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Simulation of a cathodically protected pipeline with capacitive ac-mitigation devices for the interpretation of the falsification of instant-off pipe-to-soil potential measurements

N. Kioupis (DESFA), N .Kouloumbi and G. Batis (NTUA) – Greece

DESFA: Hellenic Gas Transmission System Operator S.A.
NTUA: National Technical University of Athens

Abstract

Several capacitive ac-mitigation devices are usually utilised which connect the pipe to earthing electrodes at various locations along the pipe route, in order to decrease the induced ac voltage of a cathodically protected pipeline buried in soil. During instant-off pipe-to-soil potential measurements, these devices tend to discharge themselves through the soil. This phenomenon must be taken into consideration since an error in the instant-off potential readings is created by the capacitor discharging currents. It can result to a false view i.e. the pipeline is sufficiently cathodically protected even when it is not.

The aim of the present work is the investigation of the role of the involved parameters with regard to the falsification of instant-off potential readings. For this purpose, an electric circuit simulation of the pipeline with connected capacitive devices is proposed. The key parameters involved are the capacitance value of every ac-mitigation device, the population number of them, the earthing electrodes resistance as well as the pipeline resistance to remote earth. Methods for reducing the error in off potential readings are presented. A modification of the conditions of off potential measurement is suggested aiming at reliable CP potentials readings. Moreover, by taking CP potential measurements under conditions of low ac voltage any impact of high ac interference on the CP parameters is avoided.

1. Outline of the falsification phenomenon of the off potential readings due to discharging of capacitive ac-mitigation devices

The falsification phenomenon of instant-off pipe-to-soil potential readings due to the capacitive ac-mitigation devices discharging effect is outlined hereto. An initial approach is attempted in this paragraph. The experimental conditions, the pipeline and its CP system description and the results of Fig.1 and Fig.2 have already been stated in a previous work [1].

A representative on/off pipe-to-soil potential waveform, prior to installing ac-mitigation devices, is depicted in Fig.1. The instant-off pipe-to-soil potential is more accurately obtained at 0,2 or 0,4sec time lapse after CP off-switching, i.e. at the break of on/off potential vs. time waveform curve (point A of Fig.1). For the acquisition of this instant-off potential measurement, special equipment is required (e.g. digital oscilloscope with active ac filter or pen recorder); besides it is a relatively time consuming process.

A closer look on the plot of Fig.1 reveals that during the CP off-time period between 0,4sec and 3sec following every CP off-switching time (time period between points A and B, i.e. A-B period), the depolarisation rate is particularly slow, during which the pipe-to-soil potential hardly moves more anodically than 50mV. Moreover, this pipe potential depolarisation resides in the first msec of each A-B period, whereas in the rest off-time the potential is almost constant.

The instant-off pipe potential used to be acquired within 1sec duration after CP off-switching [2], since the acquisition of instant-off pipe-to-soil potential at longer than 1 sec time, introduces an error. However, taking into account that this error is small and almost constant, the instant-off potential could be sampled at the end of each CP off-time period, i.e. 3sec after each CP supply off-switching (point B of Fig. 1), considering that it is enough to compare relatively inaccurate values, being aware of this constant error magnitude, instead of comparing more accurate values. Moreover, the instant-off potential measurement at the end of the 3sec CP off-time period can be merely acquired by means of a simple digital multimeter. Besides, this instant-off potential reading method is easier, without errors introduced by the operator's subjective reading and independent of the sampling rate of the multimeter, factors introducing additional errors when attempting to measure, by means of a multimeter, the instant-off potential at point A of Fig.1.

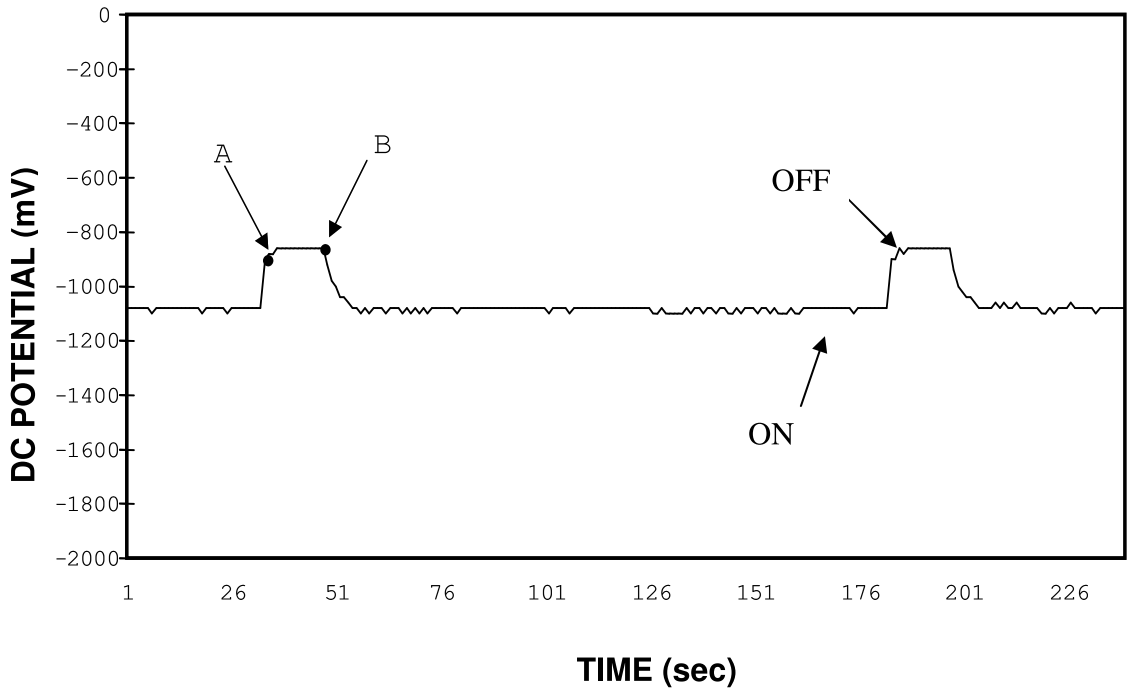


Figure 1. ***On/off pipe-to-soil potential waveform–No capacitive ac-mitigation devices are connected - Test post KG 47.3 km, Uac=13,8V.***

The discharging effect of capacitive ac-mitigation devices on the on/off potential waveform is depicted in Fig.2 where obviously the waveform shape is modified in comparison with the respective one of Fig. 1. This is attributed to the discharging effect of the capacitive ac-mitigation devices.

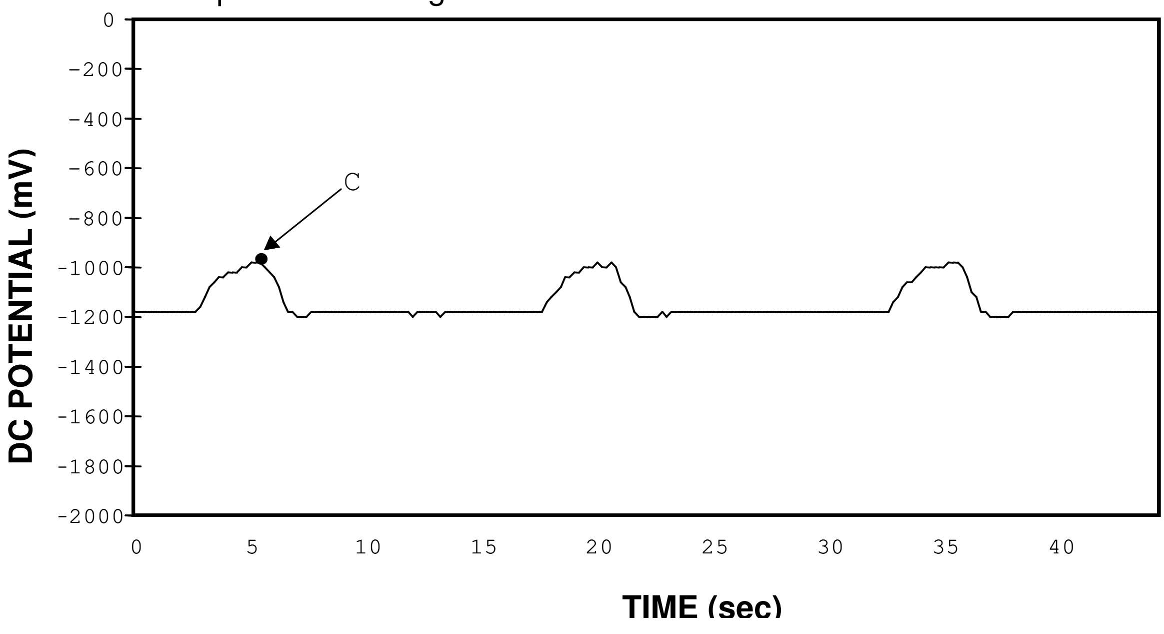


Figure 2. ***On/off pipe-to-soil potential waveform–Capacitive ac-mitigation devices are connected -Test post KG 47.3 km, Uac=1V***

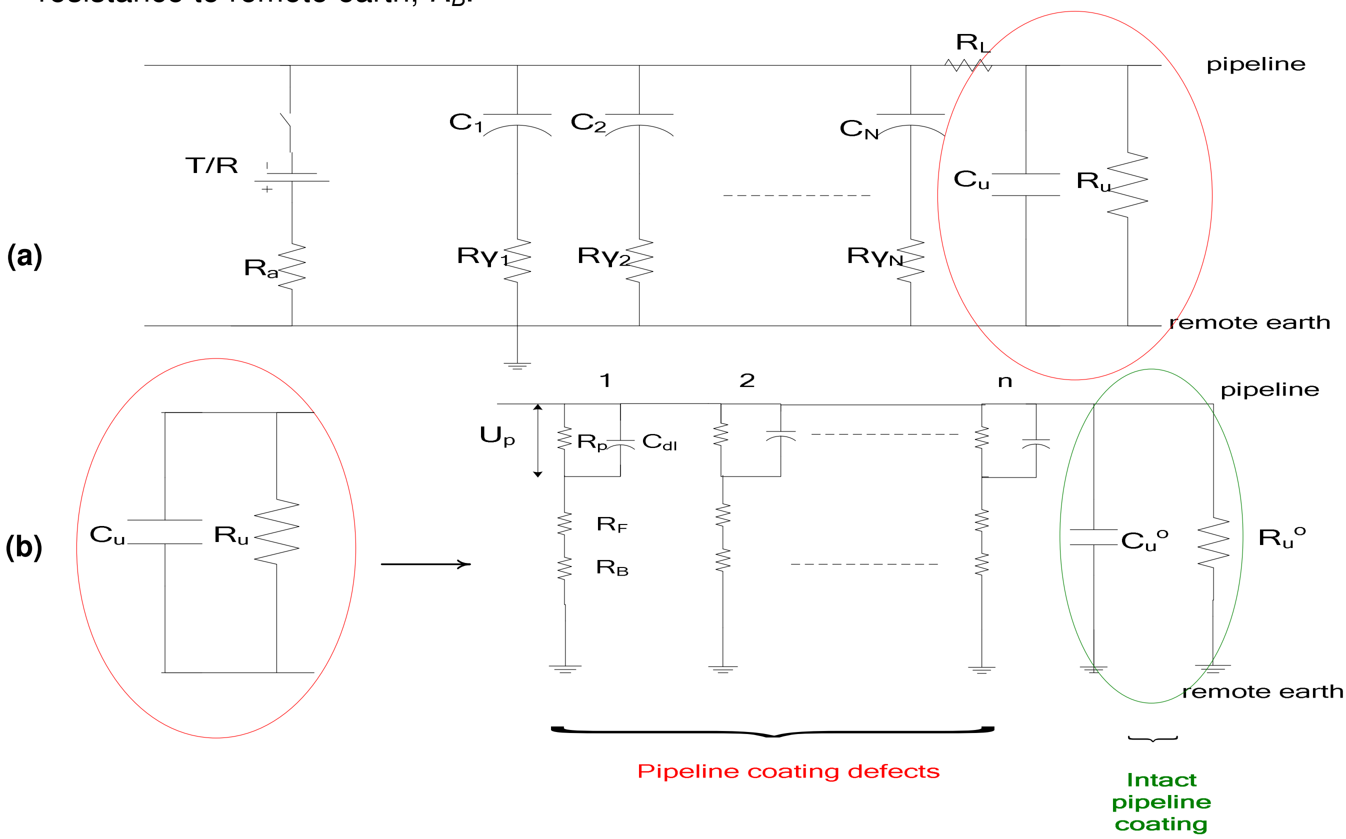
The phenomenon evolutes as below: The dc voltage between pipe and ground charges the capacitance of every ac-mitigation device. Upon switching off the CP current supply, the ac-mitigation devices, behaving similar to capacitors, start being discharged via earth electrode/soil/pipeline. The respective time constant, τ, is defined by equation (10) (see §3), resulting to 850msec in this particular case (Fig.2). Equation (10) is a special application of the general relationship for the time constant (§3-equation (6)). In this particular case, at the end of each CP-off time span, i.e. at 3sec, corresponding to 3.5τ, 97.2% of the maximum discharge current has been vanished. The instant-off potential can therefore be sampled at the end of each CP-off period, even measured by a digital multimeter, thus avoiding any significant error from the capacitance discharging current.

Prior to ac-mitigation devices installation, the instant-off pipe-to-soil potential used to be coincident with the break point of the on/off potential waveform, i.e at 0.2 or 0.4sec (point A of Fig.1), which does not differ considerably (100mV max.) from the value taken at the end of each 3sec CP-off period (point B of Fig.1). The deviation between potentials at point A and point B is small because the depolarisation rate in chronically polarised well-insulated pipelines is generally slow. Moreover the error is normally constant as long as the CP potential measurements are taken at the same CP system under similar conditions. However, if this error is critical to be known, it could be experimentally measured or theoretically calculated and its magnitude being used to correct every instant-off pipe-to-soil potential measurement.

Following to ac-mitigation devices installation, the on/off pipe-to-soil potential waveform is controlled by the gradual discharge of the capacitive ac-mitigation devices (Fig.2). In this case, the instant-off pipe-to-soil potential should be measured at longer time following every CP-off switching, particularly when the capacitive discharge current has been eliminated, e.g. at the end of every 3sec CP off period (point C of Fig. 2), otherwise the instant-off pipe-to-soil potential values are falsified towards more negative values. Unless the capacitive ac-mitigation devices discharging currents effect is taken into consideration, instant-off pipe-to-soil potential values taken within the usual 1sec after CP-off switching can lead to the misconception that the pipeline is adequately cathodically protected even when it is not the case.

2. Equivalent circuit of a pipeline system with capacitive ac-mitigation devices

An equivalent electric circuit representing the pipeline with connected capacitive devices had to be devised in order to analyse in detail the pipeline CP system response to the discharging effect of the ac-mitigation capacitive devices during the periodic on/off switching of the cathodic protection circuit. This equivalent circuit is illustrated in Fig.3. There are factors in the equivalent circuit, related to the buried pipeline, such as the longitudinal resistance of the pipeline, R_L, playing a negligible role, the capacitance of the pipeline, C_u, and the resistance of the buried pipeline to remote earth, R_u. This parallel RC circuit corresponding to the buried pipeline is further analysed, decomposed into the parallel equivalent circuits of n coating defects in parallel connected to the parallel arrangement of the capacitance C_u^o and the resitance R_u^o of the rest of the pipeline with intact coating. In respect to every pipeline coating defect, the equivalent circuit includes the parallel connected polarisation resistance, R_p with double layer capacitance, C_{dl}, in series with two resistances, the ohmic resistance due to electrolyte inside the pore, R_F, and the coating defect resistance to remote earth, R_B.



(a) circuit illustrating N ac-mitigation devices of capacitance value C_i each with earth electrode resistance $R\gamma_i$, whereas C_u R_L and R_u illustrate the equivalent circuit of the pipeline itself. (b) circuit representing the buried pipeline based on coating defects with population number n

T/R = C.P. Transformer/Rectifier, Ra=anodebed resistance, Ci=Capacitance of i-device, Rγi=ground resistance at i-device site, Cu=Pipeline capacitance, Ru=Pipeline resistance to remote earth, R_L= Longitudinal pipeline resistance, Cu^o= Capacitance of the pipeline with intact coating, Ru^o=Resistance of the pipeline with intact coating, Up=Polarisation voltage, Rp=Polarisation resistance, C_{dl}=Double-layer capacitance, R_F=Pore resitance, R_B=Resistance of coating defect to remote earth.

Figure 3. Equivalent circuit for the interpretation of the capacitive ac-mitigation devices discharging currents effect on the falsification of instant-off pipe-to-soil potential readings

Assuming that the ac-mitigation capacitive devices – connected to a pipeline of diameter and length *D* and *L* respectively – have population number *N* each with capacitance value C_i mF, where $i=1,2,3,\ldots N$. The ac-mitigation devices are considered to behave like mere capacitors whereas their parallel resistance to dc current is almost infinite; therefore ignored in the circuit. In case these capacitors are connected to a cathodically protected pipeline, they are charged by the dc current supplied by the CP Transformer/Rectifier (T/R unit), via anodebed of a resistance to remote earth, *Ra*. Consequently, a dc voltage, impressed by the CP system of the pipeline, exists at the terminals of every capacitor, of capacitance value, C_i. The order of magnitude of this dc voltage is usually in the range 0,2V - 1,5V. Additionally, each i-capacitor is connected with a grounding electrode with a resistance to remote earth, $R\gamma_i$.

During the CP maintenance measurements it is a common practice to switch the CP circuit off and on periodically. Typical times of the on/off periods are 12/3 or 27/3 sec (e.g. 12/3 means 12sec on and 3sec off etc.). When the dc voltage at the terminals of each i-capacitive device is instantly changed due to the aforementioned periodic switching of the CP circuit, the capacitor of the device starts discharging itself through the pipeline, earth electrode and soil. The initial electric charge q_i and the voltage ΔU_i of every *i*-capacitor at the end of each CP on period, as soon as the i-capacitor is charged, are defined by the following equations :

$$q_i = \Delta U_i * C_i , \qquad i = 1,2,\ldots, N \qquad (1)$$

$$\Delta U_i = E_i^{on} - Eg_i \qquad (2)$$

where ΔU_i, is the dc voltage at the terminals of each *i*-capacitive device, that is identical to the difference of the potential of the grounding electrode, Eg_i, from the on pipe-to-soil potential E_i^{on}.

Upon switching off the CP current, the dc voltage at every *i*-capacitor is instantly jumped from ΔUi to $\Delta Ui'$ thus every capacitor starts discharging itself from the initial charge q_i to the new charge q_i', where:

$$q_i' = \Delta U_i' * C_i, \qquad i = 1,2,\ldots, N \qquad (3)$$

$$\Delta Ui' = E_i^{off} - Eg_i \qquad (4)$$

where $\Delta Ui'$ is the dc voltage at the terminals of each *i*-capacitive device, that is identical to the difference of the potential of the grounding electrode, Eg_i, from the instant-off pipe-to-soil potential, E_i^{off}. The difference ΔU_i - $\Delta U_i'$ is obviously equivalent to $E_{on} - E_{off}$, i.e. the IR voltage drop.

3. Calculation of the time constant for the discharging of the capacitive ac-mitigation devices connected on a cathodically protected pipeline

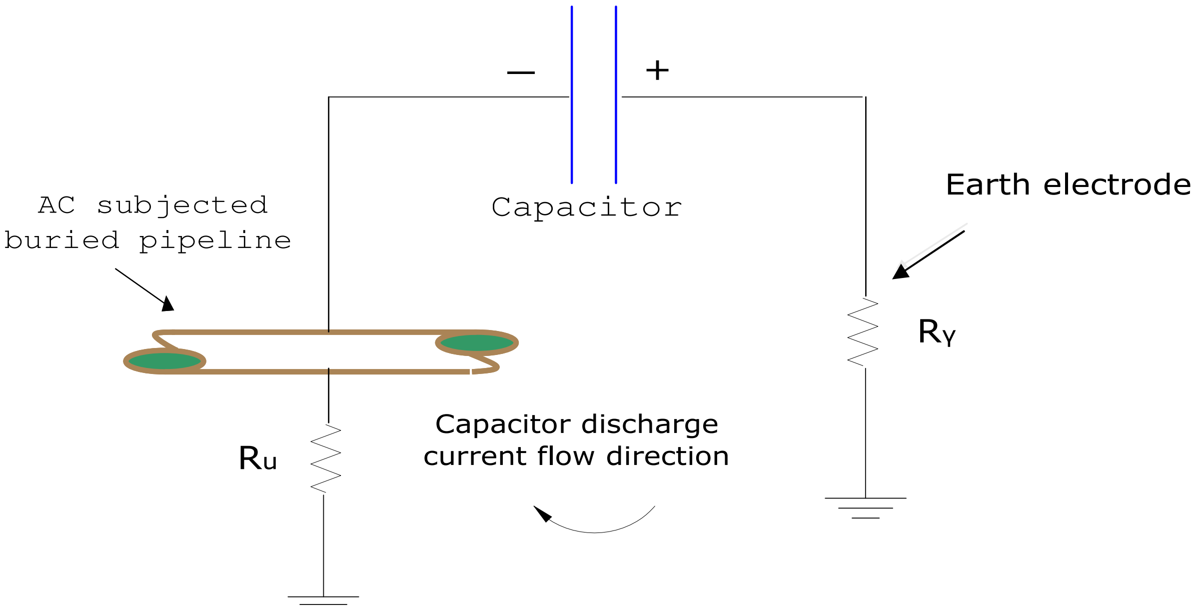


Figure 4. ***Schematic of a cathodically protected pipeline connected to ground via a capacitor***

It is known that the discharge rate of a capacitor depends on the time constant, τ, of the circuit related to the pathway of the discharge current flow. Hereto the discharge current is flowing basically through two resistances connected in series. Even though these resistances look like parallel, they are actually in series as to the capacitive discharge current flow. Those resistances are first the grounding electrode resistance to remote earth, $R\gamma_i$, at the position of each *i*-capacitor and second the pipeline resistance to remote earth, R_u (see Fig.3 and Fig.4). Consequently, the time constant τ for the simple case of discharging one capacitor of capacitance value C with local grounding resistance $R\gamma$ is given by:

$$\tau = (R_u + R\gamma) * C \qquad (5)$$

In case of N i-capacitive devices with capacitance Ci each with grounding resistance $R\gamma_i$, the equivalent circuit is simplified to that of one capacitor of capacitance $\sum_{i=1}^{N} Ci$ in series with a resistance $(\sum_{i=1}^{N} 1/R\gamma_i)^{-1}$. It can be proved that it is so, through study by means of any electric circuit analysis software (e.g. SPICE) of the response mode of similar circuits to transient phenomena of capacitive charging/discharging. By ignoring the longitudinal resistance and the capacitance of the pipeline, which play a negligible role [3,4], the time constant of the capacitors discharging, τ, is defined by the following equation :

$$\tau = [R_u + (\sum_{i=1}^{N} 1/R\gamma_i)^{-1}] * \sum_{i=1}^{N} C_i \qquad i = 1,2,\ldots, N \qquad (6)$$

Based on the same realistic assumption that the capacitance of the pipeline and the longitudinal resistance of the pipeline have a negligible effect on the charging of the capacitive ac-mitigation devices, the time constant of the capacitors charging, τ', which is given by equation (7), depends on grounding resistance $R\gamma_i$ and anodebed resistance R_α (which both have normally low values) :

$$\tau' = [R_\alpha + (\sum_{i=1}^{N} 1/R\gamma_i)^{-1}] * \sum_{i=1}^{N} C_i \qquad i = 1,2,\ldots, N \qquad (7)$$

Accordingly, it comes out from a comparison of equations (6) and (7) that the charging rate is usually more rapid than the discharging rate, since R_α is normally lower than R_u in well-insulated pipelines.

The following analysis will focus on the capacitors discharging as this is the phenomenon which has influence on the falsification of instant-off pipe-to-soil potential readings. For a better understanding of the factors with higher impact on the investigated phenomenon, some simple cases are examined here below. For instance, in case of N ac-mitigation devices, each of them having the same capacitance value C and the same grounding resistance $R\gamma$, the equivalent circuit of all capacitors and grounding resistances corresponding to all N ac-mitigation devices is simplified to that of one capacitor of capacitance value NC in series with a grounding resistance of value $R\gamma/N$. Then from equation (6) it comes out:

$$\tau = (R_u + R\gamma/N)\ NC = (NR_u + R\gamma)\ C \qquad (8)$$

It is evident from equation (8), the time constant of the capacitive discharging is mainly dependent on the pipeline resistance to remote earth R_u, as well as on the population N and the capacitance C of the ac-mitigation devices. On the contrary, the grounding resistance, R_γ, has a limited impact compared to R_u, owing to their normally low values and because as shown in equation (8), $R\gamma$ is not multiplied with N in contrast to R_u.
The capacitive ac-mitigation devices connected to grounding electrodes, with comparatively higher grounding resistance, they must discharge themselves later than the rest of them with lower grounding resistances, if seen separately. However, since there is a mixing of all discharging currents, as also shown by equation (6), the lowest of the resistance values $R\gamma_i$ play a dominant role on the time constant, whereas the highest $R\gamma_i$, might be ignored. As soon as $R\gamma = R_u = R$, it comes out that

$$\tau =(R_u + R\gamma/N)\ NC = (R+ R/N)\ NC = (N+1)\ RC \qquad (9)$$

It is worth mentioning that the time constants related to concentration polarisation and diffusion effects are ignored in the previous calculation of the time constant since these processes are much slower than the capacitors discharging effects. Additionally, this is an assumption justifying the measurement of instant-off potential at longer times after CP off switching.
In case that $R_u \# R\gamma$ and $R\gamma << R_u$ and specifically when $N>>1$, the time constant τ becomes:

$$\tau = (R_u + R\gamma/N)\ NC \cong N\ R_u\ C \qquad (10)$$

an approximation that is often valid in practice, since $R\gamma$ values are usually rather low. Even supposing the grounding resistances, $R\gamma$, are comparable to that of the pipeline grounding resistance, R_u, the approximation is still applicable for large N, since then $R\gamma/N \rightarrow 0$. This equation (10) was applied in order to estimate the time constant of the capacitive discharge effect 18 ac-mitigation devices installed on a 45km long pipeline (ND30´´) [1]. The time constant was calculated to be around 0,85s thus at the end of every 3s CP off period the capacitive discharge could be considered as negligible, thus the instant-off potential taken at 3s after every CP off switching could be regarded as unaffected from the capacitive discharging effect. On occasions the discharging of the capacitive devices has been finished before 1sec, this occurring when the maximum values of the time constant are τ_{max} = 0.2-0.3sec, no practical problem is anticipated.

4. Practical suggestions to reduce the time constant of the capacitive ac-mitigation devices discharging effect

For the control of off-potential readings falsification, the time constant of the discharging effect of the capacitive ac-mitigation devices, τ, is recommended to be less than 1sec, with the intention of having the discharging practically terminated before the end of every 3sec CP-off period, i.e.

$$\tau < 1\ sec \qquad (11)$$

Assuming the inequality (11) is aimed at, then according to relation (10)

$$NR_uC<1 \quad (12)$$

or

$$R_u<1/NC \quad (13)$$

or

$$r_u< \pi DL / NC \quad (14)$$

and if

$$N/L = N' \quad (15)$$

where *N'* the population of capacitive dc-decoupling ac-mitigation devices per unit pipeline length, by rearranging inequality (14) it results to

$$r_u < \pi D / N' C \quad (16)$$

The inequality (16) shows that the main factors affecting the time constant of this capacitive discharging are the pipeline diameter, *D,* the capacitance value, *C* of every ac-mitigation device and their population number per unit length, *N'* (which could be an indicator of the intensity of the ac interference too).

Apparently, two opposing phenomena exist. On the one hand, the lower the earthing resistance values and the higher the capacitance values of the ac-mitigation devices the more effective the ac-mitigation since the impedance to the ac current is reduced. On the other hand, the higher the capacitance values the longer the capacitive discharging time will be, subsequently resulting to a deterioration of the falsification of the off potential readings. The objective is the ac-mitigation to be effective with the lowest possible number and capacitance value of the capacitive ac-mitigation devices (reduction of *N* and/or *C* in formula (6)) aiming at reducing the time constant of the capacitive discharging (see inequality (16)). When an even more effective ac-mitigation is pursued, it can be achieved either by:

1) increasing the population number of the capacitive ac-mitigation devices or their capacitance values, or
2) improving the earthing electrodes effectiveness, which can be achieved two ways :
   a) Improving the grounding resistance of existing earthing electrodes at the same locations. It can be achieved by installing additional earthing electrodes or by using special backfilling materials that improve the earthing resistance.
   b) Increasing the number of earthing sites by installation of earthing electrodes at additional locations.

The measures 1 or 2b lead to the necessity of compromising two opposing phenomena, ac-mitigation on the one hand and diminishing the falsification of the off potential readings on the other. On the contrary, the more effective earthing electrodes (i.e. implementing measure 2a) result in more effective ac-mitigation thus limiting the need for increase of *N* and/or capacitance value *C* of the ac-mitigation devices. Fortunately, in soils where the susceptibility to the risk of ac-corrosion is higher, as in very conductive soils, low values of grounding resistances, R_γ, are favoured. Additionally, an improved spatial distribution of the ac-mitigation devices, by installing them at appropriate locations along the pipeline, is also very helpful. For the choice of the most suitable installation sites for ac-mitigation devices along a pipeline, various data should be considered, i.e. soil resistivity data, measurements/recordings of ac voltage/current along pipeline, data from corrosion coupons/ER-probes as well as theoretically calculated ac-interference levels obtained from the use of contemporary sophisticated theoretical models [5,6] which can produce more realistic results.

In relation to the pipeline sizing effect two opposing features exist. On the one hand, the time constant of capacitive ac-mitigation devices discharging effect tends to increase in the case of smaller diameter and shorter pipelines since the resistance R_u generally becomes higher. On the other hand, the ac induced voltage is normally lower in shorter pipelines which can be mitigated with fewer capacitive devices. On that occasion, the factor *N* is lower (see formula (6)) and the time constant can generally be controlled within 1 sec.

The pipeline resistance to remote earth, R_u, is generally increased on the following occasions [3,4]:

- High coating resistivity
- Small number of coating defects
- High spread resistance of coating defects
- Small pipeline diameter
- Short pipeline length

Moreover, the time constant of the capacitors discharging, τ, can be controlled within certain limits by reduction of pipeline resistance to remote earth, R_u, via corrosion coupons, which in parallel can help monitor better the cathodic protection efficiency. Inserting characteristic quantities in formula (16), i.e. if $C=5\ mF$ and in the unfavourable case of pipe diameter $D=0.2m$ and $N'=10^{-3}$ (i.e. one capacitor per km of pipeline) it becomes $r_u<1,26\cdot 10^5\ \Omega.m^2$. This limit is not far away from the coating resistivity of PE-coated pipelines with few coating defects (10^5-$10^6 \Omega m^2$). It therefore comes out that even in an unfavourable situation where a reduction of r_u is necessary for the inequality (16) to be valid, this can easily be achieved by addition of few corrosion coupons connected to the pipeline. The coupons should be buried in a conductive environment so as to exhibit low spread resistance values. Their surface area should not be very large so that the cathodic protection effectiveness is not disturbed. Alternatively, the instant off pipe-to-soil potential readings could be taken at times longer than 3 sec after switching, provided that the depolarisation rate is slow in chronically cathodically polarised PE-coated pipelines.

It becomes evident that for obtaining reliable off potential readings it is not always necessary to disconnect the capacitive ac-mitigation devices. After disconnection of the ac-mitigation devices the CP measurements are taken under high ac voltage again. This fact can increase the probability of dc potentials being falsified by high ac-interference [7] and creates safety risks during the CP measurements.

The disadvantage of the time wasted to disconnect and reconnect all ac-mitigation devices on a pipeline can be avoided by the use of devices equipped with automatic disconnection system (intelligent switching). However, the complicated sensitive electronics used to achieve intelligent switching may make them prone to malfunctions.

It is recommended that a similar analysis of the optimisation of those parameters playing a role in reducing the time constant of capacitors discharging effects must be incorporated in the calculation software of ac induced voltages on a pipeline. In this context, it seems also critical the theoretical models of calculations of the induced voltages to be sophisticated giving more realistic results. Thus, either under-design (e.g. insufficient number of earthing electrodes) or over-design (e.g. more grounding electrodes than necessary) could be avoided while the spatial distribution and grounding resistances of earthing electrodes could be optimised.
Evidently, the most unfavourable situation is a small diameter, long and well-insulated pipeline with strong ac-interference requiring a large number of capacitive devices connected to earth electrodes exhibiting a high grounding resistance. In any case, a simulation of the system with circuit elements for estimating the capacitors discharging currents effect is generally recommended to assure the error of instant-off potential readings is controlled within acceptable limits.

5. Conclusions

The ac-mitigation dc-decoupling devices connected between pipeline and grounding electrodes usually present a capacitive behaviour interfering with the acquisition of correct instant-off pipe-to-soil potential readings. During the periodic switching of the cathodic protection circuit, these capacitive devices tend to be discharged through pipeline and earth, creating capacitive discharging currents that falsify instant-off pipe-to-soil potential readings. To study this phenomenon, the system of a well-insulated pipeline with capacitive ac-mitigation devices connected to earthing electrodes is simulated as an electric circuit and the role of the most influential circuit elements is investigated.
The optimisation of the instant-off potential readings is effected through the reduction of the time constant of capacitive discharge. One of the determining factors of the capacitive discharging currents effect is the pipeline resistance to remote earth which depends on the population number, the surface area and the spread resistance of the pipe coating defects. On most occasions, the pipeline resistance to remote earth is within acceptable limits. However, in case a further reduction of its value is required to minimise the falsification of instant-off potential readings, this could be easily achieved by installing additional buried corrosion coupons to the pipeline that also help monitor the cathodic protection efficacy.
Other means of reducing the time constant of the capacitive discharging effect are the optimisation of the capacitance values as well as the population number of the ac-mitigation devices along with the lowering of the grounding resistance of earthing electrodes. It is also suggested to have the instant-off pipe-to-soil potential taken at the end of each CP-off switching period tolerating a constant error in potential reading, generally lower than 100mV. Thus the instant-off pipe-to-soil potential readings can be reliably acquired while the complications of the capacitive ac-mitigation devices disconnection from the pipeline are dispensed with. Additionally, by keeping the induced ac voltage within low levels during the whole time of the periodic CP maintenance measurements, possible effects of the ac interference on the dc parameters of CP operation is prevented too.
The analysis of the factors affecting the error of instant-off pipe-to-soil potential measurements due to capacitors discharging currents is advisable to be included in the ac interference studies thus optimising the number and properties of both the grounding sites and the capacitive dc-decoupling devices used for ac-mitigation.

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