Instant E_{OFF} measurement error in cathodically protected pipelines: A parametric assessment study

C. Melios, A. Dimitriou, N. Kokkinos, N. Kioupis, T. Manolis and C. A. Charalambous

***Abstract*— Buried pipeline systems benefit from mitigation wires (earthing systems) in order to be protected against electric shock hazards. Moreover, cathodic protection (CP) systems are incorporated into pipeline systems to provide protection against corrosion by injecting an impressed DC current. DC decoupling devices are normally installed between the pipeline's metallic wall and the earthing wire, functioning as a filter that blocks the DC component (of the CP system) while allowing the hazardous AC interference current to be dissipated into the earth. However, the internal capacitance of the DC decoupling devices introduces an error in the routine survey measurement of the CP effectiveness, as frequently reported by pipelines' system operators. In this paper, the factors influencing this measurement error are investigated by modeling the electrical behavior of the CP-pipeline system. This investigation concluded that the capacitive discharge time constant and by extension, the measurement error highly depends on the pipeline resistance to remote earth (coating resistance), as well as on the number and the capacitance C of the capacitive DC decoupling devices. To this extent, methods for minimizing *Eoff* measurement error are proposed.**

***Keywords*: pipeline, cathodic protection, earthing, capacitive discharge, modeling**

I. INTRODUCTION

Natural gas plays a crucial role in the energy supply of Europe and the world. It is sufficiently and readily available, is traded, and is storable. Natural gas has inherent advantages over other fossil fuels with respect to harmful emissions. Natural gas continued its trend towards greater cost competitiveness while contributing to global energy security and reductions in air pollution and emissions. Gas was the second-fastest growing source of primary energy demand, behind renewables. Therefore, the ever-increasing trend for natural gas demand will result in large land areas being occupied by pipelines. In extension, a large number of DC decoupling devices are expected to be installed to ensure the proper function of the CP and earthing systems. Environmental and economic reasons and crowding of various constructions usually force pipelines to follow routes in close proximity to high-voltage power lines (right-of-way). To this extent, pipelines close to high-voltage power lines are subjected to the influence of the electromagnetic field created by operational and fault currents from the high-voltage lines. Therefore, the pipeline is exposed to induced long-term AC voltages and short-term interference caused by lightning strikes and/or phase faults [1]. The generation of electromagnetic fields from power lines under steady-state and fault conditions can cause safety hazards [2] and corrosion issues [3] on a nearby pipeline. To avoid corrosion activity through the pipeline's coating holidays, cathodic protection (CP) systems are used [4]. The CP system supplies the surface of the pipeline with an external DC current to provide corrosion control of the exposed metallic surface by forcing this surface to become the cathode of an electrochemical cell [5]. Fig. 1a shows the different causes for induced AC voltages on a pipeline and the application of the CP system to mitigate the corrosive effects of the induced AC voltages.

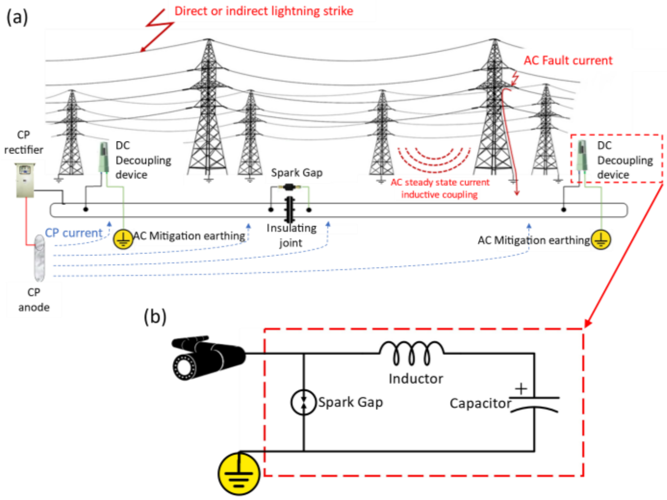

Fig. 1. (a) Schematic representation of a pipeline parallel to a high voltage power network which illustrates AC inductive interference mechanisms, faults as well as the use of CP and decoupling devices systems. (b) electrical circuit of DC decoupling device.

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II. THE USE OF DC DECOUPLING DEVICES IN CATHODICALLY PROTECTED PIPELINES

A. The passive DC decoupler

A DC decoupling device is an electrical equipment that is widely used in pipeline systems [3]. This device is installed between the pipeline's metallic wall and each mitigation (earthing) wire in order to provide concurrently a) DC blocking, b) AC mitigation (earthing) and c) Lightning protection to the pipeline, as shown in Fig. 1a. The most commonly used type of DC decoupling device incorporates passive components (i.e. inductance and capacitance). A simplified internal circuit is shown in Fig. 1b. The connection of capacitance and inductance in series with the metallic wall of the pipeline act as a low-pass filter which allows the currents of network frequency (i.e. 50 Hz) to flow to the earth (via the mitigation wires), while at the same time blocks any DC incoming current. In brief, the DC decoupling devices are installed between the pipeline and the mitigation wire to offer: (i) DC blocking for the proper operation of the cathodic protection system. The cathodic protection system, with the use of a rectifier, supplies the surface of the pipeline with a cathodic current. This establishes a cathodic polarization (shift of the pipeline's electrochemical potential to a more negative value) between the pipeline surface and the earth, reducing the corrosion process. In extension, DC blocking is necessary in order to maintain the cathodic polarization of the pipeline. (ii) AC mitigation-Earthing: Pipeline systems are frequently running in parallel with power lines in a shared right-of-way. However, this practice may induce hazardous AC voltages along the pipeline [2]. Moreover, the failure of nearby power equipment (i.e. short circuit in a power substation) can generate an AC fault current on the pipeline, which can cause safety integrity hazards. Under these circumstances, the decoupler should operate as a closed switch in order to discharge the induced AC currents/fault currents, maintaining the pipeline's potential at an acceptable level. In addition, in the case of an excessive current that may occur due to a lightning event, an integrated spark gap (see Fig. 1) is used to reduce the potential overvoltages.

B. The issue of the Eoff measurement error

It is known that the instant on/off technique to determine the *Eoff* potential of a cathodically protected pipeline is considered a simple and economical method[6]. Through this technique, the protection potential (E_p) which is established by the cathodic protection current along the pipeline, can be examined [7], since it reflects the effectiveness of the CP system. The *Eoff* value is compared against the recommended values given in the relevant standard[4]. Most importantly, the instant *Eoff* measurement eliminates the *IR* drop between the pipeline and the reference electrode[7]. In brief, the *IR* drop results from the cathodic protection current (ICP), which flows through the soil, the reference electrode and the pipeline. The result is an increase in the electronegativity of the pipeline. To this extent, when the ICP is interrupted (to perform the *Eoff* measurement), this drop is eliminated[6]. As it was mentioned above, decouplers are integrated into pipeline systems to ensure the dissipation of the AC interference while ensuring DC blocking. When the rectifier is active, the capacitor of the decoupler is fully charged. When the CP current is interrupted to perform the *Eoff* measurement, a transient current (I_{trans}) flows from the capacitor to the pipeline, through the soil. This current will ultimately lead to a potential measurement error until the capacitor is fully discharged [4]. In more detail, the rate of the current discharge depends on the *RC* (resistance × capacitance) time-constant, considering an equivalent electrical circuit consisting of: (i) the pipeline coating's resistance to remote earth, (ii) mitigation wire earthing resistance (dictated by soil conditions, material, geometry and dimensions of the earthing electrode), (iii) and most notably on the capacitance of the decoupler. The new ISO 22426:2020 standard[8] acknowledges the above-described complications. At this point, it is imperative to mention that proper sizing of the capacitor needs to account for the AC current (magnitude and duration) that will flow under steady-state and fault AC conditions. For example, when a higher AC interference is expected, a larger capacitor will be needed; therefore, the RC time constant will be significantly longer.

However, considering that the coating and soil resistance are expected to vary over the length of any given pipeline (due to damage or voids in the coating) segment and variations over time due to weather and soil moisture will lead to variations in time-constants. To summarize the above, the accuracy of the *Eoff* measurement will be influenced by the following aspects:

- The measurement interval following the interruption of the CP current
- Amount of CP current
- Soil resistivity
- Pipeline coating resistance and coating holidays
- The length and diameter of the pipeline
- The size and number of decouplers present

C. The DC Decoupler Dilemma

As discussed above, DC decouplers are a vital element of most CP systems. Currently, two leading technologies of DC decoupling devices are used: (i) Passive capacitive decouplers (including polarization cells) and (ii) Solid-state decouplers. Despite the emergence of the solid-state technology, the most preferable is the use of passive designs (i.e. capacitive decouplers), due to their simplicity, ruggedness and low cost. Moreover, most of the existing pipeline global network still uses this technology. Thus, the issue of the *Eoff* measurement error exists where passive DC decoupling devices are used. Historically, the following techniques were employed to overcome this issue, however, are deemed ineffective:

(a) Temporarily disconnecting the decouplers from the system for the test duration. This is effective in eliminating the transient current flow and the resulting voltage dissipation time, as the decoupler capacitance has been removed from the system. However, in addition to affecting the DC potentials, if induced high AC voltage is present and no means to dissipate them (decoupling devices are disconnected), a significant safety hazard arises. More importantly, physically disconnecting all of the DC decoupling devices is impractical.

(b) Account for the rectifier's sufficiently long on/off cycle times to guarantee decoupler voltage has been discharged. However, long on/off cycle time would lead to an inefficient survey.

Therefore, during the design of a passive DC decoupling device, the engineer must account for a sufficiently large capacitor to safely discharge the continuous AC current under steady-state operating conditions and fault conditions.

III. CONTRIBUTIONS BEYOND THE STATE-OF-THE-ART

An interrupted survey aims to obtain an *Eoff* potential measurement taken with all CP current sources synchronously interrupted momentarily. The purpose of such a measurement is to evaluate the CP system's effectiveness by determining the pipeline's polarised potential (i.e. instant *Eoff* potential). Interrupted surveys are typically done over the pipeline length as part of a Close-Interval Survey (CIS) or Direct Current Voltage Gradient (DCVG). However, as discussed in the previous section, this technique may introduce an unknown measurement error, leading to an overestimation of the CP effectiveness. Considering the industry and standard preference, as well as the tendency to use passive DC decoupling devices, we propose a method that allows accurate *Eoff* measurement without using expensive and sensitive active decouplers. Our proposed method calculates the measurement error in existing infrastructure, providing a correction factor in the measured data and performing an optimum selection of adequate and effective DC decoupling systems that will allow both the discharge of AC interference and minimize the measurement error.

The basic principles of the proposed methodology, which is used to calculate or eliminate this error, are based on the following steps:

1. Determine an appropriate capacitance value of the DC decoupling device based on the steady-state and fault conditions currents to the earth.
2. Performing parametric *Eon/Eoff* transient simulations based on the actual pipeline-CP system configuration model. The simulation model considers the characteristics of the: (a) DC decoupling devices, (b) pipeline and c) CP system.
3. Calculation of *Eoff* measurement error to decide the *Eon*/*Eoff* measurement interval or the selection of appropriate capacitors to be used in the DC decouplers.

IV. SIMULATION MODEL THAT REPLICATES THE FACTORS INFLUENCING THE EOFF MEASUREMENT

A simulation model has been developed in SIMULINK (following the principles described in Kioupis et al paper[6]) that is able to provide a complete understanding of the electrical behavior of the CP-decoupling system. The simulation model replicates the electrical behavior of a real case-study pipeline system to understand the DC decoupler device's *Eon*/*Eoff* transient response.

A. Case-study description

The development of the electrical simulation model that is able to calculate the *Eoff* measurement error was based on a 61 km pipeline system which features CP. The case-study described in this section corresponds to the CP area 20 of the Lavrio (Greece) branch pipeline, operated by the Natural Gas Transmission System Operator in Greece (DESFA). The gas pipeline routing is shown in Fig. 2 in purple color, along with the HVAC interfering source (red color). Moreover, Table I provides a description of the technical characteristics of the pipeline.

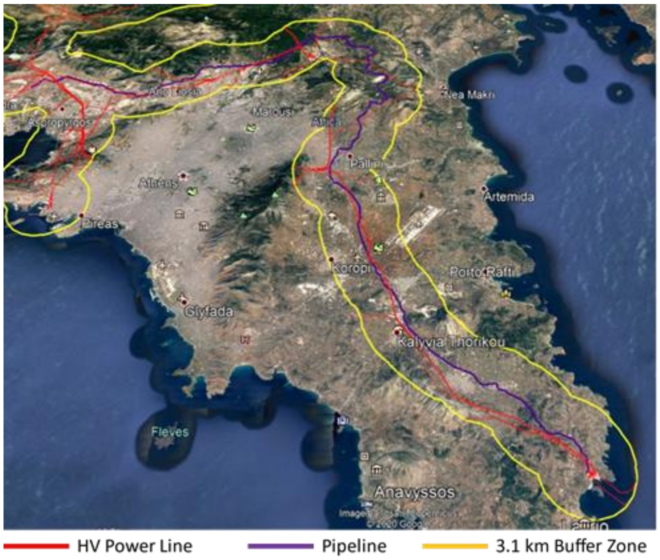

Fig. 2. Physical layout (Google Earth) of the gas pipeline section (purple), the HVAC power lines (red) and the 3.1 km Buffer Zone (yellow) area used as a case-study.

TABLE I
PIPELINE AND CATHODIC PROTECTION SYSTEM CHARACTERISTICS

Parameter	**Value**	**Remarks**
Coating Resistance	5×10^5 Ω.m^2	Uniform coating resistance is assumed along the entire pipeline system.
Pipeline Length (CP 20)	~61 km	-
Pipeline Radius	0.381 m	-
Pipeline wall resistivity (relative to annealed copper)	10	-
Anode-Bed Resistance	2 Ω	Assumed value
Rectifier Voltage (V_R)	1.3 Volts	Indicative value
Polarization of the Pipeline (E_P)	0.9 Volts	Indicative value

B. Model principles description

As it was mentioned above, decouplers are integrated into pipeline systems to ensure AC mitigation while ensuring DC discontinuity. To assist with the understanding of the two different operating conditions of a DC decoupler device, Fig. 3

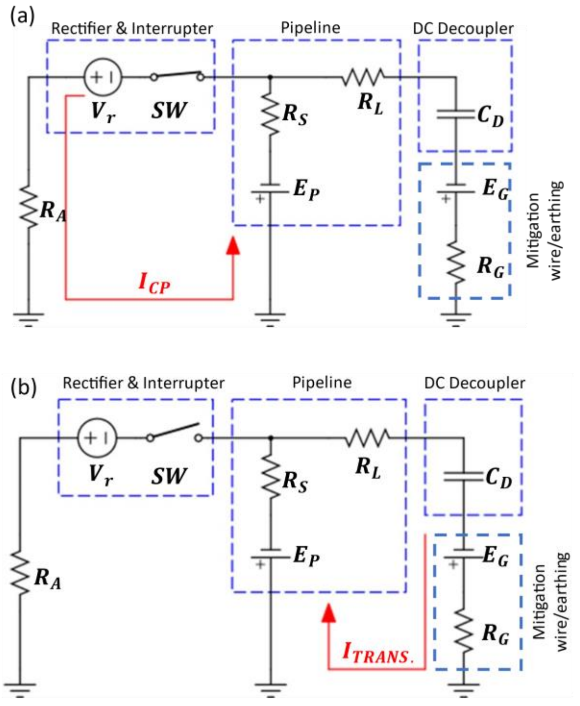

Fig. 3. Electrical circuit illustrating the operating principles of DC decouplers in a pipeline system when the CP is (a) activated and (b) disconnected.

shows the current flows when the CP is connected (Fig. 3a) and when the CP is disconnected (Fig. 3b). When the rectifier is active, the capacitor of the decoupler (C_d) is fully charged (Fig. 3a). Furthermore, the decoupler is connected to the earthing system (mitigation wire) which exhibits an earthing resistance R_g and also a free corrosion potential E_g (EN 12954:2001[4]). The issue with this configuration comes when CP current is interrupted for the *Eoff* measurement. This process is shown in Fig. 3b, where the transient current (I_{trans}) flows through the soil from the capacitor to the pipeline. This current will ultimately lead in a potential measurement error until the capacitor is fully discharged[6]. In more detail, the current discharge rate depends on the RC time-constant of the circuit and therefore is influenced by the pipeline coating's resistance to remote earth and mitigations wire earthing resistance (dictated by soil conditions), and most importantly, on the capacitance of the decoupler. For example, if a section of the pipeline lies in soil with high resistance (i.e. due to low moisture present), R_s is expected to increase as a direct consequence of the rise of RC time-constant. Therefore, considering that R_s is expected to vary over the length of any given pipeline (due to damage or voids in the coating) segment as well as variations over time due to weather and soil moisture, will lead to variations in time-constants.

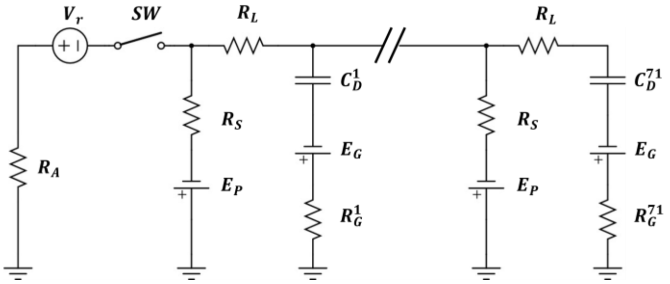

Fig. 4. Electrical circuit used to model the pipeline-CP system case-study.

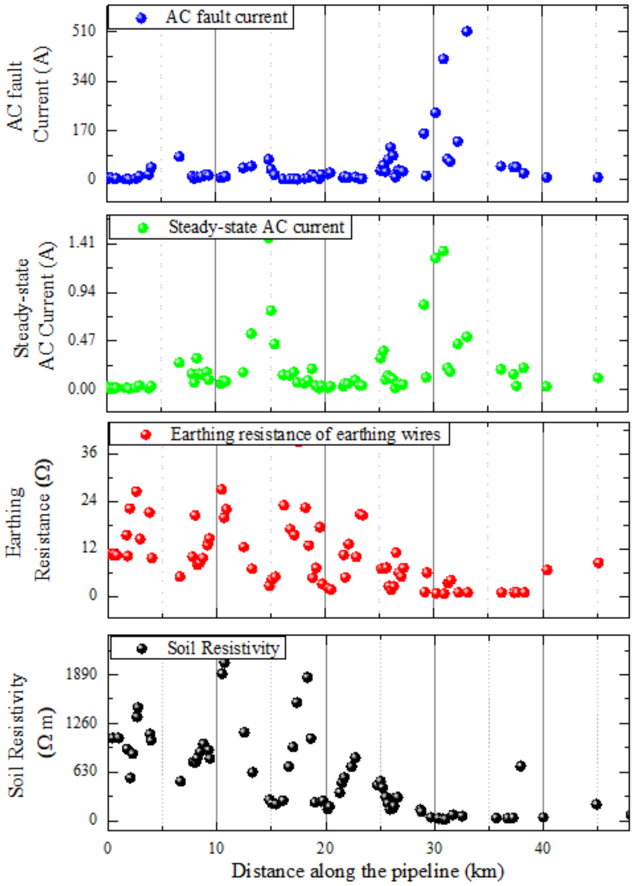

Fig. 5. Design parameters used for the design of the simulation model. The soil resistivity (black) was measured along the pipeline. Based on the soil resistivity and mitigation wire dimensions, the earthing resistance (red) at each point was calculated. The steady-state (green) and fault (blue) AC currents were calculated based on an electromagnetic interference study.

To create an electrical model of the pipeline-CP system (which includes the DC decoupling devices) the circuit in Fig. 4 was simulated. Moreover, for the realistic design of the electrical circuit model, the use of the soil resistivity at the place where each earthing mitigation system is installed (black color in Fig. 5) and in extension, the calculated earthing resistance of each mitigation wire (red color in Fig. 5) was used. It is important to note that each mitigation wire location indicated with a point in Fig. 5 benefits from a DC decoupling device. In addition, the coating insulation resistance was used (assuming a uniform value along the entire length of the pipeline). To this extent, this model is able to accurately reproduce the *Eon/Eoff* transient behavior in realistic scenarios, which features a CP system and 71 decouplers (C_D^n) distributed along its length (pipeline longitudinal resistance (R_L)), while taking into consideration variations along the pipeline's length such as (i) pipeline coating resistance, (ii) soil resistivity and decoupling devices with different capacitor sizes. The CP current (generated by the rectifier, V_R) is passed to the pipeline through an anode (R_A) and the soil. The interruption of the CP current is done using the incorporated switch. In addition, the circuit models the DC potential that the pipeline exhibits with respect to the soil (E_P), the pipeline coating resistance (R_S) and most importantly, the distributed earthing resistance R_G along its corrosion potential E_G. In an effort to calculate the voltage drop error due to the capacitors' charge the depolarization effects are ignored, and the potentials were modeled as constant voltage sources.

C. Calculation of Eoff measurement error

The capacitance (C) selection of the decoupling device is initially related to the steady-state AC current at 50 Hz (I_{AC}) that is expected to flow through the device. Therefore, selecting a large enough capacitor is essential to allow for the expected currents' steady-state flow. As shown in Fig. 5, the electromagnetic interference analysis of the pipeline section indicated that the average steady-state AC current that is expected to flow from each mitigation wire to the ground is $I_{AC} = 0.192$ mA ($I_{AC}^{max} = 1.46\,A$ and $I_{AC}^{min} = 12\,mA$). Therefore, based on commercially available capacitors, a selection of $C = 2500$ μF would be adequate in this case. It is important to note that during the design and size selection of each DC decoupling, it is imperative to ensure that the capacitor can withstand the expected steady-state and fault AC currents (as calculated in Fig. 5 with green and blue, respectively).

Fig. 6 shows the *Eon/Eoff* waveform as it has been simulated from the model shown in Fig. 4 and the parameters described in Table I. During the CP maintenance measurements of a cathodically protected buried pipeline, the CP current is switched off and on periodically at typical on/off periods of a few seconds. However, as discussed previously, understanding the timing of this on/off interval is crucial to collect a reliable measurement. During the period when the switch is closed (i.e. CP is connected), each *n*-capacitor of the 71 DC decoupling devices is charged. This charge can be calculated using Eq. 1:

$$q_n = (E_n^{on} - E_G)C_D^n \qquad \text{Eq. 1}$$

Where E_n^{on} is the potential of the pipeline at the location of the *n* DC decoupler. The DC voltage at the terminals of each n-capacitive DC decoupling device is instantly changed at the switching-off moment and the capacitive DC decoupling device starts being discharged via the pipeline, the earth electrode and the soil. The waveform describes the discharging of the DC decouplers upon disconnecting the CP rectifier from the pipeline at t=0. As time passes, the measured voltage on (Vm) deviates from the Eon potential of 1.1525 V and approaches the polarization potential of the pipeline (Ep). The evaluation of the *Eon/Eoff* error at time intervals t=0.5 second, t=1 second and t=1.5 second is based on Eq. 2:

$$Error = \frac{(Vm - Ep)}{Ep} \times 100\ \% \qquad \text{Eq. 2}$$

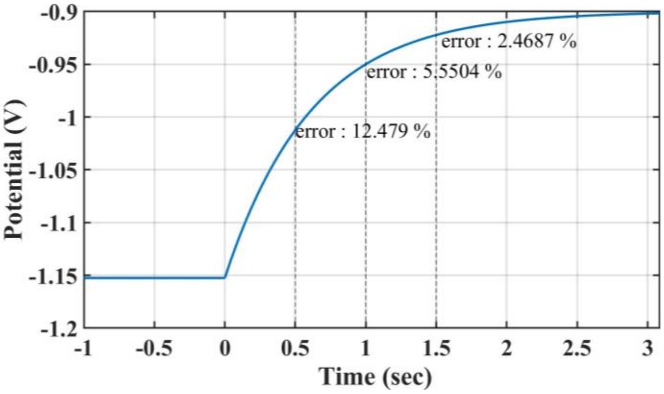

Fig. 6. Transient behavior of discharging of the DC decoupling device following disconnection of the CP current. With dashed lines the measurement error is calculated based on Eq. 2 at times 0.5s, 1s and 1.5s.

It is evident that if the pipeline potential was to be measured immediately after discontinuing the CP current, at t=0.5 seconds, a significant error of 12.479% would be introduced, overestimating the pipeline polarization potential. From this figure, it is also evident that for the particular CP-pipeline system, even measurement at t=1 second would introduce a significant error of 5.55%. This is an important note since standard EN 12954:2002 suggestions dictate that measures should be taken at t=1 second after disconnecting the CP current[4]. It is, therefore, necessary to wait at least 1.5 seconds

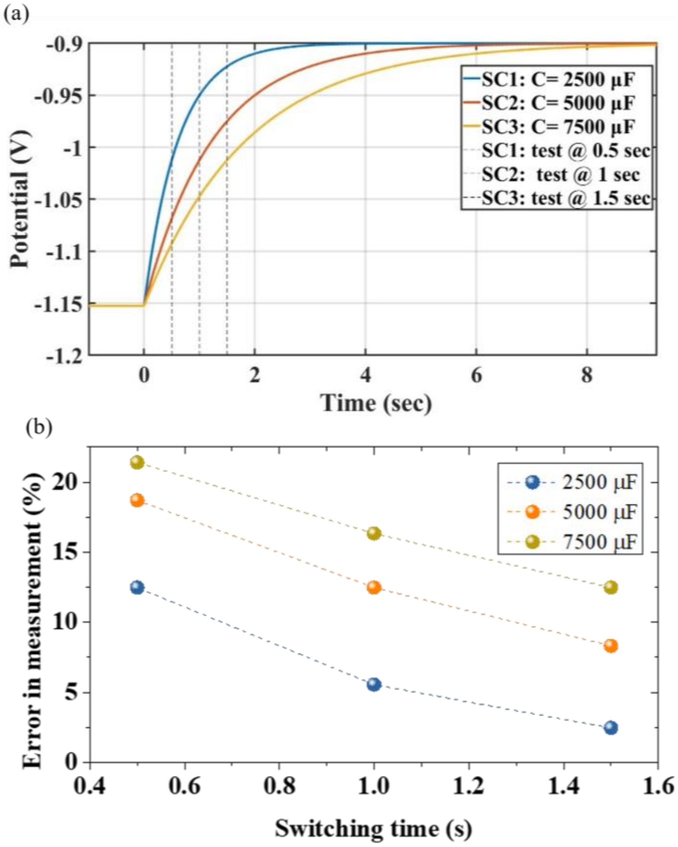

Fig. 7. (a) Simulated *Eon/Eoff* waveforms for different size of the internal capacitance (b) Error in *Eon/Eoff* measurements at different switching time and for different size of the internal capacitance.

before performing the *Eoff* measurement since earlier measurements would lead to the misconception that the pipeline is adequately cathodically protected, even if it is not.

D. Sensitivity Analysis

In this case-study, DC decoupling devices using 2500 μF capacitors were utilized, larger capacitors are often required due to the larger steady-state AC currents flowing to the ground. To further understand the effects of capacitance on the measurement error, a sensitivity analysis was performed with capacitors values of 2500 μF, 5000 μF and 7500 μF. These values correspond to capacitors used in commercially available DC decouplers. Fig. 7a shows the *Eon*/*Eoff* waveforms that are produced when we use three different sizes for the internal capacitance of the DC decoupling device. As expected, the increase in capacitance further increases the measurement error at a given interval as the discharge time constant $\tau = RC$ of the circuit increases. The capacitance sensitivity analysis is also shown in Fig. 7b, where the measurement error is plotted as a function of the switching times (measurement intervals) for t=0.5, t=1 and t=1.5 seconds. The sensitivity analysis of capacitance demonstrates that when using both the 5000 μF and 7500 μF capacitors in the DC decouplers of this pipeline system, a low enough measurement error could not be achieved even after 1.5 seconds following the CP disconnection. At this point it is crucial to note the importance of careful design and optimization of the DC decoupling devices based on electromagnetic interference (EMI) studies. Since the main objectives of a DC decoupling device are to provide concurrently DC blocking and AC mitigation (earthing) to the pipeline, it is important to design a DC decoupling device with a large enough capacitor to be able to withstand the expected steady-state and fault AC currents, but also small enough to allow for minimum *Eon/Eoff* measurement error. Therefore, a suggested strategy for correct optimization is to perform an EMI study and calculate the expected steady-state and fault AC currents. Subsequently, based on these currents, select a capacitor with the appropriate capacitance value for each DC decoupling device. For example, using the data shown in Fig. 8, instead of using 14 DC decoupling devices of 5000 μF to ensure that the capacitors are rated for maximum steady-state AC currents, DC decoupling devices were optimized to use the smallest possible capacitors (ensuring that they are rated for the expected currents). In this case, the *Eon/Eoff* measurement error was improved by 70%. However, an alternative strategy to ensure minimum *Eon/Eoff* measurement error is to decrease the earthing resistance of mitigation wires, therefore reducing the expected steady-state AC currents, and allowing smaller capacitors to be used in the DC decoupling devices.

In addition to the capacitance, another factor that affects the *Eoff* measurement error is the coating resistance of the pipeline. To investigate this effect, the coating resistance of the pipeline was varied for values 1×10^6 Ω.m^2, 5×10^5 Ω.m^2 and 1×10^5 Ω.m^2. Fig. 9a shows the sensitivity analysis performed for the different values of the coating resistance, reflecting a pipeline coating that is ageing and therefore degrading. Since the coating resistance R_S (1×10^6 Ω.m^2) is significantly larger than the anode resistance R_A, the voltage drop of R_S plus the electrochemical potential E_P (*Eon*) is almost equal to the rectifier voltage.

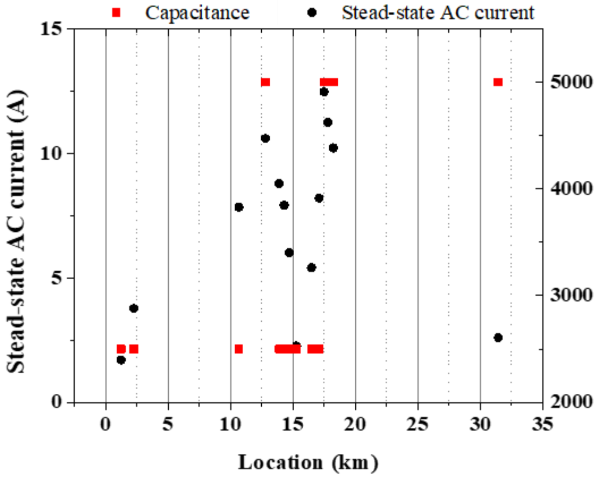

Fig. 8. Steady-state AC currents and proposed optimized capacitances. Example of DC decoupling device optimization showing the expected steady-state AC current and selected capacitor size for each mitigation wire location.

Furthermore, a pipeline with a high coating resistance will have a longer discharge time when compared to a pipeline with a lower coating resistance. In comparison, the pipelines with higher coating values exhibit an *Eon* potential closest to the

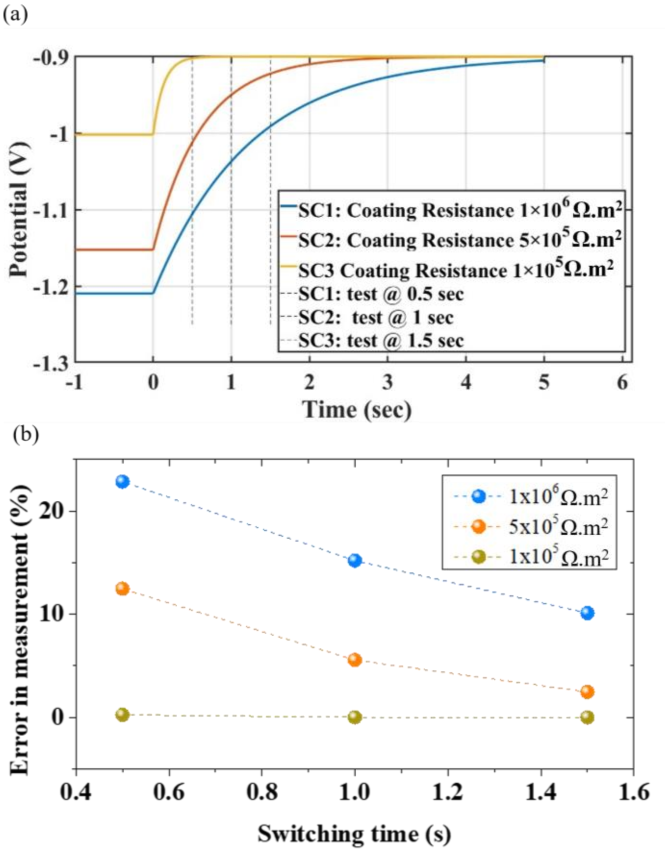

Fig. 9. (a) Simulated *Eon/Eoff* waveforms for values of coating resistance (b) Error in *Eon/Eoff* measurements at different switching time and for different values of coating resistance.

rectifier value, while the discharge time is proportional to their coating resistance value. Moreover, Fig. 9b presents the expected errors for measuring the *Eoff* potential at t=0.5, t=1 and t=1.5 seconds, demonstrating that the measurement error will be higher when the pipeline has a high coating resistance (i.e. new pipelines).

From the sensitivity analysis and since the earthing resistance *Rg* is significantly smaller than the parallel coating resistance R_S, it is evident that the time constant of the capacitive discharging and, therefore, the measurement error mainly depends on the pipeline resistance to remote earth (coating resistance), as well as on the number *n* and the capacitance *C* of the capacitive DC decoupling devices.

V. CONCLUSIONS

To investigate the effectiveness of a cathodically protected pipeline, the CP current is disconnected during the *Eon/Eoff* measurement. During this time, the DC decoupling devices connected between the pipeline and earthing electrodes tend to discharge through the pipeline and earth, creating capacitive discharging currents that induce significant errors in the instant *Eoff* measurements. This capacitive behavior interferes with the acquisition of accurate instant *Eoff* readings and, therefore, with reliable CP effectiveness monitoring.

To investigate the *Eon/Eoff* measurement error due to the presence of DC decoupling devices, the transient electrical behavior of a cathodically protected pipeline was simulated. This investigation concluded that the capacitive discharge time constant and by extension, the measurement error highly depends on the pipeline resistance to remote earth (coating resistance), as well as on the number *n* and the capacitance *C* of the capacitive DC decoupling devices. To this extent, the following methods are proposed to minimize the misleading *Eoff* measurements due to high errors:

- Optimization of the capacitance values and the number of the DC decoupling devices based on the maximum expected steady-state and fault AC currents.
- Decreasing the earthing resistance of mitigation wires. However, the earthing resistance is directly related to soil resistivity, which seasonal and environmental variations affect. Therefore the, extreme cases should be investigated.
- If the above mitigation methods cannot be implemented (the pipeline system has already been constructed), the electrical behavior of the systems must be modelled using the above methodology to calculate the expected *Eoff* error and decide on the *Eon/Eoff* switching interval.

Lastly, the method demonstrated in this paper can assist in the design of bespoke DC decoupling devices by performing a parametric assessment to select the appropriate number and size of capacitors along the pipeline length for the most accurate *Eoff* measurements while maintaining compliance with the relevant standards.

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