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A Method for Evaluation and Mitigation of AC Induced Voltage on Buried Gas Pipelines

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This paper has been prepared, based on reports regarding extraordinary induced ac voltage on buried gas pipelines in residential and industrial areas of the capital city of Tehran, especially in densely populated central areas. Also, some reports are considered on the existence of ac induced voltage in buried gas pipelines under the overhead transmission lines, for example, one case located 80 Km to the west of Tehran, in an agricultural region of the town of Abyek. In this paper, the results of an extensive theoretical, experimental and practical investigation and implementation of methods carried out during the last two years are introduced. Furthermore, this paper includes evaluation of the existence of ac induced voltage in gas pipelines, their effect on cathodic protection systems and the pipelines coatings. A method will be introduced for determination of electromagnetic induced ac voltage in gas pipelines under overhead transmission lines. Finally, a method of ac induced voltage mitigation for application on buried gas pipelines under overhead transmission lines is introduced and verified by application in the above mentioned region, which resulted in a complete cancellation of induced ac voltage in the pipeline. A computer program is developed based on these methods.

INTRODUCTION

The secondary low voltage electrical power distribution circuits in the central part of Tehran are underground cables. In the presence of electrical current, those cables generate heat which is transfered through the surronding soil to air. The rate of rise of cable temperature must be under the safety level in order to protect its insulation from damage. Also there are other risks of damage for underground cable in the present networks, such as mechanical damage, due to any maintenance or new installation works carried out on other utilities near to the underground pipes (i.e., gas pipelines, water pipelines) or facilities located around the cable at a short distance from it. In case of damage to the cable insulation, it will result in a local short circuit of the cable to the ground, a current leakage will pass through the path of minimum resistance and a potential distribution will appear around this point.

However, under the overhead transmission lines, the induced electromagnetic voltage in gas pipelines is known as the main source of ac voltage.

Existance of any ac voltage in the pipeline, with respect to the ground, is a matter of concern for gas companies [1,2].

A computer program for evaluation of induced voltage, due to electrostatic effects was introduced in [3]. In [4] it has been stated that normally the electric potential which appears in the metalic pipelines is in a range of frequencies from 20 to 430 Hz. A design procedure for the arrangement of pipelines, with respect to a nearby transmission line, in order to reduce the induced voltage is proposed in [5]. Furthermore, a computer program which calculates the electromagnetic induced voltage during short circuits in the power network was introduced in [6].

The Iranian National Gas Company was also concerned about the reports of electric shock which occured on people working on gas pipelines and, also, the customers. There was also concern about the possible effects of induced ac voltage on the performance

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of cathodic protection systems employed for protection of their steel gas pipelines against corrosion.

THE SIDE EFFECTS OF AC VOLTAGE ON CATHODIC PROTECTED GAS PIPELINES

Cathodic protection is one of the most usual methods of protection against corrosion and it is especially employed for protection of buried pipes. This method is, in fact, a kind of electrochemical corrosion. In this method, anodic points in the structure are so connected to a circuit that it will become a cathode and the focus of corrosion will transfer to a point outside the main part of the circuit which can be controlled [7,8].

Pipeline Corrosion in Soil and the Effects of Ac Voltage

Corrosion and materials destruction are among the most important technical and economic problems in todays industry.

A large number of structures are buried in soil which are lines for providing different public sevices. Any damage to one of them can result in severe problems for society, for example, water and sewages transmission lines, steel gas pipelines and fuel containers.

Coatings are employed to isolate the pipe from the surrounding area and by isolation of the electrolyte from anode and cathode the corrosion process is inhibited.

The question may arise, that, if corrosion can be eliminated by application of a coating, would other methods be necessary for further protection? In practice, according to the following reasons a perfect protection is not provided via application of coating.

1. On certain machinery, sliding of one part of the pipe under the coating machine is possible;
2. Cracking of the coatings may arise, due to mechanical and thermal stress;
3. Scratching of the coating may occur, during transportation of the coated pipe;
4. Scratching of the coating, due to contact with sharp edged stones may occur during filling of the surroundings of the buried pipeline;
5. Interference through plant roots may occur in the surrounding soil;
6. Solvents existing in the ground around the pipe may affect the pipe due to some kind of leakage;
7. In case of coatings in the form of tape, defects may occur due to the nonhomogenity of the production process.

Considering the above reasons for imperfection of the coatings, application of a combination of anticorrosion methods is useful and essential.

Application of cathodic protection is useful for the points on a pipe where the coating is defective. If a pipeline is protected with cathodic protection then a dc supply preserves -0.85 Volts on the pipe, with respect to the ground and any drop or increase of the amount of this dc voltage or change in its polarity can cause serious damage to the coatings and finally result in pipe corrosion.

Effect of ac Voltage on Pipeline Corrosion

The effects of ac voltage on the rate of pipeline corrosion are investigated experimentally in [9], where the effect of ac voltage on the rate of buried pipeline corrosion is investigated in a two year experiment on buried pipelines. Excessive reduction in the pipeline weight is observed which clearly emphasizes the corrosion intensification effect of ac voltage.

In this work, it is shown that the effect of ac voltage on the coating is completely negligible [10], due to the very low temperature rise of the coating even during any short interruption interval of the gas flow.

Other Hazards of ac Induced Voltage

It is well-known that any contact of energised conducting material having voltage above 60 and the passage of any current more than 10 mA can be harmful and dangerous to human life [1]. It is necessary, therefore, to avoid any induced voltage and current at these levels, which can result in electric shock.

NEW IDEAS IN TRANSMISSION OF GAS SUPPLIES

Recently, many new ideas based on social and economic requirements have been proposed and are found practical for the present or in the near future for safe and economic transmission of gas supply over long distances. Some of them will be discussed briefly in this section.

Common Corridor for Passage of Different Public Services

As the price of land increases around the large cities, the following standard clearances become too expensive and utilities prefer to use a common right of way and share the expense. In this case, higher induced voltage is possible when a gas pipeline is parallel with a transmission line and the mitigating system cost should be reasonable.

Perfectly Insulated Gas Pipeline

It is expected that in the future, pipeline technology will employ insulated materials with reliable mechanical strength, however, no practical application is reported.

DETERMINATION OF INDUCED VOLTAGE ON BURIED GAS PIPELINES

Generally there are two possible mechanisms for voltage induction on buried gas pipelines placed under transmission lines:

a) Electrostatic induction (capacitive coupling),
b) Electromagnetic induction (inductive coupling).

Electrostatic Induced Voltage

The presence of a special distribution of electrical charges in space produces the distribution of an electric field proportional to the value of those charges. Consequently, if a conductive element is placed in this field, it will be in a potential with respect to the ground on the basis of its location around the area of the specific equipotential line. However, in the case of insulated buried pipelines which are laid down at ground level, the pipeline potential is approximately equal to the potential of the nearby ground, since they are located on the same equipotential line and their difference is almost zero. Even while handling a piece of pipeline (i.e., 20 m length), the related electrostatic voltage under a transmission line is much less than 60 volts. Gas utilities are not concerned about this kind of induction.

Electromagnetic Induced Voltage

The magnitude of low frequency electromagnetic induction depends on the value of the current, the distance of the conductor and the pipe and the specific resistivity of the ground.

Induced Voltage on Pipeline Under A Single Phase Line

The induced voltage on pipe g in Figure 1, under a single phase line, carrying a current of I_A, with a return path through the ground, can be determined based on Carson's formula [9]:

$$V_g = I_a \frac{f}{60}[0.0254 + j0.2794 \log \frac{D_{eg}}{D_{ag}}], \quad (1)$$

where D_{eg} is the equivalent depth of the return path under the main conductor "a" as follows:

$$D_{eg} = 660\sqrt{\frac{\rho}{f}}, \quad (2)$$

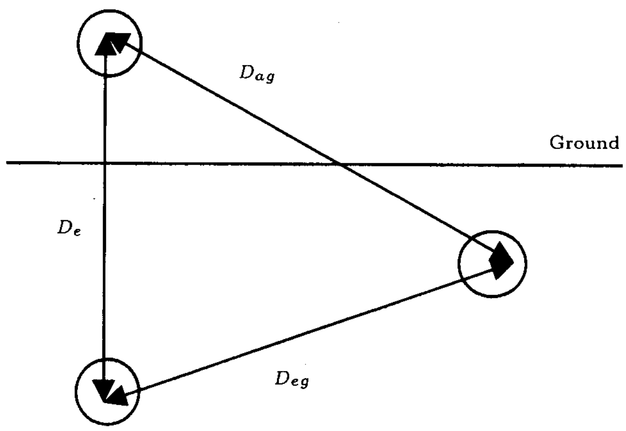

Figure 1. Arrangement of a single-phase line and a pipeline.

where ρ is the specific resistivity of the earth.

Consequently, for a three-phase line the induced voltage would be:

$$V_g = 0.286\frac{f}{60} + j0.2794\frac{f}{60}$$
$$[I_a \log \frac{D_{eg}}{D_{ag}} + I_b \log \frac{D_{eg}}{D_{bg}} + I_c \log \frac{D_{eg}}{D_{cg}}]. \quad (3)$$

Determination of Induced Voltage on a Pipeline Under a Double Circuit Line

Consider the arrangement of Figure 2. If the ground resistivity be 100 Ωm, the induced voltage on a pipeline at a distance of 20, 30, 40 and 50 meters and parallel to it, are determined and presented in Table 1.

A computer program is developed for the evaluation of the induced voltage per unit length of different transmission line conductors.

Table 1. Induced voltage for different distances.

Distance (m)	20	30	40	50
$\frac{V}{Km}$	4.884	2.703	1.667	1.112

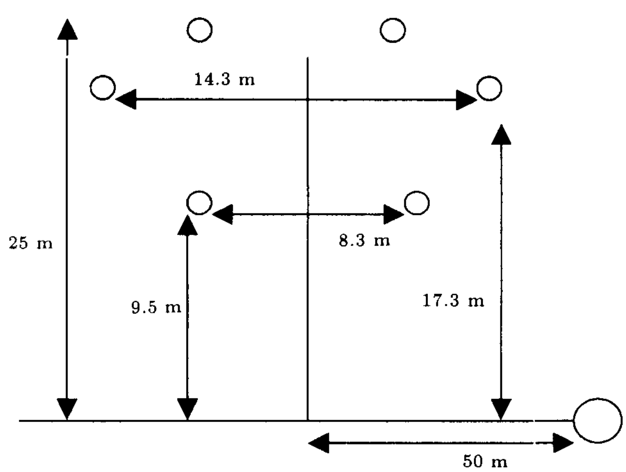

Figure 2. A double circuit line parallel with a pipe.

Laboratory Data on Measurement of Induced Voltage

A set of measurements are carried out in the laboratory for evaluation of two different induction phenomena.

The laboratory simulations were carried out one time for a pipe located over the ground and next time for a buried pipe located in a direction parallel with a low voltage, high current cable. Then, these induced voltages were measured when the cable crossed the pipe of different angles. The results of this latter section was an especially helpful means for developing a closed form formula determination of electromagnetic induced voltage on the crossed pipeline (presented in the following sections). Some of the measured results will be presented in this section.

Measurement of Induced Voltage Due to Electromagnetic Induction

In this experiment a 3 meter pipe is located at a distance of 18 cm and 35 mc from the current passing cable. The distance between the sides of the loop of the circuit is 255 cm and the voltmeter is located 390 cm away from the pipe.

The measured induced voltages are presented in Table 2 and compared with the calculated induced voltage between the two ends of the pipe.

The schematic diagram of the test circuit is shown in Figure 3. As is shown in Table 2, the computational error, with respect to the measured data, is in a range of 8 to 45 percent and the source of these errors are the difference between the real circuit conditions and the theoretical formula. Current passing through the two side arms can produce these errors, which have previously been considered negligible in the computation process, in this experimental arrangement.

Table 2. Measured and calculated induced voltage of two ends, T_1 : 35 cm, T_2 : 18 cm.

I:A	C:mV T1	M:mV T1	C:mV T2	M:mV T2
4	1.2	1.3	1.7	1.5
8	2.5	1.9	3.4	2.5
16	5.0	3.2	6.7	4.6
20	6.2	3.9	8.4	5.8
24	7.4	4.7	10.1	7.2
28	8.7	5.7	11.8	8.7
32	9.6	6.5	13.5	10.4

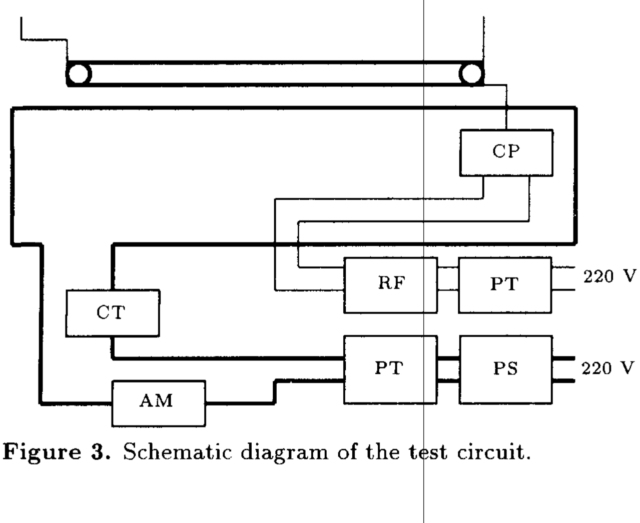

Figure 3. Schematic diagram of the test circuit.

Electromagnetic Induced Voltage on a Pipeline Crossing an O.H. Line

So far, methods have been introduced for computation of the induced voltage on a pipe under an overhead transmission line parallel with it, in which the induced voltage is, respectively, maximum. In order to evaluate the induced voltage in cases where the pipeline is crossing the direction of the transmission line, a method will be introduced which is verified against the measured data.

According to Figure 4, a single-phase and two conductor transmission lines, with a direction crossing the pipeline, are considered. The related dimensions are shown in Figure 4. The current in the line is I_a=500 Amps and the frequency of supply is $f = 50$ Hz. Since there is a nonuniformity in this problem, the classical formula of parallel cases cannot be employed here. First application of the finite element method was evaluated, however, a 3-dimensional method should be employed which its application is time consuming and impractical, since for each new case the problem should be solved independently.

Therefore, a closed form solution was sought and, based on the theoretical judgement, this method was discovered, as follows.

For determination of induced voltage, a reasonable approximation can be employed in order to use the classic parallel based formulas, introduced in the previous section. In this method, the pipeline is ap-

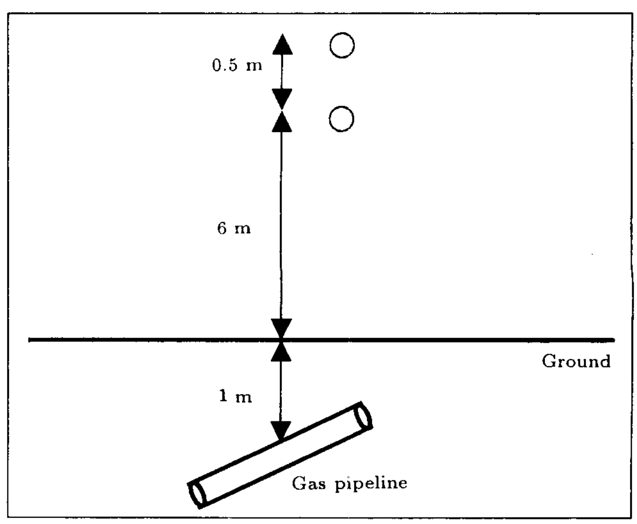

Figure 4. A pipeline crossing an O.H. line.

proximated by several pieces of short line pipe, parallel with the O.H. Line, as shown in Figure 5. According to Figure 5, the pipeline is divided into a number of small pieces, each piece simulated by a horizontal and vertical equivalent section for the sake of simplification of induced voltage calculation. The voltage induced on the parallel pieces can be determined by application of the classic formulas. There will be no voltage induced on the vertical pieces.

The induced voltage on the pipeline will be calculated by addition of the determined voltages on the horizontal pieces. However, in this method, the distance of different horizontal pieces and the conductors are variables which can be evaluated from Figure 6.

According to this figure, as the piece is farther from the crossing point, D'_{ag} is closer to D_{ag} and the $\mathrm{Log}\frac{D'_{ag}}{D_{ag}}=0$ and those pieces are not needed to be included in the calculation. This method is evaluated for different crossing angles and was verified.

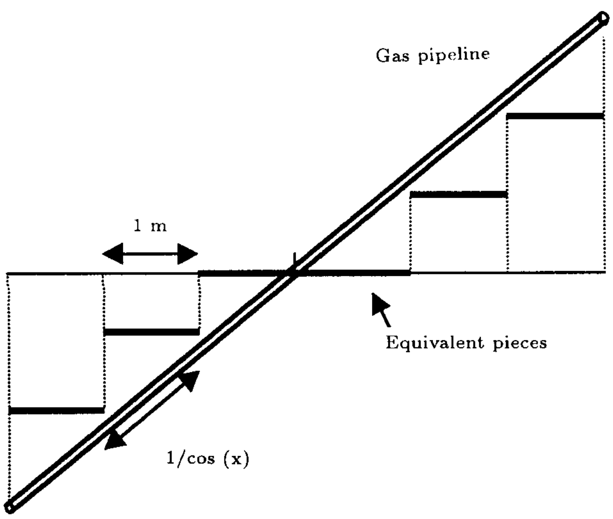

Figure 5. Approximation employed for determination of induced voltage.

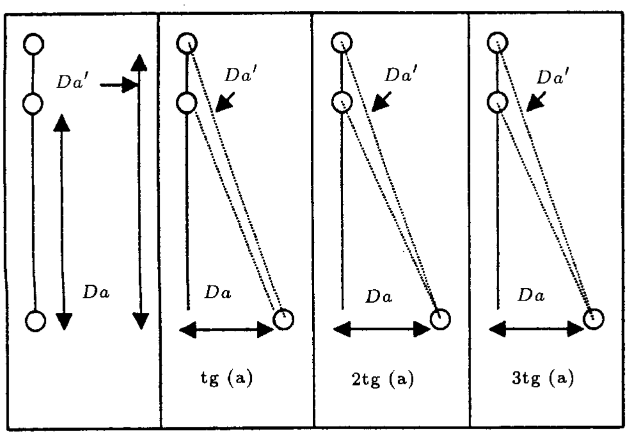

Figure 6. Diagram of distance relationship (between each equivalent piece and the conductor).

Table 3. The results of pipe electrostatic induced voltage measurements.

Distance of 220 V Conductor (m)	Voltage (V)
12	13.75
15	11.9
31	8.5
No potential on the conductor	0.4

Measurement of Induced Voltage Due to Electrostatic Induction

In this experiment, a conductor with a potential of 220 V, with respect to neutral was located at a distance from the pipe and parallel with its direction. Then, the induced voltage on the pipe with respect to neutral power supply, was measured. Table 3 shows the results of these measurements. Although the amount of electrostatic induced voltage was relatively high, they were substantialy decreased, due to application of a large impedance loading. For example, when a 68 KΩ was connected, parallel to the measuring instrument, the measured voltage reduced to about 0.1 Volts.

Therefore, in real application of gas pipelines, where a weak connection between the pipeline and ground always exists, normally no induced voltage of this type will be observed. Furthermore, in cases where this type of voltage does exist, there is no energy to supply any kind of load as a source of concern. In this case, the error of the computational results are completely negligible.

The phase sequence of conductors, especially in a double circuit line, is an important factor on the amount of induced voltage on the pipeline. Therefore, their optimum arrangement is known as a mitigation method at the designer stage of transmission lines.

Mitigation Methods

Generally, there are two main theories for the mitigation of induced voltage:

a) Reduction of magnetic field intensity in the vicinity of the pipeline,

b) Reduction of induced voltage on the pipeline by connection of a load.

Reduction of Magnetic Field Intensity

Reduction of the original magnetic field intensity is not possible, since, in this problem, its source is out of reach. However, it is possible to generate another field which reduces the main one.

If the gas pipeline is considered as a secondary winding of a hypothetical transformer, whose primary is the transmission line, by inclusion of a short circuited winding in the area between these two, and if the impedance of this short circuited winding is small enough with respect to the magnetizing impedance of this hypothetical transformer, then it is possible to reduce the induced voltage on the pipe.

The mutual inductance of the three-phase line and the gas pipeline can be computed according to the below relation [10]:

$$Z_{gi} = -j0.2794(\frac{f}{60})[\log \frac{\sqrt{D_{bg}D_{cg}}}{D_{ag}} + j\frac{\sqrt{3}}{2}\log \frac{D_{bg}}{D_{cg}}]\Omega/\text{mile}. \quad (4)$$

As an example, for a special case when:

$$D_{ag} = 20\text{m}, \quad D_{bg} = 25\text{m}, \quad D_{cg} = 30\text{m}, \quad f = 60\text{Hz},$$

then:

$$Z_{gt} = -j0.2794(\frac{50}{60})[\log \frac{\sqrt{20.30}}{20} + j\frac{\sqrt{3}}{2}\log \frac{25}{30}], \quad (5)$$

$$| Z_{gt} | = 31.78m\Omega/\text{mile}. \quad (6)$$

If it is assumed that the short circuit impedance of this circuit is resistive, then, the cross sectional area will be 2085 mm^2 or 64000 Kg of copper must be used for a mile, which is impractical.

Mitigation of Induced Voltage by Loading the Pipe

The most effective loading method is grounding the pipe, however, since the pipeline impedance is always in the circuit and very small, any grounding has a small impedance or, in other words, grounding is a kind of loading.

Ground Electrode

In this method the gas pipeline is grounded, via application of a ground electrode in series with an anode and, since a sacrificial anode electrode is employed, the pipe is protected against corrosion. Increasing the number of anodes, will reduce the induced voltage, however, the relation is not linear. Grounding can also be done through connection of the pipe to a buried conductor.

Horizontal Conductors

Connecting horizontal conductors to one end of the gas pipeline and grounding its other end is also proposed in [11].

Horizontal Conductors with Interconnected Connections

If the grounded side of the horizontal conductor is connected to each other through another conductor, it will result in a reduction of impedance and an increase in mitigation effect [11].

Other mitigation methods are also theoretically proposed, however, their effects must be evaluated practically. In the next section, the results of experimental investigations will be demonstrated and a new mitigation method will be introduced.

NEW MITIGATION METHOD

Based on the mitigation methods introduced in the literature and reviewed briefly in the previous section, a set of partial application of these methods were first conducted experimentaly in the laboratory on a short length of pipe and, then, practically utilized in Abyek. As explained in the previous section, these mitigation methods were also employed during the measurement of magnetically induced voltage in the laboratory.

Mitigation Laboratory Measurement Results

In the first step, the shielding method was implemented.

In this experiment, steel bars were located parallel to the pipe (at the top of it) and the current carrying cable, was located on the ground. Theoretically, in an optimum condition it is expected that the magnetic flux lines generated by the cable pass through the steel bars and not link the pipe or, if a steel sheet is employed instead of steel bars, then the induced current in the sheet reduces the effect of the magnetic field in the area around the pipe. However, as discussed previously, practically no substantial reduction was recorded during the induced voltage measurement on the pipe.

In fact, as expected, the theoretical formulas are not satisfied, because of the limitation of distance and dimension of the real problem [12].

The effects of grounding different points on the pipe were then investigated. The idea is that by grounding, for example, the middle of the pipe, the effective length of the pipe for induced voltage addition will be halved and almost the highest induced voltage will approximately be halved. Figure 7 demonstrates this theory. An insulated pipe three meters long was buried 30 cm under the ground and two anodes were employed for grounding different points on the pipe. In

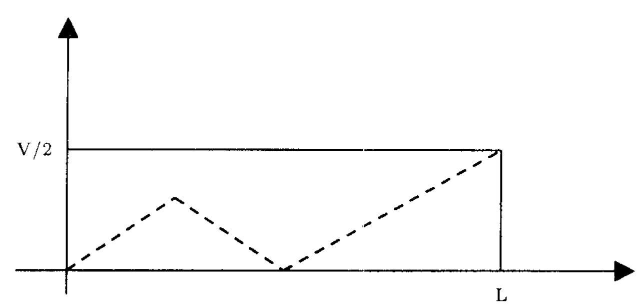

Figure 7. Voltage mitigation due to grounding.

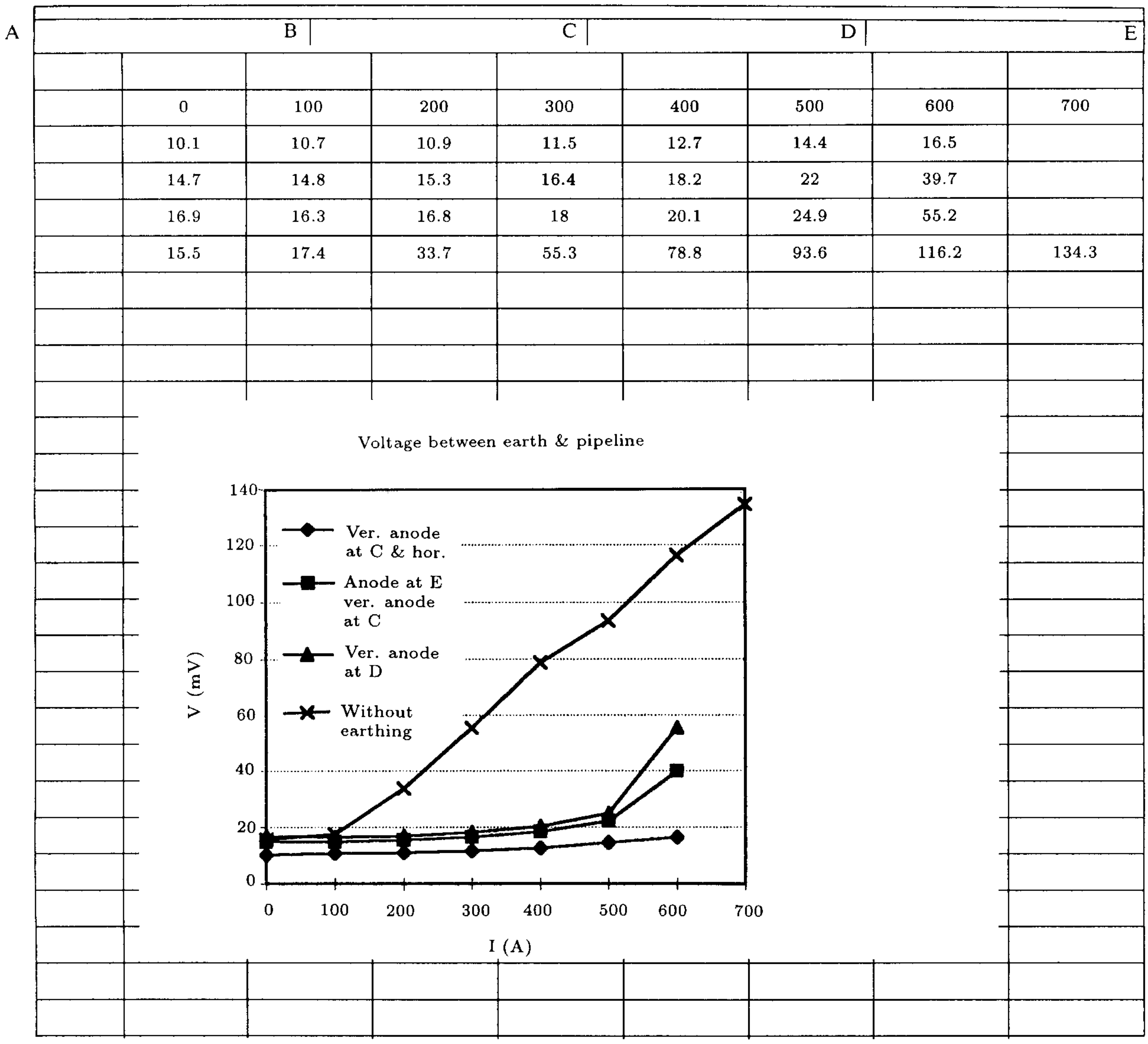

Figure 8. Induced voltage variation by grounding.

this experiment, the different grounding points on the pipe are shown in Figure 8. The measured voltage at point A is recorded in Table 5.

These results are also demonstrated in Figure 8, in which it is clear that by application of this method, as the number of grounded points increases in length of pipe, the measured voltage at point A is reduced. Of course, in a more careful investigation, it can be shown that the location of these grounded points are also effective on the amount of induced voltage reduction.

Therefore, another experiment was carried out, in which the current in the cable was 500 Amps and the grounding points differed. According to Table 5, the voltage of points E and D was measured with respect to the ground. According to these results, the

Table 4. The potential of point A on the pipe in mV.

I(A)	E,C GR.	C GR.	D GR.	Not GR.
0	10.1	14.7	16.9	15.5
100	10.7	14.8	16.3	17.4
200	10.9	15.3	16.8	33.7
300	11.5	16.4	18.0	55.3
400	12.7	18.2	20.1	78.8
500	14.4	22.0	24.9	93.6
600	16.5	39.7	55.2	116.2

Table 5. Grounding point effect on induced voltage.

Experiment/ Test Point	D (mV)	E (mV)
No G. connection	483	601
G. connection at A	432	584
G. connection at A and C	372	536
G. connection at A,C,E	144	292
G. connection at E and C	75	155

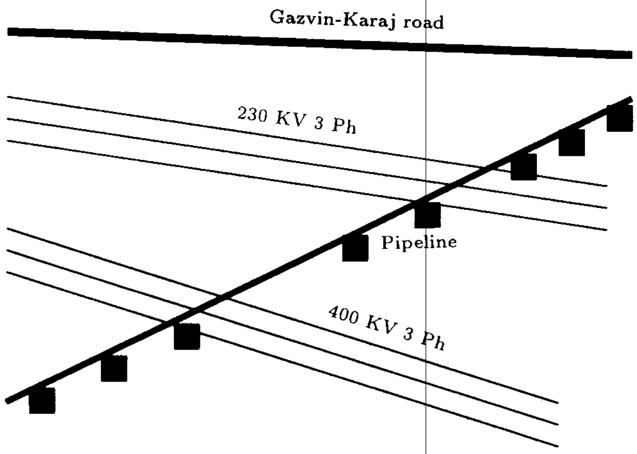

Figure 9. The layout of real cite in abyek.

effect of grounding points E and C is more than that of grounding points A and C on the induced voltage reduction, as expected. Based on the above measured results, these mitigation methods were evaluated and the qualified methods were selected for a preliminary test of concern to the Iranian National Gas Company, as shown in Figure 9.

New Mitigation System Implementation

In Figure 9, a 16-inch gas pipeline crosses one 230 KV transmission line named Ziaran-Montazerghaem and a double circuit 400 KV transmission line, named Ziaran-Rudeshur. According to Figure 9, an attempt was made to employ the most effective and economic mitigation method in the area.

Induced Voltage Measurement

A 30 degree angle can approximately be seen between the pipeline and the direction of the 230 KV transmission line. These measurements were carried out on the 8 test points, which are shown in Figure 9. The maximum voltage of the test points to the nearby ground was recorded at test points 2, 3 and 4 with a peak to peak value of 14 volts (ac voltage) at the cross point, while this value decreases as the distance between the cross point and the test point increases. It should be pointed out that when the 230 KV transmission line was out of service, the peak to peak value of ac voltage on the pipe, with respect to the ground, was 4 volts. The recorded waveform of the test point TP2 is shown in Figure 10.

The Proposed Mitigation System

The work in Abyek was concentrated on a 230 KV transmission line, which offers the main contribution to the induced voltage on the gas pipeline, since the 400 KV transmission line is a double circuit line with the taller height of the towers and lower line currents.

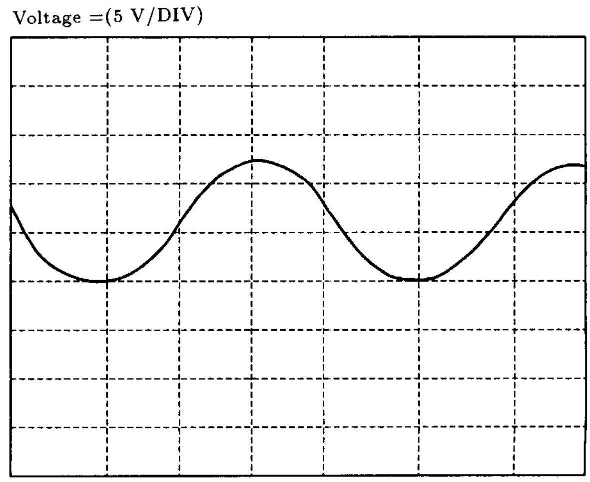

Figure 10. voltage waveform at test point TP2.

The method developed in this work recommends laying a grounded plate under the pipeline. However, since there already was an existing pipeline, a mitigation system was proposed according to Figure 11 to be established at a length of about 200 meters around the cross point and stainless steel plates were employed, which were connected to the ground through a set of capacitors.

Table 6 shows the effects of increasing the number of grounding capacitors on the voltage between the pipe and the ground, above and under the pipe. Finally, the effectiveness of the mitigation system can well be evaluated by figures presented in this table.

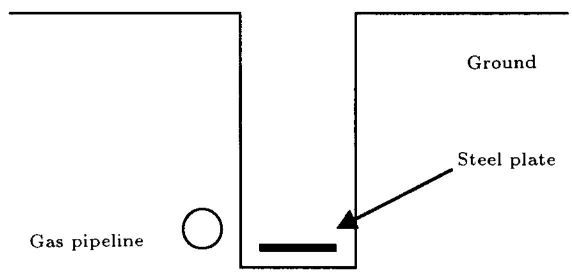

Figure 11. The mitigation system arrangement.

Table 6. The pipe voltage variation, changing No. of caps.

Test Point	11 Caps	11 Caps	20 Caps	20 Caps
	Top	Beneath	Top	Beneath
TP1	1.82	1.64	1.49	1.23
TP2	1.57	1.1	1.22	0.64
TP3	1.88	1.62	1.49	1.22
TP4	1.97	1.94	1.63	1.55
TP5	2.03	1.85	1.69	1.52

MEASURED AC VOLTAGE ON BURIED GAS PIPELINES IN THE CAPITAL CITY OF TEHRAN

A rectifier is a circuit or device which modifies the alternative signal to a direct current signal. Even a full wave rectifier without a filter has a relatively high ripple factor:

$$RF = \frac{V_{ac}}{V_{dc}}, \tag{7}$$

where:

$$V_{ac} = \sqrt{{V_{rms}}^2 - {V_{dc}}^2}.$$

The other parameters of a single-phase full wave rectifier are:

$$\text{efficiency} = \frac{P_{dc}}{P_{ac}} = 0.081,$$

$$V_{ac} = 0.3V_r, \; RF = \sqrt{1.11^2 - 1} = 0.482.$$

In the cathodic protection stations at the Iranian National Gas Company, this kind of rectifiers is normally employed and for a 1.2 volts dc output, there is a 0.4 volt ac signal. Three sets of these rectifiers are investigated and evaluated in three cathodic protection stations of the Iranian National Gas Company in Ghom, Nazarabad and Tehran.

Investigation on the Presence of ac Voltage on Residential Areas Gas Pipelines

Based on reports by the I.N.G.C. (Iranian National Gas Company) of relatively high voltage on gas pipelines, seven different cases around the central part of Tehran were investigated and the voltage was recorded by a digital scope. Through analysis of these waveforms and their harmonic contents, it was found that the source of this voltage was a kind of current leakage, which changed during the day.

Existence of these leakage currents is related to the occurence of a short circuit in an underground low voltage cable, which produces a distribution of equipotential lines around the short circuited point and, consequently, any point in the ground around the area will posses a voltage between 0-220 Volts. A simple procedure for considering safety measures can be employed for discovering the faulty locations and repairing the damaged part. Of course, this should be conducted while coordination is established between the related power companies in the area.

SUMMARY AND CONCLUSION

In this paper, the fundamentals of voltage induction is discussed, electrostatic and electromagnetic induction is evaluated and a method of its determination is proposed.

Different methods of induced voltage mitigation under overhead lines are also briefly discussed.

Based on the results of this research, a computer program is developed for determination of the effects of electromagnetic induced voltage on buried gas pipelines under different transmission line tower configurations and the parameters of the new efficient mitigation method are presented.

They problem regarding application of nonideal rectifiers in the Iranian National Gas Company cathodic protection stations was discussed. Seven cases of ac voltage occurence on gas pipelines in Tehran were investigated and resulted in the discovery that current leakage was the source of these abnormal conditions, which were related to some kind of low voltage, underground cable short circuit to the ground.

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