

Cathodic protection testing of onshore gas pipelines insulating joints and similar piping accessories

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Abstract

The insulation effectiveness of isolating appurtenances is of paramount importance in cathodic protection systems, especially in case of pipelines covered with highly insulating coatings (e.g. PE). The commonly applied routine tests to monitor the electrical isolation integrity (e.g. the detection of on/off potential waveform and the isolation impedance measurement) might lead to inconclusive or misleading results. A modified test methodology, based on impedance measurements, is suggested for improved isolation assessment of insulating piping accessories. The proposed methodology was theoretically verified via a simplified electric circuit analysis. It has furthermore proved its value in practice on the 3-layer PE coated gas transmission pipelines of Greece. The obtained results made possible to establish empirical criteria for isolation efficiency. Some shortcomings, such as inherent inaccuracies of the particular impedance measurements, the time lag and work strains involved, as well as spatial limitations of the test setup are also cited. Nevertheless, practical benefits and convenient data interpretation promote the suggested technique for verification of results or even as routine test.

Prüfung auf kathodischen Schutz von Isolierstücken und ähnlichem Rohrzubehör für Onshore-Gasleitungen

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Zusammenfassung

Die Wirksamkeit der Isolierstücke ist bei kathodischen Schutzsystemen von höchster Bedeutung, insbesondere bei Rohrleitungen mit stark isolierenden Beschichtungen (z. B. PE). Die üblicherweise angewandten Routineprüfungen zur Überwachung der Integrität der elektrischen Isolation (z. B. die Erfassung der Ein/Aus-Potential-Kurvenform und Messung der Isolationsimpedanz) kann zu nicht überzeugenden oder irreführenden Ergebnissen führen. Deshalb wird eine modifizierte, auf Impedanzmessungen beruhende Testmethodik zur besseren Bewertung der Isolation von isolierendem Rohrzubehör vorgeschlagen. Die vorgeschlagene Methodik wurde theoretisch über die Analyse eines vereinfachten elektrischen Stromkreises überprüft. Darüber hinaus hat sie ihre praktische Gültigkeit auf den 3-fach PE-beschichteten Gasleitungen in Griechenland erwiesen. Durch die erhaltenen Ergebnisse war es möglich, empirische Kriterien für eine wirksame Isolierung zu erstellen. Einige Mängel, wie inhärente Ungenauigkeiten von bestimmten Impedanzmessungen, die Zeitverzögerung und die Arbeitsaufwände, sowie räumliche Beschränkungen des Versuchsaufbaus werden ebenfalls zitiert. Dennoch empfiehlt sich die vorgeschlagene Methodik aufgrund ihrer praktischen Vorteile und zweckdienlichen Datenauslegung für die Überprüfung von Ergebnissen oder sogar Routinetests.

Essais de protection cathodique de joints d'isolation de conduites de gaz terrestres et d'accessoires de conduites similaires

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Résumé

L'efficacité d'accessoires de canalisation isolants est d'une importance primordiale dans les systèmes de protection cathodique, tout particulièrement en ce qui concerne les conduites recouvertes de revêtements hautement isolants (par ex. PE). Les essais de routine couramment menés pour surveiller l'intégrité de l'isolation électrique (par ex. la détection de formes d'onde de potentiel ON/OFF et la mesure de l'impédance de l'isolation) peuvent aboutir à des résultats non concluants ou trompeurs. Une méthodologie d'essai modifiée, basée sur des mesures d'impédance, est suggérée pour améliorer l'évaluation du pouvoir isolant d'accessoires de conduites isolants. La méthodologie proposée a été vérifiée sur le plan théorique via une analyse de circuit électrique simplifié. Elle a de surcroît démontré sa valeur dans la pratique sur les conduites de transport de gaz couvertes de 3 couches de PE en Grèce. Les résultats obtenus ont permis d'établir des critères empiriques pour l'efficacité de l'isolation. Certaines lacunes, comme les inexactitudes inhérentes des mesures d'impédance particulières, le retard et la charge de travail impliqués, ainsi que les limitations spatiales de l'installation d'essai sont également citées. Néanmoins, les avantages pratiques et la commodité de l'interprétation des données préconisent d'utiliser la technique suggérée pour la vérification de résultats ou même comme essai de routine.

Introduction

The periodic measurements of cathodic protection maintenance can be classified into three main categories, according to the physical quantities involved, i.e. voltage/potentials, currents and resistances/impedances.

Carrying out cathodic protection testing without recognition of the limitations of every measurements technique may lead to erroneous results, even to wrong decisions. For potential measurements, various methods of controlling the measuring errors have been proposed (1) (2) (3). A critical spirit is often needed and more than one measurement techniques are sometimes recommended to ensure conclusive results. It is somewhat risky to rely only on ranges and thresholds of supposedly normal values. Furthermore, the initial measurements may serve as reference values only if:

- during the initial measurements, the piping system and its cathodic protection under test is in normal operating conditions.
- upon evaluating measurements, taken at different times, alterations of the system in the meantime, such as coating breakdown/aging, additions or subtractions of pipeline sections, stray current and AC interference sources shall be taken into consideration.

In the present work, we focus on resistance measurements usually performed on insulating joints of gas transmission pipeline systems, in an attempt to suggest an improved methodology to early detect isolation ineffectiveness in piping systems wrapped with highly insulating coatings.

Earth resistance measurements

In the monitoring of cathodic protection of buried structures what is usually termed as resistance, is the resistance to an AC voltage (namely impedance). The DC resistance is rarely measured because of complications arisen by electrochemical polarization effects.

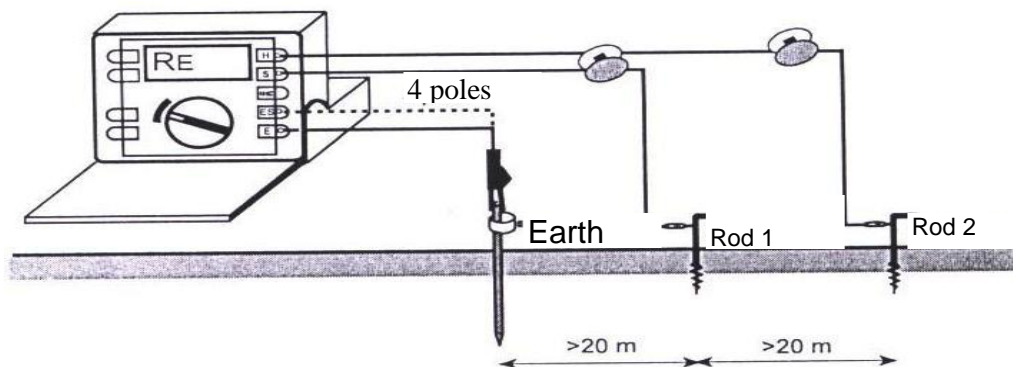


Fig. 1. *Illustration of earth resistance measurement setup.*

The widespread applied method is the so called Wenner with three or four poles by means of an instrument, usually the so called 'earth resistance meter'. What is illustrated in Fig. 1 is the measurement setup of resistance to remote earth (being actually impedance but called resistance for simplicity) of an earth electrode or a buried structure. The principle of the method is based on the application of an AC voltage with a frequency other than harmonics of 50/60 Hz so that interference from power frequency is eliminated (in our case, of voltage around 48V and frequency 94, 111, 105 or 128 Hz), then the response current is measured by the instrument, resulting in a resistance reading given by the ratio of voltage to current. Two earthing

rods are implemented. Between rod 2 and earth electrode, the voltage is applied and between rod 1 and earth electrode the current is measured. For better accuracy, i.e. for compensation of error caused by the resistance of wires involved, 4 poles measurement is chosen. The same principle applies when testing at two terminals.

Brief description of Greek NNGS pipeline and cathodic protection system

The results have been taken on the National Natural Gas System (NNGS) transmission pipelines of Greece installed in the time interval between 1993 and 2003 and buried at a depth of 1 to 2m in the soil.

Buried piping, piping components and vessels are externally coated with a 3-layer PE system according to EN ISO 21809 (4) and DIN 30670 (5).

All main and branches pipelines are protected by a Cathodic Protection System. The system complies with the requirements of DIN 30676 (6) and EN 12954 (7).

The pipeline system has been divided in electrically isolated sections using underground insulation joints. Each section is protected by its own CP system. Each CP system consists of one transformer rectifier unit, one permanently installed reference electrode, and one complete anode bed. The cathodic protection is applied by means of one Transformer/Rectifier (T/R) unit, protecting pipeline lengths usually between 25 and 60km. The groundbed is composed mostly of magnetite (Fe_3O_4) anodes. In order to have a sufficient Cathodic Protection System, a number of Measuring Posts have been installed alongside the pipeline's routing. The measuring posts provide the means to locally perform various types of measurements (Potential, Protective Current, AC Current measurements, Efficiency of the Isolating Devices etc.). Furthermore, there is an Earthing System through overvoltage arresters for the mitigation of AC interference on the pipeline.

Proposed methodology for assessment of isolating joint effectiveness

The concept behind the proposed test method is not actually an entirely new one. It is based on the equivalent electric circuit illustrating the test setup of an insulating joint already depicted in the norm EN 13509 (Fig. 2). When the isolating joint is electrically effective, the resistance, R_{iso} , of the joint is very large in comparison with the resistances to remote earth of adjacent sections, R_1 and R_2 , therefore the resistance reading taken by the measuring instrument as connected in Fig. 2, should theoretically indicate the sum R_1+R_2 , since R_{iso} tends to infinite. The core idea of the proposed test methodology is the comparison of the resistance of the insulating joint with the sum of resistances to remote earth of each of the two sections on either side.

This concept was conceived after the electrical failures of isolating joints in the NNGS. Some isolating joints failures were revealed by use of the commonly applied tests, particularly when their resistance was particularly low. On other isolation joints, the tests results, led to a confused view. For the verification of isolation effectiveness, various tests were carried out. These tests were generally time-consuming and rather complex. Thus we looked for a credible, quick and handy test method, that could be incorporated in the periodic test measurements with a view to replace or supplement the routine tests followed that time.

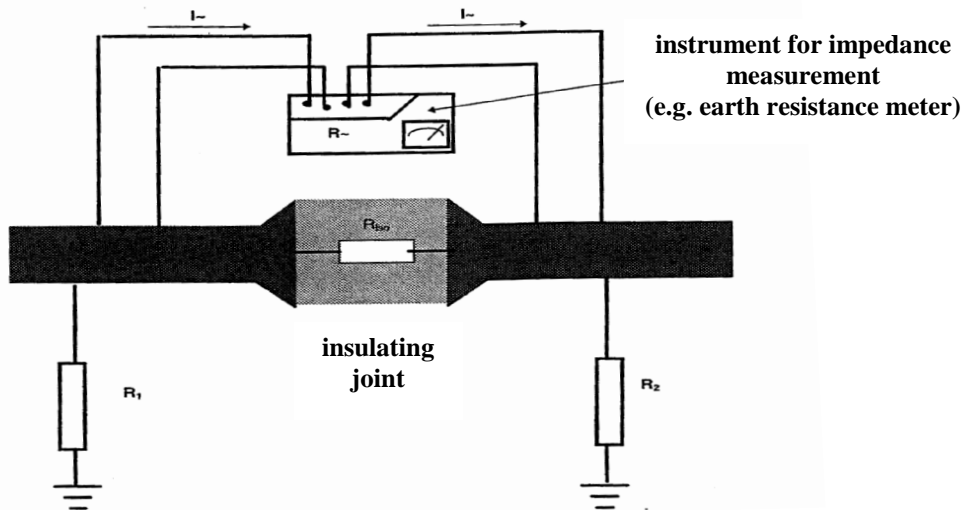


Fig. 2. Schematic of insulating joint resistance measurement by means of earth resistance meter.

Formerly, the insulation joints or flanges used to be checked by a combination of on/off potential and resistance measurements, i.e. with concurrent on and off potential measurement on both sides and by measuring the resistance of the buried or immersed isolation joint using earth resistance meter (Wenner method), the two poles which were connected at one end of the insulation joint and the two other poles at the other end. However, this test was hardly sensitive on occasion of a marginally detectable electrical leakage of the joint.

The corroboration of the electrical integrity of the insulating piping apparatus (e.g. insulating joint or flange) between two cathodically protected areas was very often carried out by installing on/off switching relay and rising the output voltage on the rectifier which cathodically protected one adjacent section and disconnecting the rectifier protecting the other section of insulating joint tested. In this manner, a secure and distinct detectability of insulation fault was attempted by the clear reading of a synchronous on/off swing on both ends of the insulation. After the test was finalized, the rectifiers had to be regulated back to their original settings. This test method encompassed enhanced personnel resources, time and cost, caused by the travelling back and forth between test site and rectifier that is not negligible in long transmission pipelines (it can only be tackled by a remote monitoring and control system that is not always available). This was partly resolved by a remote monitoring system enabling us to remotely control the on/off switch; although we were not able to remotely adjust the rectifier settings.

When employing a different tactic that allowed cathodic protection on both sides of insulating joint without resorting to boosting the CP level on one side and switching off CP on the other side, then the test results could be more confusing, specifically in presence of stray currents and in case of minor electrical leak of the insulating equipment under test. Despite limited travelling, hardly any advantage was gained in terms of resolution of the obtained data that could enable the operator to utterly detect the insulation flaws.

The on/off switching swing detection technique was based on the simple principle that under normal conditions the periodic on/off waveform from the periodic

interruption of CP circuit in one area must not be transferred to other structures where the cathodically protected pipeline is isolated from. Sometimes, the detection of a synchronous on/off waveform is hardly clear-cut and can even go unnoticed particularly in the event of electric leak of a cathodically protected pipe to an earthed structure exhibiting a low earthing resistance. For instance, we have been given some interesting figures, referring to an insulated flange in an oil storage found to have lost its isolating properties; it was however not obvious to everybody (8). The on/off potentials on the primary side were -1200mV/-270mV. On the secondary side the on/off potentials were -242mV/-241mV. When connected an ac-source to the pipe system (primary side), an ac-current, approximately 670mA, passed through the pipe section towards the defective isolating flange, indicating that the insulating joint was defective. Upon opening the flange, the on/off potentials measured on the primary side were -5800mV/-950mV and on the secondary side -140mV/-170mV. What is taught from this example is that a combination of test methods should therefore be applied to ensure conclusive results.

In the Greek NNGS, The measured quantity initially analyzed was the resistance of the insulating joint. One of the criteria that had been adapted was the resistance of the insulation joint not exceeding a certain limit, e.g. 1Ω. This criterion had serious drawbacks since several factors were not taken into consideration. As this resistance relies on the resistances to remote earth of the piping accessories on either side of insulation, the resistance reading is subject to variations with time so that a lot of measurements throughout time are required before conclusions are made by a comparison of the values on a graph of resistance versus time $R=f(t)$. Such a methodology can hardly give conclusive results unless there is a sudden large drop of insulation properties. It can stand only as an assisting method, supplementary to alternative techniques; otherwise the insulation fault can even go undetected. The success of this assessment method presupposes reliable initial values, taken early enough, when the installed insulation apparatus is intact; these can function as reference values facilitating thus the analysis of results.

The insulation resistance measured with Wenner method, amongst other, depends on the dimensions and the coating quality of the pipe sections of either side, if earthings are connected or not and by the earthing resistance of earthing electrodes. This fact can lead to resistance variations that are independent of the electrical integrity of the insulation joint. For example, when the measurement is taken during accidental direct earthing of the pipe on either side, the measured value will still appear low, although this is irrelevant to insulation joint breakdown. Another reason of resistance diminishing can be the dimensional changes of the pipelines involved, e.g. when an involved pipe branch is added. On the opposite, resistance can increase either if a pipeline section is cut off or a bridge (jumper) of insulation joint is disconnected. Seasonal variations of the earthing electrodes resistances or pipeline/coating resistance changes can complicate the results as well. Inherent errors of earth resistance measurement can further mystify the interpretation of the resistance readings. Therefore, the measured resistance of the insulating joint, R_{ij} must be compared with the sum of the earthing resistance readings ($R_1' + R_2'$). of either side of the insulating equipment R_1' and R_2' respectively. Furthermore, a theoretical foundation of the inequality, $R_{ij} \ll R_1' + R_2'$, is given in Appendix A. The meaning behind the inequality is that when the reading of the resistance of the insulating apparatus is well below the sum of resistances to remote earth of the

pipeline sections on either side of the insulating apparatus, this is an indication of ineffective isolation that may require further investigation.

Pros and cons of the proposed methodology

The comparison of the insulating joint resistance with the resistances of the adjacent pipeline sections of either side has the advantage that it is generally not affected by pipeline system alterations, such as voluntary or involuntary earthing of the pipeline, lengthening or shortening of adjacent pipeline sections, e.g. via installation of additional pipeline segments or incorporation of additional insulating joints or removal of jumpers of intentionally bridged insulating joints, events that can considerably change the resistance of the adjacent pipeline sections thus altering the measured resistance of the insulating joint. Therefore, the usually applied practice to spare comparison with the resistances of adjacent pipeline sections can lead to misleading conclusions. Meanwhile, the proposed assessment practice can be incorporated in the periodic cathodic protection maintenance routines, being a simple method of checking the isolation integrity of the insulating appurtenances not requiring any sophisticated measuring equipment. It can give the opportunity to detect even slight reductions of insulating properties. The proposed assessment method can be specifically useful under circumstances that the usual on/off swing detection technique fails. Situations that the on/off swing detection technique may fail or at least may require alternative testing are for instance when the on/off waveform is hardly detectable in case one of the adjacent pipeline sections is earthed via small earthing resistance and when affected by stray currents. Furthermore, an eventual fault of isolating joint properties can be promptly detected by the straightforward comparison with the sum of resistances on both sides of the joint, as it is not absolutely necessary to trace back to initial reference values and historical data review. The technique can be applied to all insulating joints, either buried or aboveground. It does not require any excavations to unbury the isolating joint. Moreover, the normal operation of the cathodic protection is not disturbed, as disconnection, adjustments of settings or other kind of interventions on the cathodic protection rectifiers are not necessary. The proposed methodology spares staff mobilisation i.e. moving back and forth to connect/disconnect the on/off relays or adjust/readjust the rectifier settings, actions that are necessary when using the on/off swing detection technique, especially with rectifiers which are not remotely operated. When compared to merely measuring a simple resistance on the insulating joint, the main disadvantage of the proposed methodology relies on the necessity of carrying out more measurements, thus inevitably increasing the testing time. As the earthing resistances of both sides of the joint must be additionally measured, the installation of earthing rods at least 40m away from the pipeline involves certain practical constraints. Obviously, such problems arise particularly in densely built urban areas. Another problem, concerning the measurement accuracy, is related to other metallic constructions located nearby (e.g. metallic fences), the soil texture and resistivity, since the accuracy of earthing resistance measurement may be aggravated in highly resistive soil conditions and when big metallic structures are located nearby.

Results and discussion

Within the framework of the aforementioned methodology, the insulating joints can be characterized by the magnitude of their measured resistance R_{ij} deviation s from the sum of the measured resistances to remote earth of adjacent sections ($R_1' + R_2'$).

The percentage deviation, s , is defined as follows:

$$s = \frac{R_{ij} - [R'_1 + R'_2]}{R'_1 + R'_2} \times 100 \quad (1)$$

Typical measurement results of the resistances and the respective deviation calculations, s , on several insulating joints of the Greek gas transmission grid are presented in Table of Appendix B. Those insulating joints that are definitely electrically failed are depicted in Appendix B with bold. All of the insulating joints with a confirmed reduction of their isolation effectiveness, being proven through various measurement techniques, showed negative deviation, s , much lower than -10%. Evidently, after the replacement of the insulating joints 7-8 and 8-9 in December 2007, the deviation, s , shifted towards percentage values above -10%. Other insulating joints exhibited deviations in the range -10% up to 0% (see Table). These smaller deviations are interpreted as follows. According to the first scenario, it can be attributed to the inherent errors of the test method, as the readings are dependent on the position of earth rods used for the measurement. In soils of reduced conductivity the measurement result is even more sensitive to the position of earth rods. In case the earth rods are not located far away enough from the electrical fields being around earthing electrodes or metallic structures under measurement, the measured resistance readings are lower than the real values, whereas on the opposite, the measured resistance readings are higher when there is close distance between the two earth rods used for the measuring setup (9).

According to the second scenario, those insulating joints exhibiting small deviations may indeed present a small deterioration of the electrical isolation properties. According to our experience a tiny reduction of the isolation efficiency can be tolerable to a certain extent unless linked with a mechanical trouble. Under such circumstances, more measurements may be needed to guarantee the effectiveness of cathodic protection.

In case the deviation, s , is positive or close to 0, then, almost without any doubt, the insulating joint is electrically efficient.

Table 1. Results from electrical tests, with on/off potential switching method for testing electrical isolation integrity of insulating joint between (a) CP areas 2-3 and (b) CP areas 8-9.

(a)		
CP area	Potential on (V)	Potential off (V)
2	-2,85	-1,42
3	-0,86	-0,85

(b)		
CP area	Potential on (V)	Potential off (V)
8	-2,95	-1,51
9	-2,75	-1,47

A measurement series carried out with the switching on/off potential methodology for the insulating joint between CP areas 2-3, typical of a joint having a small reduction of isolation efficiency hardly affecting smooth cathodic protection operation, is presented on Table 1(a). The slight reduction of isolation efficiency, detected from the amplitude of the on/off potential waveform, being just 10mV at CP area no.3 (measured while CP was off at CP area no.3, and simultaneously CP level

augmented at CP area no.2), can be considered negligible for cathodic protection function.

For comparison, a measurements series on the insulating joint between CP areas no. 8 and 9, carried out with the same switching on/off potential methodology is presented on Table 1(b). It is evident in the second case, there is a considerable effect on cathodic protection function, given that the data shown on Table 1 have been obtained after a deliberately high cathodic adjustment of rectifiers of CP areas no. 2 and no. 8 respectively while CP is off at CP areas no. 3 and 9.

These results and other empirical data encouraged us to suggest another criterion for the isolation efficiency of insulating joint that is based on the negative deviation, s , as defined in equation (1). This new empirical criterion could be formulated as below.

If the deviation, s , is more negative than -10%, the insulating joint is considered to have a more or less acceptable isolation efficiency, without affecting normal cathodic protection efficiency (at least for well insulated long pipelines).

If the deviation, s , is between -10% and 0, then two possibilities exist, separately or simultaneously, i.e. either the insulating joint has a slight reduction of the isolation efficiency that in most cases is acceptable in terms of cathodic protection function, or this is caused by inherent measurements errors. In such case, additional tests are suggested in order to confirm the isolation efficiency. It is also imperative to determine the criticality of the problem of any small electrical leakage of the joint on the smooth operation of cathodic corrosion protection.

In case one side of the insulating joint/flange is an earthed structure, the measurements of on/off potential swing can lead to inconclusive results to the extent that even a faulty joint can go undetected. For instance, when the primary structure resistance to remote earth and subsequently the insulating joint resistance are orders of magnitude larger than the grounding resistance of the secondary structure (e.g. 1000 Ω versus 1 Ω respectively) and when cathodic currents are very low (e.g. in the order of 1mA) as is the case of well insulated pipelines, then the IR drop on the secondary structure, i.e. the amplitude of the on/off swing, due to the very low current and grounding resistance, can be so small that can go undetected.

Despite this weakness, the on/off potential swing technique works well in most cases. In combination with resistance measurements can even more successfully detect isolation efficiency faults.

If an asynchronous on/off potential swing is detected on the secondary side, it is an indication of anodic influence from the cathodic protection current flowing through soil and coating defects or alternatively by a current bypass of the joint internally via a conducting fluid/solid. In such a case, the internal insulating materials of the joint are intact (10).

Similarly, other kind of electrical isolation facilities (e.g. between pipe and casing) can be tested. On Table 2, typical measurement results are indicated for a real case of confirmed electric contact between pipeline and casing, being at one end of casing. Prior to repairing the contact, (carried out by cutting off the casing end), the deviation, s , according to equation (1) was <-60%, and after the repair, the negative deviation shifted to as little as -0,38%.

Table 2. Resistance measurement results and deviation, s , casing at 28,6km of Volos branch (CP area 17)

Test date	R pipe/casing (Ω)	R casing/earth (Ω)	R pipe/earth (Ω)	Deviation s (%)	Remarks
10/10/2005	12,30	22,94	11,11	-63,88	prior to repair
30/10/2006	12,74	22,80	10,49	-61,73	prior to repair
27/2/2007	94,30	82,70	11,96	-0,38	after repair

Similar results (see Fig. 3 & Fig. 4 and Appendix B) were obtained on insulating joints that were electrically faulty and replaced afterwards (on Table of Appendix B the results for insulating joints 7-8 and 8-9 marked as 'acceptable' have been obtained on newly installed insulating joints that replaced the faulty ones at exactly the same sites).

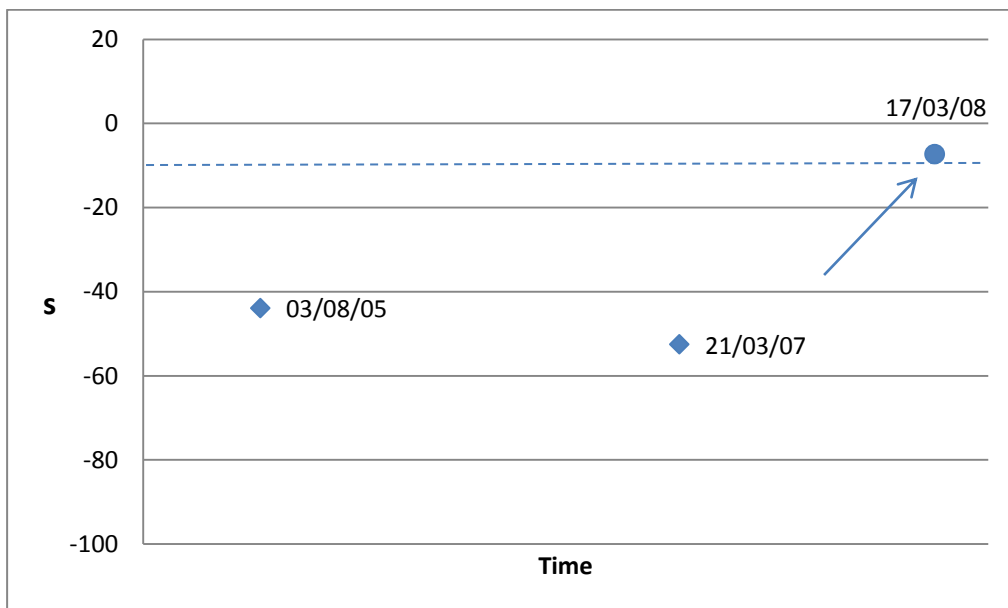


Fig. 3. Sudden shift of deviation s after replacement of insulating joint between CP areas 7-8 (see round circle shifted below dashed line of -10% criterion).

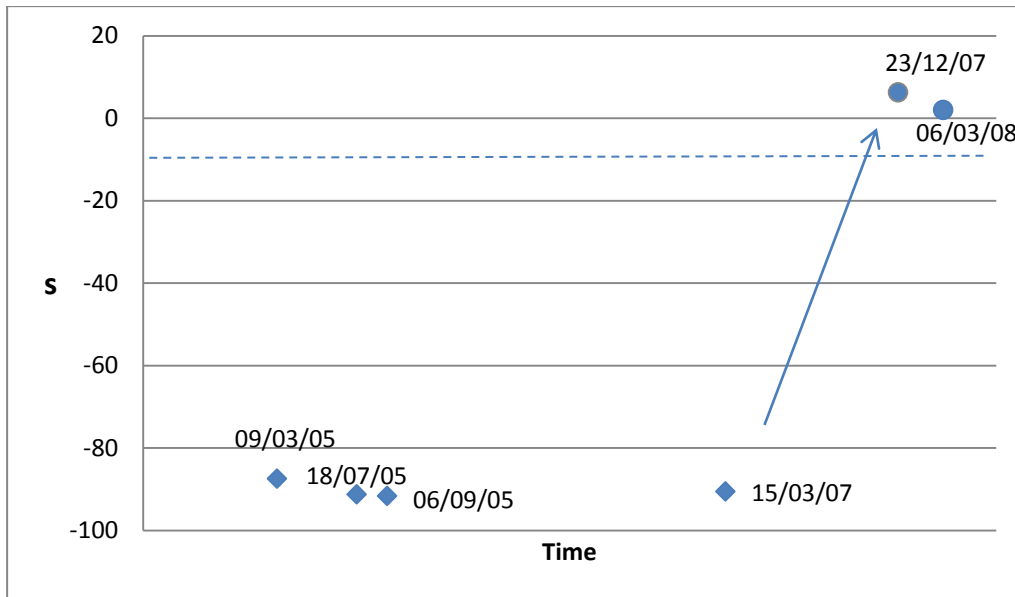


Fig. 4. Sudden shift of deviation s after replacement of insulating joint between CP areas 8-9 (see round circles shifted below dashed line of -10% criterion).

Conclusions

A modified approach has been suggested for the testing of isolating efficiency of installed insulating equipment in gas pipeline transmission systems. This approach is based on resistance measurements. The proof of the suggested methodology has been given both theoretically, through a simplified circuit analysis and experimentally by results obtained from real data on natural gas transmission pipelines. An empirical criterion has been formulated for acceptance of the electrical isolation of installed buried in the soil isolation equipment in gas transmission piping systems.

This modified methodology has some advantages, such as:

- it is not affected by modifications on the piping systems on either side of isolating equipment
- direct detection of an isolation efficiency problem
- more sensitive to minor decline of isolation efficiency
- can be applied on both buried and above ground isolating joints
- the pipeline does not need to be unburied
- no special equipment is required
- cathodic protection operation is not disturbed
- CP operation staff's unnecessary travelling is saved.

However, some disadvantages can be as follows:

- it is a relatively more time consuming and strenuous method, as earth rods have to be driven to ground, at distant locations from the pipeline under test (although usually less than 50 m away is enough)
- in narrow spaced areas or in urban environment practical problems arise as to the earth rods location needed for the measurement.

Nevertheless, the proposed approach for testing insulating joints and similar pipelines accessories can be suggested either as a supplementary verification test or a routine test included in the periodic measurements of cathodic protection of gas pipelines.

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Appendix A

Theoretical proof of the proposed methodology

When measuring resistances of the installed insulating joints, the measurement circuit includes the resistances to remote earth of the adjacent metallic constructions (e.g. pipelines etc.) on either side of the insulating joint. For simplification we will refer to ohmic resistances instead of impedances, but it hardly alters the substance of our reasoning and the calculations involved, since the resistances mathematically behave the same as impedances.

Generally speaking, a low resistance value of an isolating joint is not always a safe indication that the insulating joint is deficient, as the measured resistance depends on the resistance of either side R_1 and R_2 , as mentioned above.

The measured resistance, R_{ij} , of an isolating joint, comes from the following equation:

$$1/R_{ij} = 1/R_{iso} + 1/(R_1 + R_2) \quad (a1)$$

transformed into:

$$R_{ij} = \frac{R_{iso}(R_1 + R_2)}{R_{iso} + R_1 + R_2} \quad (a2)$$

where R_{iso} is the resistance of the isolating joint, R_1 and R_2 the resistances to remote earth of either side of the joint, as illustrated in Fig. 2.

When the insulating joint resistance is not close to infinite (as it is the case when the resistance of the joint has been diminished) because of relationship (a2) the following inequality is valid:

$$R_{ij} < R_1 + R_2 \quad (a3)$$

In normal conditions, when the insulating joint has good insulating properties, the resistance, R_{iso} , tends towards infinite or at least it is some orders of magnitude greater than the resistances R_1 and R_2 , that is

$$R_{iso} \rightarrow \infty \quad (a4)$$

or

$$R_{iso} \gg R_1 \quad (a5)$$

and/or

$$R_{iso} \gg R_2 \quad (a6)$$

then

$$R_{iso} \gg R_1 + R_2 \quad (a7)$$

Then the relationship (a3) tends towards the following equation

$$R_{ij} = R_1 + R_2 \quad (a8)$$

In intermediate conditions, when the insulating joint resistance either is not close to infinite or not much greater than R_1 and R_2 , i.e. in case the insulating joint experiences a reduction of its insulating properties, the values of measured resistances of either side of the insulating joint will be then apparently lower than the ones that would have been measured when $R_{iso} \rightarrow \infty$. In such a case, the reduced resistance readings are symbolized as R_1' and R_2' instead of R_1 and R_2 respectively.

When attempting to measure the resistance to remote earth on either side of the joint, in essence one measures the equivalent resistance of the circuit of Fig. 5. In particular, when measuring R_1 between points 1 and 3, in reality what is measured is the equivalent resistance from the parallel combination of R_1 and the sum of R_2 and R_{iso} , being in series, and consequently the following relation is valid:

$$R_1' = \frac{R_1(R_{iso} + R_2)}{R_{iso} + R_1 + R_2} \quad (a9)$$

For resistance R_2' respectively:

$$R_2' = \frac{R_2(R_{iso} + R_1)}{R_{iso} + R_1 + R_2} \quad (a10)$$

From equations (a9) and (a10) the following inequalities are obviously valid:

$$R_1' < R_1 \quad (a11)$$

$$R_2' < R_2 \quad (a12)$$

$$R_1' + R_2' < R_1 + R_2 \quad (a13)$$

Apparently, when formulas (a5), (a6) and (a7) are valid, then:

$$R_1' = R_1 \quad (a14)$$

$$R_2' = R_2 \quad (a15)$$

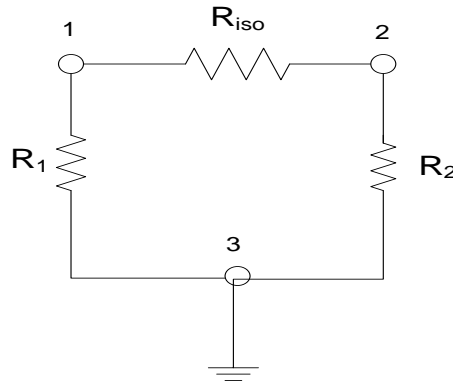


Fig. 5 Simplified circuit of an insulating joint resistance measurement.

The measured resistance of the insulating joint R_{ij} , is actually the equivalent resistance coming from R_{iso} in parallel to the sum of resistances to remote earth R_1 and R_2 , that is expressed by the formula (a2). The resistance values R_1 and R_2 coincide with the measured resistances of either side when R_{iso} tends to infinite. In case the insulating joint has a reduced defined resistance, then the measured resistance readings become R_1' and R_2' . In any case the following inequality stands:

$$R_{ij} < R_1' + R_2' \quad (a16)$$

since from equations (a9) and (a10) follows that :

$$R_1' + R_2' = \frac{R_{iso}(R_1 + R_2)}{R_{iso} + R_1 + R_2} + \frac{2R_1R_2}{R_{iso} + R_1 + R_2} = R_{ij} + \frac{2R_1R_2}{R_{iso} + R_1 + R_2} \Rightarrow$$

$$R_{ij} = \left(R_1' + R_2' \right) - \frac{2R_1R_2}{R_{iso} + R_1 + R_2} \Rightarrow$$

$$R_{ij} < R_1' + R_2' < R_1 + R_2 \quad (\text{a17})$$

because of inequality (a13).

Thus, it is theoretically proven that the resistance reading of an electrically defective insulating joint of a pipeline system should be generally lower than the sum of resistances (either apparent readings taken from the measuring instrument or real values) of each of the adjacent sections of the isolating joint (see inequality (a17)).

Appendix B

Table. Series of resistance measurements, obtained at various test times, on insulating joints of Greek NNGS in terms of acceptance or rejection of isolation efficiency based on the deviation criterion, s , as defined in equation (1).

INS. JOINT	CHAINAGE (km)	DATE OF TEST	R_1 (Ω)	R_2 (Ω)	R_{ij} (Ω)	R_1+R_2	s (%)	COMMENT on isolation efficiency
8-9	336,7	3/8/2005	6,6	8,1	8,24	14,7	-43,9	NON-ACCEPTABLE
8-9	336,7	21/3/2007	7,8	9,92	8,42	17,72	-52,5	NON-ACCEPTABLE
8-9	336,7	17/3/2008	12,38	14,21	24,64	26,59	-7,3	ACCEPTABLE
7-8	279,0	9/3/2005	4,08	4,32	1,05	8,40	-87,5	NON-ACCEPTABLE
7-8	279,0	18/7/2005	4,07	4,32	0,73	8,39	-91,3	NON-ACCEPTABLE
7-8	279,0	6/9/2005	4,08	4,35	0,70	8,43	-91,7	NON-ACCEPTABLE
7-8	279,0	15/3/2007	5,69	5,86	1,08	11,55	-90,6	NON-ACCEPTABLE
7-8	279,0	23/12/2007	6,46	7,62	14,97	14,08	+6,3	ACCEPTABLE
7-8	279,0	6/3/2008	7,14	9,52	17,00	16,66	+2,0	ACCEPTABLE
6-7	220,8	9/3/2005	7,73	8,34	2,19	16,07	-86,4	NON-ACCEPTABLE
6-7	220,8	12/9/2005	7,9	7,66	2,37	15,56	-84,7	NON-ACCEPTABLE
6-7	220,8	14/3/2007	8,01	8,44	2,41	16,45	-85,4	NON-ACCEPTABLE
6-7	220,8	18/3/2008	6,1	6,46	2,76	12,56	-78,0	NON-ACCEPTABLE
5-6	185,6	11/3/2005	4,12	3,82	0,65	7,94	-91,9	NON-ACCEPTABLE
5-6	185,6	22/8/2005	8,1	7,98	0,27	16,08	-98,4	NON-ACCEPTABLE
5-6	185,6	12/3/2007	3,74	3,96	0,58	7,70	-92,4	NON-ACCEPTABLE
5-6	185,6	14/3/2007	4,35	3,82	1,14	8,17	-86,1	NON-ACCEPTABLE
5-6	185,6	18/3/2008	3,56	4,83	0,76	8,39	-90,9	NON-ACCEPTABLE
4-5	140,7	4/8/2005	5,1	3,6	2,77	8,70	-68,1	NON-ACCEPTABLE
4-5	140,7	13/3/2007	9,93	8,53	3,17	18,46	-82,8	NON-ACCEPTABLE
4-5	140,7	20/3/2008	6,18	4,21	2,81	10,39	-73,0	NON-ACCEPTABLE
12-B	512,0	18/10/2005	4,17	3,01	7,00	7,18	-2,5	ACCEPTABLE
10-11	413,8	15/9/2005	12,52	4,85	16,20	17,37	-6,7	ACCEPTABLE
13-MR	22,7(K)	23/11/2005	3,07	0,821	3,62	3,89	-7,0	ACCEPTABLE
13-MR	22,7(K)	23/10/2006	3,05	0,825	3,82	3,88	-1,4	ACCEPTABLE
17-7	228,0	18/3/2005	34,2	2,38	33,50	36,58	-8,4	ACCEPTABLE
9-10	377,0	10/5/2005	13,29	7,6	20,90	20,89	0,0	ACCEPTABLE
9-10	377,0	6/9/2005	7,6	13,25	20,88	20,85	0,1	ACCEPTABLE
11-22	431,8	15/6/2005	6,47	6,9	13,71	13,37	+2,5	ACCEPTABLE
11-22	431,8	19/9/2006	6,35	6,52	13,68	12,87	+6,3	ACCEPTABLE
12-13	481,6	23/10/2006	17,34	13,65	35,35	30,99	+14,1	ACCEPTABLE