protect the pipeline from stray currents and to prevent leakage of cathodic protection DC currents. The entry point for a stray current is the mitigation system connected to the pipeline. That is the reason why AC couplers/DC decouplers or surge diverters are installed between the pipeline and its mitigation system. This applies for both systems in consideration here. In the case of gradient control wire, use of decouplers enables the use of alternative materials like copper (which could be a cheaper option depending on its price on commodity markets).

8. CONCLUSIONS

Based on computer simulations of two pipeline mitigation systems in an existing corridor, it was shown that an induced voltage mitigation system employing gradient control wire has significant benefits compared to systems with insulating joints.

Despite lower costs of systems with insulating joints, their weaker performance and much higher costs in relation to cases of shorted or leaking joint, makes induced voltage mitigation design with gradient control wire superior.

9. ACKNOWLEDGEMENTS

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APPENDIX

Tower No.	Insulating Joints Volts	Gradient Control Wire Volts
2226	1185	819
2227	578	184
2228	467	252
2229	892	468
2230	761	592
2231	671	506
2232	2167	827
2233	265	440
2234	403	482
2235	709	564
2236	799	482
2237	1287	633
2238	1598	1029
2239	1529	917
2240	1265	1004
2241	563	816
2242	1626	973
2243	3167	1393
2244	1919	975
2245	1101	548
2246	1620	590
2247	525	403
2248	837	435

Table 1: Total Coating Stress Voltage (inductive and conductive components together) on the pipeline for the fault at each tower in the corridor

T Point	Insulating J	Gradient CW	Max TV
1	157	135	453
1	199	229	453
2	306	267	993
2	372	269	993
3	646	274	947
3	665	266	416
4	263	208	391
4	537	276	416
5	671	528	391
5	949	507	993
6	925	522	947
7	478	195	947
7	637	247	947
8	129	307	947

Table 2: Total Touch Voltage (inductive and conductive components added) on Test Points for faults at two closest towers and Maximum Touch Voltage calculated by IEEE recommendations based on 50 kg body weight