Mitigation of the AC corrosion of the metallic pipelines using the hydroxide and solid-state polarization cells; A comparative study

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Mitigation of the AC corrosion of the metallic pipelines using the hydroxide and solid-state polarization cells; A comparative study

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ABSTRACT

High voltage overhead transmission lines (HVOHTLs) often pass close to metallic pipelines. The parallelism between HVOHTLs and pipelines, where electromagnetic fields couple them, may cause several problems. If the pipelines are metallic, a corrosion problem has occurred because these fields induce an AC voltage on the pipelines. This paper presents a novel contribution of a low electrical hazard that can control by grounding the pipelines with a polarization cells system to mitigate the induced AC voltage without deteriorating the cathodic protection (CP) performance. This work further utilizes a comparative analysis of two different mitigation units: a potassium hydroxide polarization cell (KOH-PC) and the solid-state polarization cell (SS-PC) to decide which one of these methods is more suitable for cathodic protection distribution. This paper also explores the potential of the hill-climbing algorithm in optimizing the two proposed mitigation units' parameters to guarantee better CP performance. Moreover, the effect of changing the numbers and parameters of polarization cells on both induced AC voltages and CP performance is introduced to achieve a global minimum DC voltage degradation. From the comparative analysis, it is observed that SS-PC is more controllable in comparison with KOH-PC in mitigating the induced voltage and minimizing the DC voltage disturbance. Therefore, the SS-PC is considered the most efficient mitigation technique due to fewer potential safety hazards produced. The proposed model is implemented through simulations on the MATLAB/Simulink platform with experimental validation. The obtained results reveal that the robustness of SS-PC in mitigating the induced voltage with minimum disturbance in the DC CP voltage. Also, it is found that the effectiveness of the hill-climbing algorithm for optimizing the polarization cell's parameters and has capable of compensating the cathodic protection disturbance.

1. Introduction

If there is an interference effect between the pipeline and neighboring power transmission lines, corrosion can occur. This ac corrosion is detected in buried pipelines, causing the pipeline coating material to deteriorate [1]. The pipeline-induced voltage, caused by the interference effect, is defined by a variety of mechanisms. The form of coupling (capacitive, inductive, and conductive) between the pipeline and the power transmission line determines these mechanisms [2]. The first mechanism depicts the induced AC voltage by the electric field. Furthermore, in the case of either fault conditions or buried pipelines below a certain level, this mechanism has no impact on the pipelines [3-4]. One of the three couplings, the inductive effect is the most powerful. The magnetic field, produced by the power line, causes inductive coupling [5]. The final mechanism is conductive coupling, which happens only in the event of an overhead line ground fault [6]. In general, cathodic protection (CP) is the most effective strategy for preventing corrosion [7]. It can be used exclusively with an external power source to convert all anodic areas on the covered pipeline to cathodic regions, making them non-corrosive. The protected pipeline must be attached to another external metal (anode) to allow the diffusion of the fault current [8, 9]. The "sacrificial anode cathodic protection (SACP) system" and the "impressed current cathodic protection (ICCP) system" are two CP methods. An internal stabilization circuit is used in the first system to generate the output dc voltage and current. Furthermore, the dc voltage can be manually adjusted. On the other hand, the second system is more versatile in terms of regulating the protection dc voltage. Any DC source can use to impress current in a gas pipeline [8, 10]. The

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buried pipeline should be connected to the negative terminal of the power supply, while the auxiliary anode should attach to the positive terminal [11]. In the cathodic protection (CP) device, transformer rectifier (TR) units are used as a power source. The disadvantage of the traditional system is the difficulty in regulating the output precisely and requiring further human interference [12]. In addition, [13] explains the specifics of the anode bed design and cathodic safety requirements. Then, impressed current cathodic protection can prevent the coating defects formation on the pipeline's surface [14-15]. Mitigating induced AC voltage along the pipeline is a critical activity for reducing induced voltage and preventing corrosion. According to the NACE standard [16], the primary goal of most AC mitigation is to reduce the AC steady-state induced voltage to 15 V (RMS). As a result, the pipeline-induced voltage should be mitigated based on AC corrosion thresholds and the 15V criterion [17]. Cancellation wires, gradient control wires, insulating joints, and polarization cells (PCs) can reduce induced AC voltages along pipelines. As opposed to cancellation wires and gradient control wires, the polarization cell is the most economical mitigation method [18-19]. While the direct connection of the pipeline to a suitable grounding system will reduce AC-induced voltage, but at the same time, this will negatively impact cathodic protection. Decouplers have a long history of effectively providing DC isolation of cathodically protected structures from other objects or grounding systems, as well as removing the effects of direct bonds. The most popular decouplers designs used for AC mitigation are the solid-state and potassium hydroxide polarization cells [20-21].

The mathematical simulations of underground pipelines, transmission lines, AC voltage mitigation units (potassium hydroxide polarization cell or solid-state polarization cell), and impressed current cathodic protection systems are introduced in this paper. Furthermore, the proposed model of two mitigation units includes the parameter optimization for each cell. This paper also discusses various polarization cell models, including KOH-PC-25, KOH-PC-50, and optimized-PC. Furthermore, several solid-state polarization cell models, such as SS-PC and optimized SS-PC, are used to ensure that the best performance on both induced AC and DC cathodic voltage is selected.

The paper presents a novel contribution of low induced voltage produced on the pipeline by using different polarization cell models. An optimized KOH-PC's parameters are presented and compared with a conventional polarization cell. Further, a comparative performance evaluation of various polarization cell models considering the variation of the numbers of cell plates is introduced. The obtained results reveal the robustness of the hill-climbing algorithm for optimizing the parameters of a polarization cell. A comparative analysis of the obtained results shows that the optimized KOH-PCs mitigates the induced voltage to the desirable limit remarkably compared to traditional polarization cells. First, solid-state polarization is presented and compared with potassium polarization cells to enhance the cathodic protection performance. Further, a comparative performance evaluation of three polarization cells models, namely KOH-PC-25, KOH-PC-50, and SS-PC are presented to compare the KOH-PC and SS-PC performance in terms of both induced AC and DC voltages. Second, this study presents the optimization of the SS-PCs' parameters, and it is found that the performance of the optimal SS-PC is better than that of the optimized KOH-PCs. Besides, this study introduces the effect of varying the parameters and numbers of the solid-state polarization cell on AC voltage induced on the pipeline, in addition to the DC voltage. As a result, the numbers and parameters of suitable SS-PCs can be effective in the induced voltage reduction. Besides, the negative effect of the mitigation unit on the DC voltage distribution along the pipeline has vanished within a desirable limit. Finally, the solid-state polarization cell, which has more controllability than traditional polarization cells, is presented as the most recent development in the field of induced AC voltage mitigation.

The main contribution of this study is listed as follows:

1 The potassium hydroxide and solid-state polarization cells are electrically modeled.
2 The induced AC and DC voltages distribution along the pipeline are verified with the experimental measurement.
3 The hill-climbing algorithm is utilized for optimizing the parameters of a polarization cell to mitigate the risk of AC corrosion.
4 The effect of the different configurations and parameters of solid-state polarization cells is introduced on both induced AC and DC voltage.
5 The DC CP voltage is negatively shifted for preventing pipeline AC corrosion that provides robustness of the solid-state polarization cell.
6 A comparative analysis is introduced between different polarization cells models without and with the optimization of its.

The paper is structured as follows: The problem statement is described in Section 2 with details on hydroxide and solid-state polarization cells. The specifics of the hill-climbing algorithm for optimizing the parameters of two polarization cell types are described in Section 3. Section 4 also shows the proposed model results as well as a comparative performance assessment for two polarization cell types with optimized models. Finally, conclusions and suggestions for future work are given in Section 5.

2. Problem statement

This section presents a comprehensive discussion of the induced voltage mechanisms with a detailed description of the cathodic protection system technique for long pipelines. This section also handles the construction of hydroxide and solid-state polarization cells. In addition, the optimization of polarization cells' parameters on the mitigation of induced voltage is introduced.

2.1. Mechanisms of induced voltage

Capacitive, inductive, and conductive coupling are some of the mechanisms that explain the causes of AC voltage on a pipeline. The electric field induces the AC voltage in the first mechanism. The capacitive coupling has no impact on the pipelines in the case of fault conditions or buried pipelines below a certain level [21-22]. At power frequencies, capacitive coupling only affects overhead pipelines. As a result, the transversal electric field in the soil is practically negligible. Furthermore, conductive coupling only occurs in the case of a power line fault to earth. This mechanism is an unusual phenomenon and continues only a fraction of a second. On the other hand, corrosion has a long-term effect, so that the impact of conductive coupling may be neglected [23-24]. The inductive coupling is the only component that has a significant effect on the pipeline. Therefore, this study investigates only the inductive coupling at normal conditions because the studied pipeline is installed underground. The induced AC voltage along the pipeline can calculate using a variety of methods. The procedures, explained in [25-26], are used in this analysis, and good agreement between measurement and calculation results is achieved. Fig. 1 shows the pipeline electrical circuit, which is built based on the lossy transmission line theory. Mathematically, the pipeline can be divided into small portions, while each section has uniform grounding parameters such as soil resistance and pipeline coating resistance. In this study, the pipeline is divided into 77 sections; each section is defined as a π circuit, with the length of each section equal to the power line's tower span. At the end of each segment, the pipeline to ground voltage can be easily calculated and measured.

As shown in Eq. (1) [27], the AC voltage that appears at each π-section for the buried pipeline due to the magnetic field of the inductive coupling ranges from V_1 to V_{i-1}.

$$V_i = \frac{E_i}{\gamma}\left\{-\frac{Z_A}{Z_A+Z_C}e^{-\gamma x}+\frac{Z_B}{Z_A+Z_C}e^{-\gamma\left(L_p-x\right)}\right\} \tag{1}$$

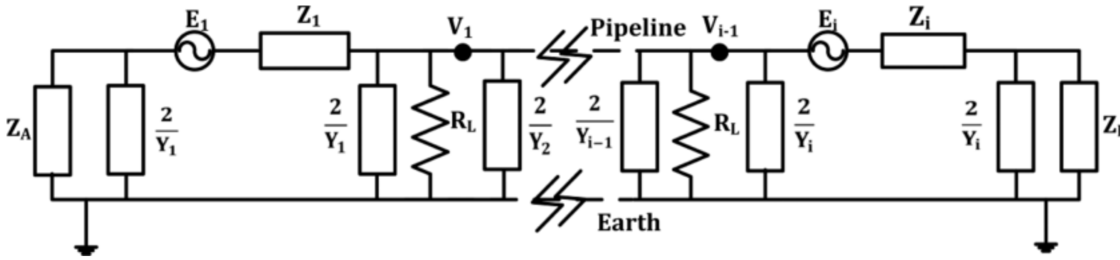

Fig. 1. Equivalent circuit of multiple π-section pipelines

Where E_i denotes the electromotive force (EMF) per unit length along the pipeline (V/km), $\gamma = \sqrt{ZY}$ denotes the pipeline propagation constant (km^{-1}), and $Z_C = \sqrt{Z/Y}$ denotes the lossy pipeline characteristic impedance (Ω). Z and Y are the pipeline-earth impedance and admittance per unit length (Ω/m), respectively. The equivalent impedance of the left and right sides of a buried pipeline per unit length (Ω/m) is denoted by Z_A and Z_B, respectively. L_p is the length of a pipeline subsection (m), and x is a variable distance along the buried pipeline's length (m). In [28-29], the comprehensive descriptions and formulas for these parameters are introduced.

2.2. Corrosion prevention technique in underground pipelines

The common methods for corrosion prevention can divide into four categories [30-31]. The first defense method is the selection of a corrosion-resistant material, such as stainless steel or plastic. The second method includes the use of inhibitors. The third technique incorporates the implementation of protective coatings that electrically separate the pipeline from the soil, such as epoxy paints. The last mechanism is cathodic protection. Therefore, the process of insulation coating is the first protection line against the pipelines' corrosion. A high percentage of corrosion protection occurs when the appropriate coating is selected. However, it is difficult to obtain 100% corrosion protection with the insulation coating due to mechanical damage during pipeline commissioning. As a result, a well-designed cathodic protection system provides the remaining corrosion protection. A direct current is injected into the structure using an external source in the cathodic protection process. The sacrificial anode cathodic protection (SACP) method and the impressed current cathodic protection (ICCP) method are the two major forms of cathodic protection techniques. The area of the structure to be protected and the soil resistivity influence the choice of these two methods in cathodic protection design. The anode, cathode, DC power source (in ICCP, an external power source), and electrolyte are the principal components in both methods. The electrolyte allows electrons to flow from the anode to the cathode. According to moisture content, oxygen level, soil resistivity level, and various types of electrolytes exist [31]. The most powerful technique is the impressed current cathodic protection scheme [32]. This technique can reduce the metal surface corrosion rate by making it the cathode of an electrochemical cell. Therefore, the pipeline's potential is shifted in the negative direction by using an external power source. For example, a three-layer polyethylene-coated pipeline requires a current density of 0.03 mA/m^2 [33].

The impressed Current Cathodic Protection scheme consists of an external DC power source, an auxiliary anode, the electrolyte, and the structure to be protected. As shown in Fig. 2, the pipeline connects to a negative potential, and the anode attaches to a positive potential. When the protection impressed current equals or exceeds the corrosion current, the corrosion process will be stopped [38-39]. The difference voltage between the reference electrode and the negative end of the voltage supply must be between -0.85V and -1.5V, according to the cathodic protection criteria [34]. An electrical (or electrochemical) system is formed by burying the pipeline and anodes together in the soil. Then, the earth serves as an electrolytic solution (conducting medium),

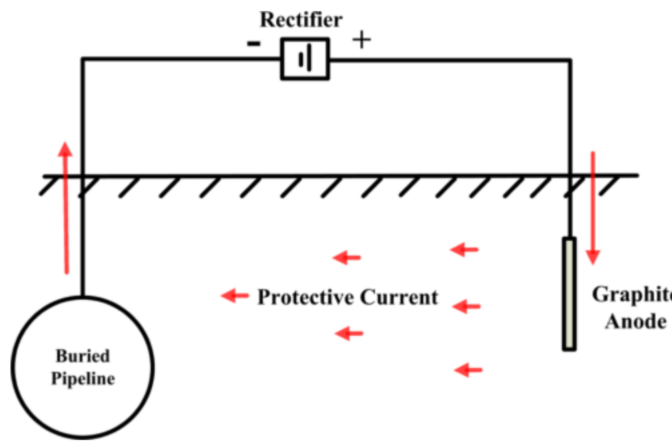

Fig. 2. Schematic model of impressed current cathodic protection (ICCP) system

and the outer metallic pipe surfaces serve as electrodes. The electrical field applied to the soil electrolyte is assumed to be uniformly conductive. Therefore, the law of charge conservation must use. Consequently, the potential distribution in the soil is defined by the Laplace equation, which expresses the charge conservation [35]:

$$\nabla.\vec{i} = 0 \tag{2}$$

The current density vector is denoted by $\vec{i}$.

The current density $\vec{i}$ is calculated using Ohm's law as follows:

$$\vec{i} = -\sigma.\nabla\varnothing \tag{3}$$

Where $\nabla\varnothing$ is the electric field, and σ and $\varnothing$ are the conductivity and potential of the electrolyte (soil), respectively.

Corrosion of the pipeline, buried in the soil, can be reduced by using current cathodic protection. Current flows from the rectifier to the anodes, through the earth, and to the pipe. This current comes back to the rectifier through a wired system to complete the electrical circuit. Then, the exposed current to the pipeline prevents corrosion and transforms the pipeline's anodic areas into cathodic areas. The corrosion rate is determined by the amount of current flowing among the metal and the adjacent medium. Moreover, the soil resistivity decreases as the corrosion activity of steel in the soil increases [36]. Fig. 3 shows a detailed schematic of the ICCP system. The negative point is linked to the pipeline for holding the metal at a high negative potential, while the positive terminal is attached to the silicon-iron anodes. Each silicon-iron anode is represented as a direct current source, but its output depends on the DC input voltage. It is reasonable to conclude that all anodes share the same dependent current source. All sources are linked in parallel and have the total current of $\sum_1^n \alpha_n V_o$.

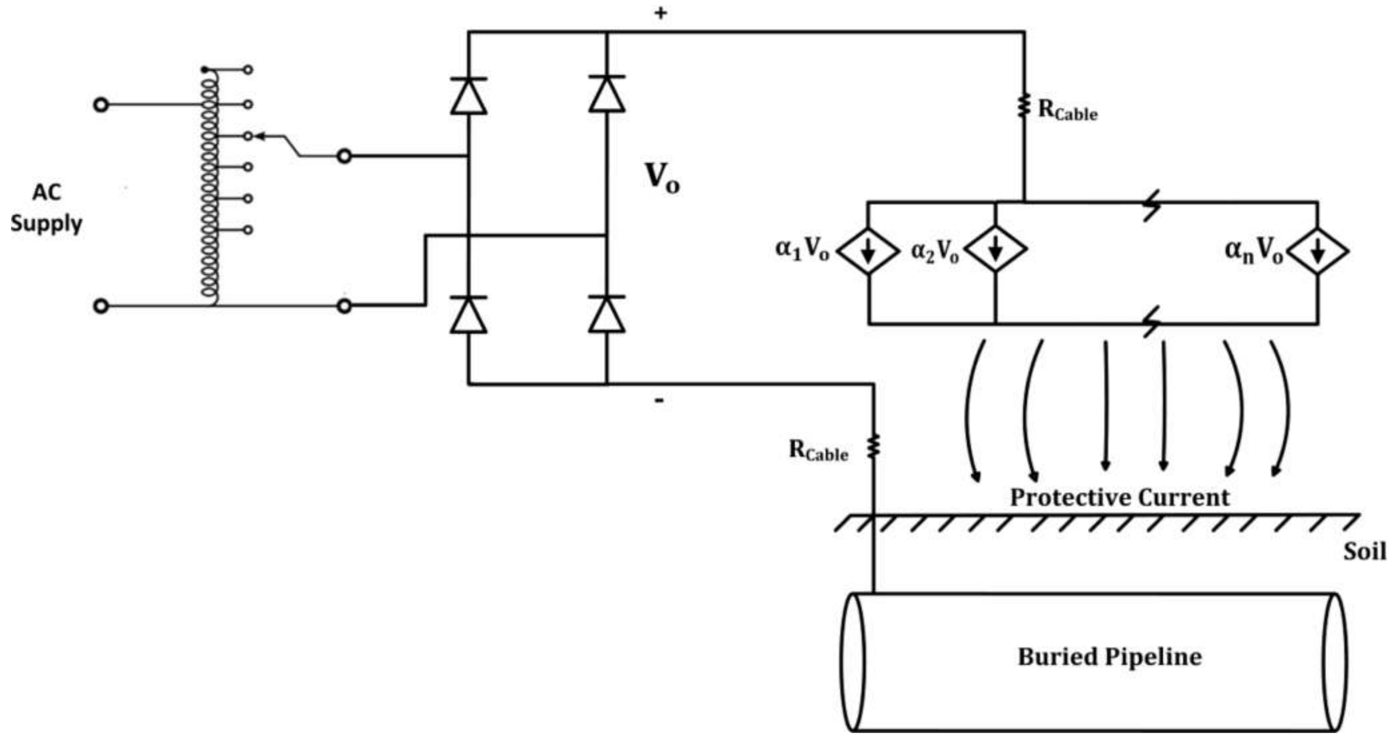

Fig. 3. Electrical connection of impressed current cathodic protection along the pipeline.

2.3. AC voltage mitigation units

Unwanted AC voltage can endanger nearby people as well as damage pipelines due to AC corrosion. Grounding the pipeline at proper locations has been developed to ensure both steady-state and fault AC voltages are maintained at safe limits. One of the most intricate features of these systems is to provide efficient grounding without weakening the cathodic protection (CP) system used for pipeline corrosion control. Cancellation wires, gradient control wires, insulating joints, and polarization cells (PCs) are some of the methods that can reduce induced AC voltages along gas pipelines. On the other hand, the polarization cell is the most practical mitigation technique.

This section gives a quick overview of the different types of decouplers that contribute to the overall effectiveness of AC voltage mitigation systems [37]. Furthermore, this study will concentrate on the most recent two mitigation methods for corrosion control, namely conventional KOH-PC and solid-state PC. The main goal of any mitigation technique is to reduce the induced AC pipeline voltage. These can be accomplished by connecting the pipeline to a suitable low impedance grounding system at appropriate locations to reduce the voltage to an acceptable level. However, the most challenging part of any mitigation method is the effect on the performance of impressed current cathodic protection (CP) systems. As a result, mitigation methods develop to reduce induced AC pipeline voltage without adversely influencing on the cathodic protection system.

Firstly, the polarization cell is an electrochemical switch, which shunts the harmful induced voltage into the soil. It consists of many sets of stainless steel or nickel plates immersed in a 30 percent potassium hydroxide solution. The AC impedance of polarization cells is usually about 0.1 milliohm, depending on the number of plates, the surface area of the plates, and the distance between plates. The cells are typically designed to handle high currents in the tens of kA range without causing harm to the cell while still providing a significant DC voltage blocking [38]. The cell function is to shunt dangerous AC voltages to the earth. This means that it primarily has two terminals, the first point connects to the pipeline, and the other connects to the ground. The pipeline terminal is often recognized as an upper terminal, whereas the earth terminal is defined as a lower terminal. On the other hand, this cell has a low resistance to alternating current when blocking direct current [39-40]. Polarization cells have become less popular since the evolution of solid-state devices in the 1980s. Besides, the potassium hydroxide polarization cells require regular fluid level maintenance and a large package size. When these cells fail due to evaporation dilutes the KOH solution within the cell, and the solution will overheat to the boils-off point. Therefore, an undesirable open circuit is created, which poses a possible safety hazard. Furthermore, the plates have been known to corrode. The cell will continue to move direct current under the steady-state alternating current drain, posing a risk of corrosion on the anodic plates.

Secondly, solid-state decouplers create a switch between two terminals connected to the cathodic protected pipeline and the grounding system using high-power solid-state electronic switching components. Decouplers provide a continuous conduction path for AC steady-state in addition to provide a grounding path for AC faults and lightning. Under normal conditions, the solid-state switch remains open, the pipe's DC isolation will achieve. When the differential voltage across the decoupler terminals reaches a predetermined voltage threshold, as it may during a fault or a lightning strike, the solid-state switch closes almost instantly and forces the induced voltage on the pipeline to safe levels. Besides, this device automatically switches back to the OFF state after an overvoltage event to isolate the cathodic protection system.

Both KOH-PC and SS-PC are modeled based on the electrical circuit representation of all of its components to achieve accurate results. Firstly, to model the equivalent circuit of KOH-PC, this cell primarily consists of two terminals, each of which has a group of stainless steel plates that are nested. In other words, the plates are separated by distances, and each upper terminal plate is followed by a lower terminal plate, and so on. The counting begins at the first upper terminal and ends at the last lower terminal plate if it starts at the first upper terminal. This means that the number of upper terminal plates equals to the number of lower terminal plates, and they are divided by equal distances. Now, the first plate is connected to the pipe and has the pipeline voltage, while the second plate is connected to the earth and has approximately zero voltage. Furthermore, the two plates are separated from one another by a certain distance d_{12}. Two materials, air, and a KOH solution, fill the dielectric of this distance. As a result, there are two capacitors between the first and second plates, one ($C_{air_{12}}$) due to the air dielectric and the other ($C_{KOH_{12}}$) due to the KOH solution. The capacitance due to the dielectric of air is negligible in most cases [41].

$$C_{air_{12}} = \frac{\varepsilon_0 \cdot A_{air}}{d_{12}} \quad (4)$$

$$C_{KOH_{12}} = \frac{\varepsilon_0 . \varepsilon_r . A_{KOH}}{d_{12}} \quad (5)$$

This capacitance is associated in parallel with a resistance that reflects the KOH path from plate one to plate two, the length of which is equal to the distance between the two plates. The area of the impressed portion in the KOH solution is the cross-section area of this path. As a result, the path's resistance is defined as Eq. (6).

$$R_{KOH} = \frac{d_{12}}{\sigma_{KOH} . A_{ip}} \quad (6)$$

Where, the solution's conductivity is σ_{KOH}, and the area of the impressed portion of the solution is A_{ip}.

Each plate is represented by a resistor R_{P_i}, with the odd order indicating plate resistors connected to the pipeline and the even order indicating plate resistors connected to the earth terminal. This resistance's value is calculated as follows Eq. (7):

$$R_{P_i} = \frac{\rho_{s.s} . L_{P_i}}{A_{P_i}} \quad (7)$$

Where, $\rho_{s.s}$ denotes the stainless-steel metal's resistivity, L_{P_i} denotes the length of plate i, and A_{P_i} denotes the cross-section area of the same plate. Finally, the KOH- PC's equivalent circuit is depicted in Fig. 4.

As previously mentioned, the kirk cell is composed of several pairs of stainless steel plates immersed in a potassium hydroxide electrolyte solution. An oil seal floating on the electrolyte prevents evaporation, atmospheric gasses absorption, and excessive foaming during flowing high currents. A film of gas forms on the plates due to direct current flow through the kirk cell, which provides high resistance to low voltage direct current. Then, the flowing current through the cell increases as the applied voltage on the cell increases. Consequently, the thickness of the polarization gas film increases. The film begins to break down when the leakage voltage exceeds the threshold value, and the cell resistance rapidly will decrease as the applied voltage increases. The kirk cell uses as a dead short at higher AC voltage. As a result, manufacturers designed the solid-state polarization cell as a mitigation alternative to liquid-filled polarization cells. A solid-state polarization cell provides DC isolation and AC grounding to provide cathodically protection pipelines. In addition, unlike the Kirk polarization cell, the solid-state is designed to work at all levels of AC induced voltage. Then, a solid-state polarization cell is appropriate for higher blocking DC voltage requirements and high AC fault conditions. The solid-state polarization cell is positioned across the pipeline at peak points to avoid cathodic protection voltage leakage and thus achieve DC isolation. All of its components must represent to build a schematic model of a solid-state polarization cell. This cell primarily contains a series resistor-capacitor in SS-PC. The solid-state is a capacitor-type system that blocks direct current while enabling alternating current along the pipeline to flow via the ground without weakening cathodic protection performance. The decoupler allows alternating current to flow but interrupts the direct current. Therefore, the solid-state decoupler provides a path for induced AC currents to drain into the earth, while it also protects cathodic protection systems from AC interference.

3. Proposed algorithm

Many optimization techniques require knowledge of the optimized function's partial derivatives. Many numerical optimization techniques, such as Newton's method, coordinate descent methods, and conjugate gradient methods, are used to find extremes analytically. These methods may be an alternative, but for larger systems, the process of obtaining accurate derivative information is generally unfeasible. Only evaluate function values are often better-suited in minimizing the potential energy of larger systems due to the lack of accurate derivative data. In this category, we'll go through a simple algorithm in better detail. Hill climbing is a numerical optimization algorithm that improves its solution iteratively by changing one dimension at a time. The algorithm adjusts a single dimension of its current state in each iteration and accepts the adjustment. This process is replicated until either no further improvements can be found or the maximum number of iterations has been completed [42]. There are three important hill-climbing drawbacks; Local optimal, where the algorithm cannot escape a local optimum since modifications are only approved if they promote the function evaluation and do not achieve a global optimum. Ridges and Alleys, where one dimension is adjusted at a time by the algorithm. The search also zigzags around non-axis-aligned ridges or alleys, taking an excessive amount of time to ascend the ridge or descend the alley. Plateau refers to an area where the value function is flat. The algorithm will either make no improvements or perform a random walk, depending on the specific implementation. The following algorithm demonstrates popular variants and potential implementation of adaptive hill-climbing

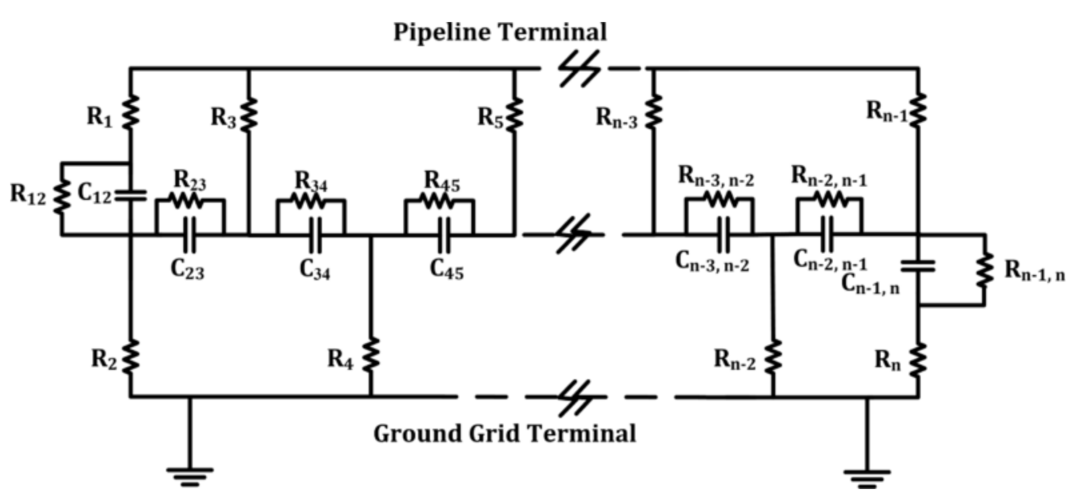

Fig. 4. The equivalent electrical circuit for the proposed Polarization cell model

algorithms by analyzing several neighboring states and continuing with the best and adaptive phase sizes for each dimension that changes in this algorithm. The hill-climbing has capable of adjusting one dimension to a (local) minimum. It should start with a valid configuration, i.e., one with finite potential energy. Hill climbing algorithm, unlike most randomized optimization algorithms, has reasonable intermediate states in allowing for proper visualization of the optimization process[43].

Input: number of iterations n, value function $f:\mathbb{R}^m \rightarrow \mathbb{R}$, and start configuration $\vec{x}_0 \in \mathbb{R}^m$

Output: $\vec{x}_n$ with $f(\vec{x}_n) \leq f(\vec{x}_0)$

acceleration←1.25
steps←$(1, \ldots, 1)$
For $i \in 1 \ldots n$ do
    $\vec{x}_i \leftarrow \vec{x}_{i-1}$
    For $j \in 1 \ldots m$ do
        $\vec{x}_j \leftarrow \vec{x}_{j-1}$
        factor←acceleration^{-1}
        For $k \in -1 \ldots 1$ do
            $\vec{x}_{i,+j,k} \leftarrow \vec{x}_{i-1} + e_j \cdot steps_j \cdot acceleration^k$
            $\vec{x}_{i,-j,k} \leftarrow \vec{x}_{i-1} - e_j \cdot steps_j \cdot acceleration^k$
            If $f(\vec{x}_{i,k,+j}) < f(\vec{x}_{i,j})$ then
            $\vec{x}_{i,j} \leftarrow \vec{x}_{i,k,+j}$
            factor←acceleration^k
            If $f(\vec{x}_{i,k,-j}) < f(\vec{x}_{i,j})$ then
            $\vec{x}_{i,j} \leftarrow \vec{x}_{i,k,-j}$
            factor←acceleration^k
        steps$_j$←*factor*.steps$_j$
        If $f(\vec{x}_{i,j}) < f(\vec{x}_i)$ then
        $\vec{x}_i \leftarrow \vec{x}_{i,j}$
    return $\vec{x}_n$

As a result, the equivalent (Thevenin) impedance can be determined by dividing the AC voltage on the alternating current dissipated throughout the cell, as shown in Eq. (8).

$$Z_{th_{PC}} = \frac{V_{AC}}{I_{AC}} \quad (8)$$

The main parameters that affect the thevenin impedance of a hydroxide polarization cell are L_H, W_H, L_V, W_V, x, T, as well as the number of plates N_P. Otherwise, the resistance and capacitance are the main parameters in the thevenin impedance of a solid-state polarization cell. Both types of polarization cells are built in MATLAB/Simulink, with initial values for all of the parameters, an AC voltage source is applied, and the flowing current is calculated. This impedance is calculated using Eq. (8), where all of these parameters are selected during the optimization process in a globalization mode. The primary goal of the objective purpose is to maximize the amount of current discharged from the pipeline to the soil. To maximize the discharged current, this impedance, Z_{th}, should be minimized as in Eq. (9). The following conditions have lower and upper limits that must be satisfied:

$$f_{min} = Z_{th_{PC}} \quad (9)$$

For KOH-PC model
Subjected to

$$L_H^{min} \leq L_H \leq L_H^{max}$$

$$W_H^{min} \leq W_H \leq W_H^{max}$$

$$L_V^{min} \leq L_V \leq L_V^{max}$$

$$W_V^{min} \leq W_V \leq W_V^{max}$$

$$0 \leq x \leq x_{max}$$

$$T_{min} \leq T \leq T_{max}$$

$$N_P^{min} \leq N_P \leq N_P^{max}$$

$$C_{th}^{min} \leq C_{th} \leq C_{th}^{max}$$

For SS-PC model
Subjected to

$$R_{min} \leq R \leq R_{max}$$

$$C_{min} \leq C \leq C_{max}$$

The main effects of induced voltage with two forms of polarization cells: KOH-PC and SS-PC, are shown in the following section. In addition, the impact of changing the number and parameter of SS-PCs on both AC and DC voltage is discussed. In addition, the induced AC and DC voltages have been investigated in optimized polarization cell conditions.

4. Results and discussion

The induced voltage has been investigated in various polarization cell configurations in this section. As previously mentioned, there are two KOH-PCs models; the first has 25 plates, and the other has 50 plates. Hydroxide polarization cells require routine fluid level maintenance, and when they fail in operation, they pose a possible safety danger. As a result, it suggests a solid-state polarization cell to mitigate the negative effect of hydroxide polarization cells. Furthermore, the parameters of KOH-PCs and SS-PCs are optimized using the hill-climbing algorithm to improve a polarization cell's construction for the best performance in minimizing the induced voltage without adversely affecting the DC voltage. Mainly, the studied pipeline considers as an extension of the previous study, which was discussed in [29-30]. The studied pipeline is a natural gas metallic pipeline owned by Egypt's Fayoum Gas Company. As is well known, this line is 72 kilometers long and runs adjacent to three overhead high-voltage transmission lines, as shown in Fig. 5. Two of the three transmission lines have a voltage of 500 kV, with only one three-phase power circuit, and two earth wires are carried on the tower of these lines. The last one has a 220 kV voltage, and the tower consists of two three-phase power circuits and one earth cable.

The El-Kurimate-Cairo and Samaloute-Cairo transmission lines are shown in Fig. 6 (a), and the Dimo-6th of October transmission line is shown in Fig. 6 (b). The technical parameter of power lines and towers are shown in Table 1. Firstly, the studied pipeline has an inner diameter of 16 inches (0.4064 m). Three layers of High-Density Polyethylene

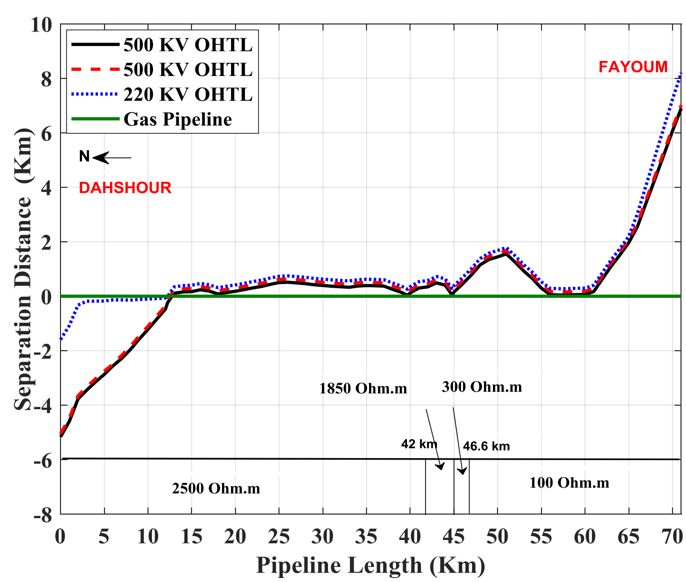

Fig. 5. Pipeline-transmission line configuration for Fayoum Gas Co.

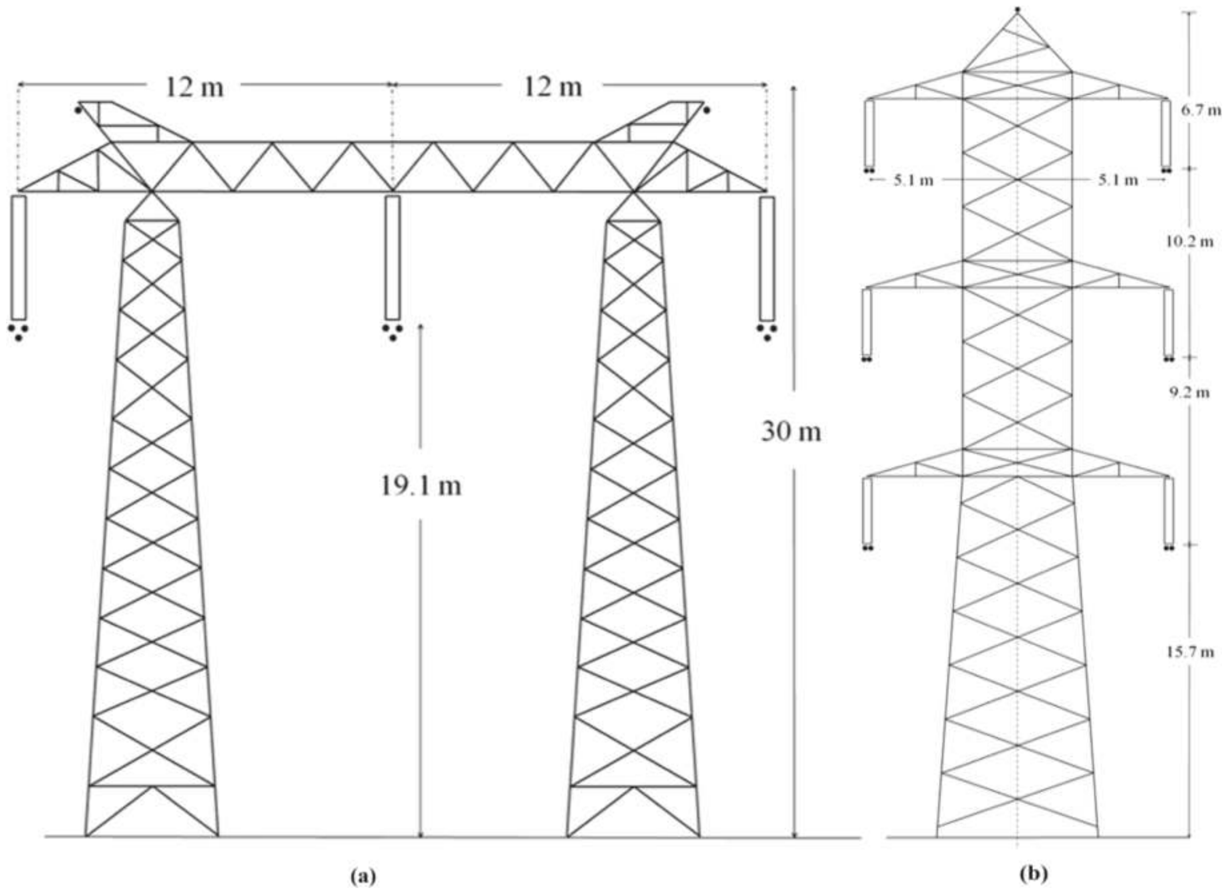

Fig. 6. The towers for the overhead high voltage transmission lines

Table 1
Power line technical details[44,45]

Parameter	Value	
Rated Power in MVA	575	158
Line to line voltage in kV	500	220
Transmission lines length in km	124	90
No. of tower circuits	1	2
No of the phase conductors	3	2
Conductor diameter in mm	30.6	27
The conductors separation in cm	47	30
Towers span in meter	400	360
The vertical height of first conductor in meter	19.1	15.7
No of ground wires	2	1
The ground wire height in meter	30	41.8
The ground wire diameter in mm	11.2	13.6

(HDPE), with a resistance of 10^6 Ω/m^2, a relative permittivity of 5, and a thickness of 4 mm, are used to coat it. This pipeline is buried at a depth of 1.5 m, with soil resistivity ranging from 2500 to 100 Ω.m. El-Kurimate-Cairo HVOHTL, Samaloute-Cairo HVOHTL, and Dimo- 6th October HVOHTL are the three transmission lines. The 124-kilometer El-Kurimate-Cairo transmission line has a rated capacity of 575 MVA at 500 kV operating voltage. This line has two earth lines and a single three-phase circuit. There are three sub-conductors in each phase. The second line is Samaloute-Cairo, which has a rated capacity of 1000 MVA and a length of 209 kilometers at a 500 kV operating voltage. Furthermore, the Samaloute-Cairo tower is constructed similarly to the El-Kurimate-Cairo transmission line. The Dimo-6th of October transmission line, with a voltage of 220 kV and a length of 90 km, is the last line. There are two circuits on this line, with one earth line. Each phase has a rated power of 158 MVA, and each phase has two sub-conductors.

The pipeline is electrically modeled, in addition to the transmission line, polarization cell forms, and cathodic protection system. The overall equivalent electrical circuit is investigated in the MATLAB/Simulink platform to study the induced voltage generated on the pipeline by interfering TLs and the cathodic protection performance along the pipeline. The circuit's parameters are determined using MATLAB code, and then the results are handled to Simulink software. The induced AC and DC voltages can easily calculate from the Simulink program's results at the end of each pipeline segment. Generated AC and DC voltages are two vital parameters used to evaluate the proposed model.

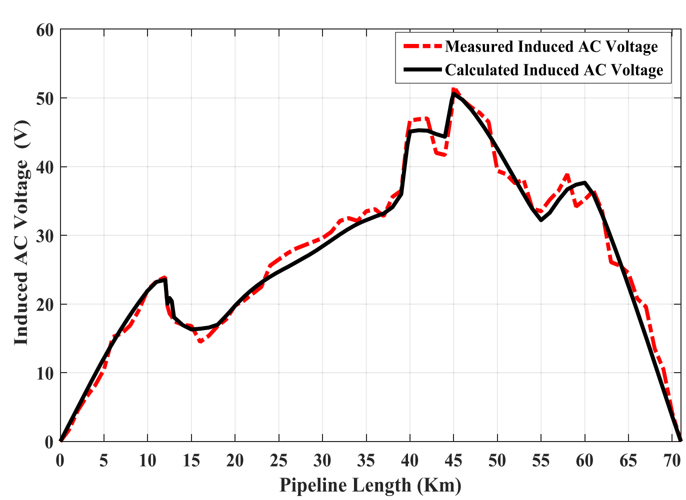

Fig. 7. Comparison between measured and calculated induced voltage along the pipeline.

Fig. 7 shows the calculated and computed induced AC voltage along the pipeline under normal operating conditions, where the model in Fig. 1 is used to calculate this voltage. The induced voltage appears at a maximum value at specified points. These are due to the shortest separation distance between the pipeline and transmission lines. It can be shown from this figure that the induced voltage increases with decreasing the separation distance between the pipeline and the transmission line. The lowest separation interval points are 12.75,18, 39.7, 44.8, and 58 km from the pipeline's start, with AC induced voltage values of 20.43, 17, 43.12, 49.79, and 35.93 volt, respectively. This means that pipeline corrosion is becoming more likely. The induced voltage must reduce to a safe level (15 V) to prevent AC corrosion. The induced voltage threshold limit can be accomplished by installing two forms of polarization cells along the pipeline at the shortest distance between the transmission line and the pipeline. It is noted that the calculated voltage agrees well with the measured voltage in the field site. However, due to the difficulty of accurately measuring transmission line operating conditions and the pipeline's surrounding conditions, there are small deviations between them.

This pipeline has two impressed current cathodic protection stations. One is installed at the pipeline's beginning, while the other is installed at the pipeline's end. In addition, negative DC voltage in (mV) is used to calculate cathodic protection (CP). As a result, it is noted that the CP values are high at the beginning and end of the pipeline, and then decrease to the lowest value in the center. The CP potential varies between -1.5 and -1.445V_{DC}, as shown in Fig. 8, with a value of about -1.5V_{DC} at the pipeline line terminals and a value of -1.445 V_{DC} in the center of the pipeline. Furthermore, due to the greatest distance from the main ICCP stations, the pipeline's minimum DC voltage occurs in the center. The recommended successful cathodic protection potential ranges from -0.85 to -1.5 V_{DC} for steel pipelines buried in the soil. Consequently, with these values, the pipeline is completely shielded from AC corrosion. The process of minimizing induced AC voltage along the pipeline is recognized as the most vital factor in preventing metal corrosion at coating impurity locations and reducing staff exposure to electrical hazards. Evaporation dilutes the KOH solution within the polarization cell, while the KOH solution dilution increases the applied voltage on the cell. Then, this solution will overheat, resulting in an open circuit. Moreover, the plates can corrode as a result of the open circuit. As a result, a solid-state polarization cell is proposed as an effective solution to these problems.

Different KOH-PC models, such as KOH-PC-25, KOH-PC-50, and SS-PC, can be used to mitigate induced AC voltages during normal operating conditions along gas pipelines in this section. As previously stated, the pipeline with the highest induced voltage is the un-mitigated transmission line. As a result, it concentrates on the impact of the mitigation system on the induced AC and DC voltages. Fig. 9 shows the mitigated induced voltage at the pipeline using the KOH-PC-25, KOH-PC-50, and SS-PC at normal operating conditions. The induced voltage values are used to choose the mitigation points. As a result, these polarization cells are installed at 12.75, 18, 39.7, 44.8, and 58 kilometers from the pipeline's start, where the induced voltage has the highest values. The overall assessment of induced AC voltage along the pipeline does not exceed 15 V (RMS) after installing KOH-PCs and SS-PCs. When using the KOH-PC-25, KOH-PC-50, and SS-PC, the maximum induced voltage is 14.32 V, 14.5 V, and 12.98 V, respectively. Furthermore, based on this figure, it can be concluded that SS-PC has the best performance for mitigating induced voltage. The effect of different polarization cells on the CP voltage distribution along the pipeline is depicted in Fig. 10. Solid-state polarization cells, as shown in Fig. 10, have a lower negative impact on cathodic protection distribution and do not cause a decrease in DC voltage as compared to traditional cells.

On the other hand, the DC voltage is slightly affected after the polarization cells are installed in the pipeline. However, as opposed to the PC-50, the DC Voltage drop is smaller in the KOH-PC-25. The KOH-PC-50 provides a simpler bridge that greatly dissipates the current into the soil. The minimum DC voltage exists in the middle of the pipeline, as shown in Fig. 10, with -0.767 V, -1.375 V, and -1.421 V for KOH-PC-50, KOH-PC-25, and SS-PC, respectively. As a result of the increased plate number in potassium hydroxide polarization cells, which causes the extra of the electrical paths to the soil, the KOH-PC-50 cell has the worst CP performance due to the CP voltage being near the minimum permissible limit of CP voltage (-0.85 V_{DC}) specified by the NACE standard. On the other hand, The KOH-PC-25 reduces the CP voltage from -1.445 V to -1.375 V, while the KOH-PC-50 decreases the DC voltage from -1.445 V to -0.767 V. Based on these results, the decrease in DC voltage in the case of KOH-PC-25 is smaller than that in the case of KOH-PC-50. Finally, these figures show that the PC-25 has a positive impact on AC voltage discharge performance while drawing a small amount of direct current. It should also be noted that as the number of KOH-PC's plates increases, the direct current discharge to the soil will gradually increase. As a result, when compared to other polarization cell models, the DC voltage is the most critical when using PC-50. Therefore, the SS-PCs must be used to regulate both the AC and DC voltages. Consequently, the decrease in DC voltage observed in the case of the SS-PC is less than that in the case of various polarization cell models, where the SS-PC decreases the CP voltage from -1.445 V to -1.421 V.

Fig. 11 depicts the calculated induced AC voltage on the pipeline at each peak point along the pipeline for various numbers of SS-PC. It is observed that the maximum value of induced AC voltage along the pipeline does not exceed 15 V (RMS) after installing one SS-PC, two SS-PC in series, and two SS-PC in parallel. At point 54 km, the maximum

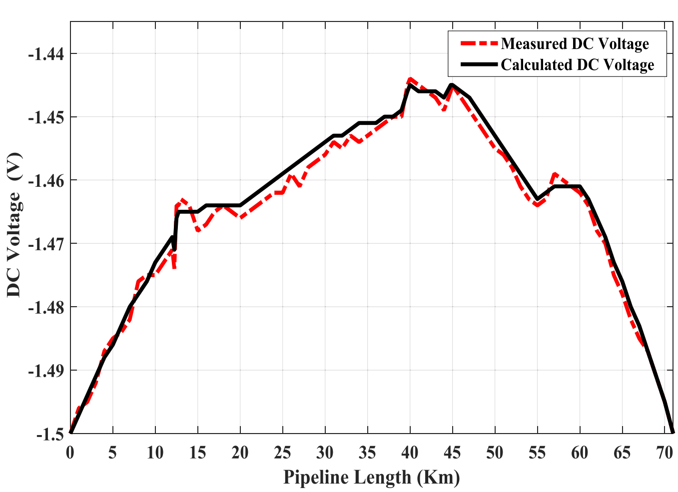

Fig. 8. CP DC voltage distribution along the pipeline without mitigation.

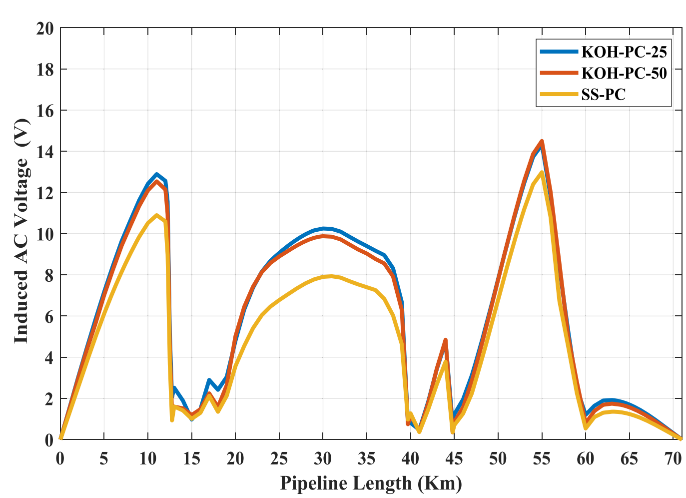

Fig. 9. Mitigated induced voltage with different models of KOH-PC and SS-PC

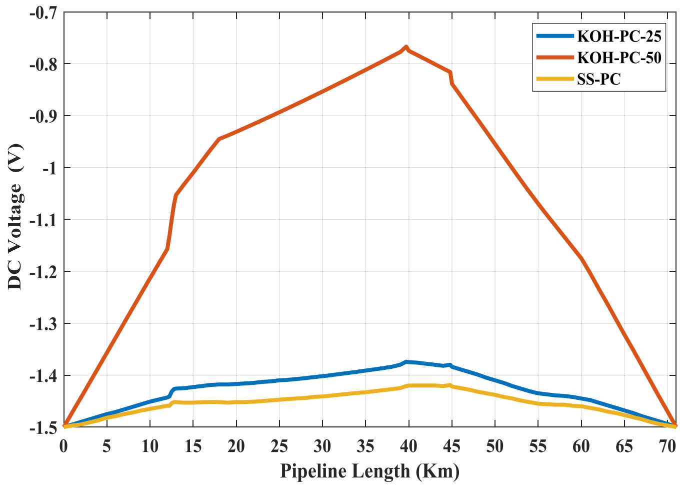

Fig. 10. DC voltage with different models of KOH-PC and SS-PC

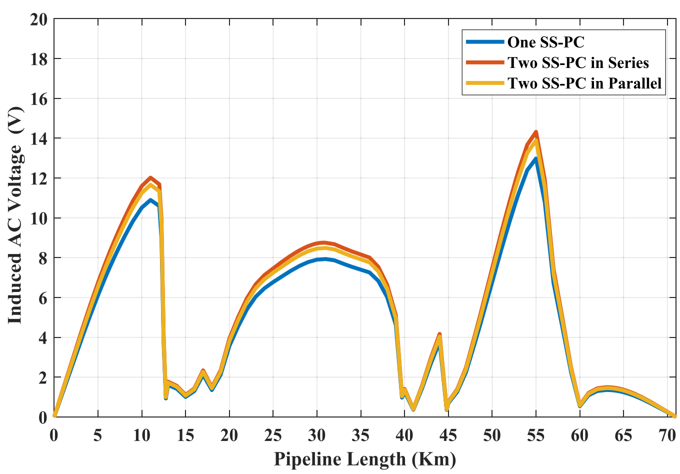

Fig. 11. Mitigated induced AC voltage with different configurations of SS-PC

induced voltage is 12.98 V, 14.319 V, and 13.89 V, in the case of one SS-PC, two SS-PCs in series, and two SS-PCs in parallel, respectively. Furthermore, from this figure, it can be concluded that the mitigated induced voltage in the case of one SS-PC is lower than that in the other SS-PC cases. These figures show the solid-state polarization cells' ability to reduce the severity of induced voltage on the pipeline, and shielding it from AC corrosion. In all-solid-state polarization cell configurations, the DC voltage is slightly affected after installing the solid-state polarization cells. The effect of different numbers of solid-state polarization cells on the CP voltage distribution along the pipeline is shown in Fig. 12. As shown in Fig. 12, one solid-state polarization cell has a less negative impact on cathodic protection than that in the case of the other solid-state polarization cell configurations. For one SSPC, two SSPC in series, and two SSPC in parallel, the DC voltage at the middle pipeline is -1.421 V, -1.392 V, and -1.410 V, respectively.

As a result, the one SS-PC provides the best CP performance due to the minimal reduction in CP voltage after installing the mitigation units. The CP voltage is reduced from -1.445 V to -1.392 V in the case of two SS-PC are connected in series, and the DC voltage is reduced from -1.445 V to -1.410 V in the case of two SS-PC are connected in parallel. Based on these results, the decrease in DC voltage in the case of one SS-PC is less than that in the case of the other configurations. Therefore, the SS-PC number is chosen based on the number of paths required to achieve two goals: the first goal is to reduce the induced voltage into the soil, and the second goal is to reduce DC voltage deterioration phenomena,

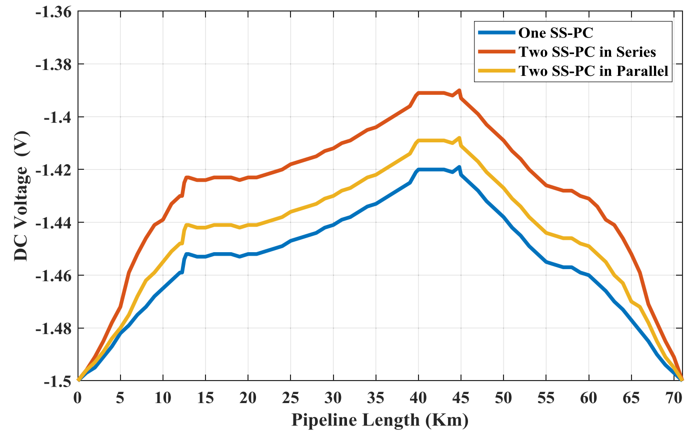

Fig. 12. DC voltage with different configurations of SS-PC

especially after installing AC mitigation induced voltage units to ensure the cathodic protection performance. Finally, it is noticed that one SS-PC provides the best performance in dissipating induced voltage into the soil in a safe way and ensuring the improvement of CP performance. Furthermore, in the case of one SS-PC, the amount of direct current discharged to the soil is reduced.

The effect of varying the SS-PC parameters on the amount of induced AC voltage generated along the pipeline is investigated. Also, this paper presents a comprehensive comparison of various SS-PC parameters to provide recommendations for deciding which one of these scenarios is the best for reducing the induced voltage while having the lesser effect on cathodic protection performance. In this study, four scenarios introduce to model and simulate the various solid-state polarization cell parameters. Figs. 13 and 14 depict the induced AC voltage and DC CP potential in the different SS-PC parameter scenarios. The solid-state polarization cell parameters for the layout in these figures are as follows:

1 Low Resistance and Low Capacitance (e.g. R=0.15 Ω, and C=100 pF).
2 Low Resistance and High Capacitance (e.g. R=0.15 Ω, and C=100 μF).
3 High Resistance and Low Capacitance (e.g. R=0.4 Ω, and C=100 pF).
4 High Resistance and High Capacitance (e.g. R=0.4 Ω, and C=100 μF).

As compared to traditional polarization cells, both scenarios result in

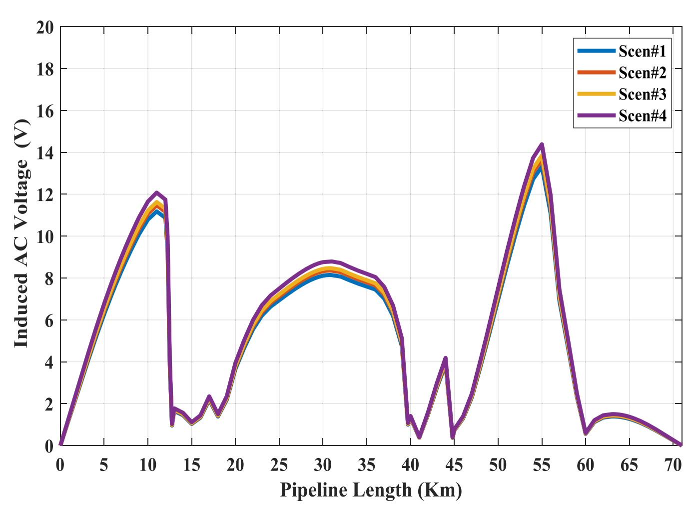

Fig. 13. Effect of variation of SS-PC's parameters on the induced voltage along the gas pipeline

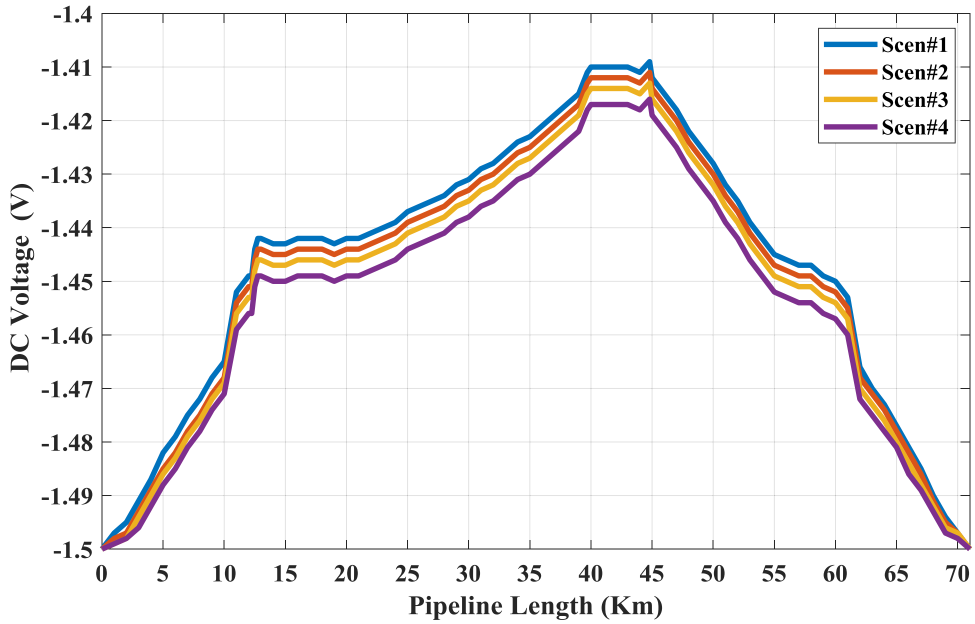

Fig. 14. Effect of variation of SS-PC's parameters on the DC voltage along the gas pipeline.

the lowest induced voltage on the pipeline. Furthermore, the decrease in DC CP voltage is lower than that in the traditional polarization cells. Finally, it is noted that the change of the parameters of the SS-PC is a popular method for improving solid-state output in terms of minimizing induced voltage and preventing DC voltage reduction. Finally, from these figures, the first scenario has a positive impact on AC voltage discharge performance. On the other hand, it causes a significant reduction in DC CP voltage. Also, it is noted that the capacitance of the SS-PC decreases, then the direct current discharge to the soil will gradually increase. The hydroxide and solid-state polarization cells parameters must optimize to reduce the induced AC voltage and increase the DC voltage. As a result, the optimized KOH-PC model is selected based on the appropriate number of polarization cell plates for dissipating induced voltage and ensuring better CP performance. On the other hand, the optimized SS-PC model is chosen based on the appropriate resistance and capacitance. Furthermore, it is noted that the most effective applied mitigation method is the optimized SS-PCs. Moreover, the capability of the optimized SS-PCs in mitigating the induced voltage and having a less negative influence on CP performance. Therefore, the optimized SS-PC is used, the amount of direct current discharged to the soil is reduced.

Fig. 15 shows the mitigated induced voltage at the pipeline using the optimized KOH-PC and SS-PC at normal operating conditions. It is noticed that the optimized SS-PC gives the best performance in achieving two purposes; the first aim is the minimizing of the induced voltage, and the second aim is the reduction of DC potential deterioration after installing the various types of PCs. Fig. 16 shows the effect of different optimized polarization cell types on the CP voltage distribution along the pipeline. From this figure, it can be shown that the optimized SS-PCs give the best DC voltage distribution, which results in the shift of DC voltage in a negative direction. As shown in Fig. 16, the optimized SS-PC has a lower negative impact on cathodic protection. Therefore, the optimized SS-PC gives a lower DC voltage reduction compared to optimized KOH-PCs. The DC voltage increases from -1.421 V with the SS-PCs at the middle of the pipeline (39.7 km) to -1.432 V for the optimized SS-PCs. In addition, the DC voltage for optimized KOH-PCs and optimized SS-PCs is -1.389 V and -1.432 V, respectively. Besides, the DC voltage is improved by 77.4% when the optimized SS-PC is implemented compared to the SS-PC. The DC voltage is also improved by 3.1% when the optimized SS-PC is implemented compared to the optimized KOH-PCs. This percentage indicates the amount of improved DC voltage in the optimized SS-PC is more than that in the optimized KOH-

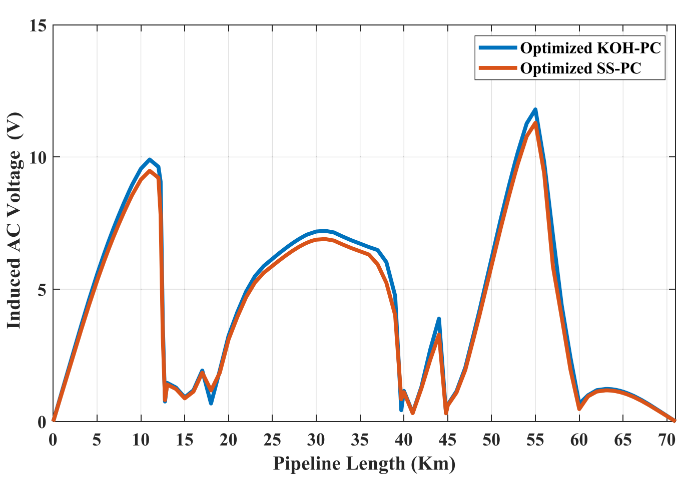

Fig. 15. Mitigated induced AC voltage with optimization of KOH-PC and SS-PC's parameters.

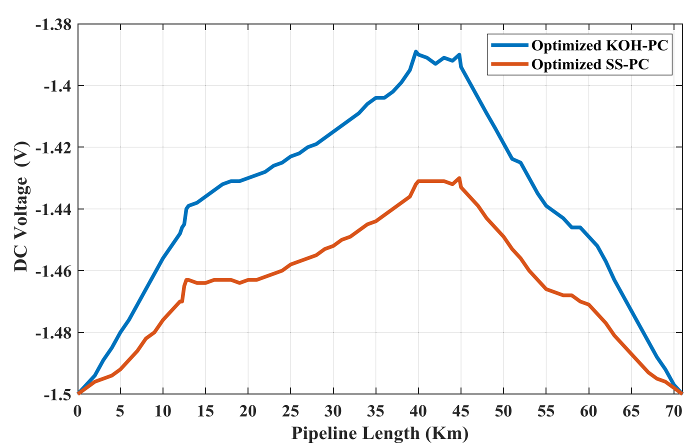

Fig. 16. DC voltage with optimization of KOH-PC and SS-PC's parameters.

PCs. Consequently, the problem of CP performance deterioration is eliminated, especially with KOH-PC. Therefore, the optimization of polarization cells parameters achieves the best cathodic protection performance. Besides, all proposed optimized PCs models can mitigate the induced voltage in permissible limits. Furthermore, all proposed different optimized PCs' models can sustain the cathodic protection disturbance. Whereas, the proposed optimized SS-PC improves the DC CP potential reduction more than that obtained by the optimized KOH-PC. From the author's point of view, the solid-state polarization cell is a considerably preferable mitigation technique, which provides highly efficient in reducing the global induced voltage and improving the CP potential distribution.

From previous figures, one can note that the optimized SS-PC is the most efficient mitigation method, then the optimized KOH-PC gives the reasonable performance in the mitigation of the induced voltage. The optimized SS-PC is the most efficient one among the suggested mitigation techniques, where the DC voltage reduction is less than that obtained from the other optimized KOH-PC model, especially with the traditional KOH-PCs' models. Therefore, it is essential to implement the optimization system to improve the DC voltage reduction and mitigate the highest induced voltage along the pipeline. As previously explained, the proposed model's main aim is to minimize AC interference without adversely affecting cathodic protection performance. This goal is accomplished by optimizing the polarization cells parameters and varying the numbers and configurations of polarization cells' models. Besides, the amount of deteriorated DC voltage in the optimized SS-PCs is less than compared to that in other polarization cells models. Consequently, the problem of the negative impact of the mitigation unit on the DC CP distribution vanishes. Besides, the amount of deteriorated DC voltage using SS-PC is less than that obtained using the KOH-PCs. Therefore, the optimization process is essential to improve the polarization cell performance for optimizing the polarization cells' parameters. The mitigation of induced voltage and the compensation of DC voltage reduction obtained from all optimized polarization cells models are better than that obtained using non-optimized polarization cells models.

To sum up, the proposed optimization method with different polarization cells models successfully achieves the two purposes; the first purpose is the mitigation of the induced voltage, and the second aim is the improvement of DC potential in all the studied cases compared to the other non-optimized polarization cells models. Also, in a comparison of the hydroxide polarization cell, the solid-state polarization cell provides a highly efficient in mitigating the induced voltage, in addition to it provides a highly efficient in saving the deteriorated DC voltage from the pipeline due to the mitigation unit. Moreover, the solid-state polarization cell gives promising results in mitigating the induced voltage and the lowest reduction in the DC voltage compared to those with hydroxide polarization cells models. Finally, the obtained results illustrate the efficacy of the hill-climbing algorithm in sustaining the decrease of cathodic protection due to the installation of a polarization cell. Moreover, the proposed optimization technique can be very significant in eliminating the negative impact on cathodic protection from the mitigation unit. After analyzing the AC and DC voltages' results, it can be observed that all optimized PCs provide high induced voltage mitigation and low DC voltage reduction, particularly the optimized SS-PCs. Comprehensive comparative studies for the different polarization cell models are introduced. Such a study is carried out to analyze the ability of various polarization cell models in terms of induced AC and DC voltages. Tables 2 and 3 show the induced AC and DC voltages calculations using the optimized polarization cells with KOH-PC-25, KOH-PC-50, and SS-PCs, respectively.

Comprehensive comparative studies for the different polarization cell models are introduced. Such studies are carried out to wholly investigate the use of various polarization cell models in terms of AC and DC voltages. As shown in Table 2, using optimized SS-PC, one can recognize that the mitigated voltage is less than that with different polarization cells models. For example, in the optimized SS-PCs at point 44.8 km, the mitigated induced voltage is 0.310 V compared to 0.803 V, 0.353 V, 0.325 V using KOH-PC-25, KOH-PC-50, SS-PC, and optimized KOH-PC, respectively. Generally, it is observed that all polarization cells provide a reasonable result in the mitigation of the induced voltage. It is concluded from the obtained results that the mitigated induced voltage levels are lower with the optimized polarization cells than those without optimization. Furthermore, compared to other polarization cells models, the optimized SS-PC can successfully reduce the overall induced voltage on the pipeline. Finally, the optimized algorithm with different polarization cells models gives acceptable results in reducing the induced voltage.

Table. 2
Comparisons for the highest AC induced voltage points with different polarization cells models.

Point (km)		12.75	18.00	39.70	44.80	58.00
W/O PC	Calculated	20.43 V	17 V	43.12 V	49.79 V	36.69 V
	Measured	18.2 V	16.8 V	44.5 V	48.4 V	38.9 V
KOH-PC-25	Calculated	1.353 V	1.582 V	0.81 V	0.803 V	5.293 V
	Measured	1.368 V	1.352 V	0.823 V	0.812 V	5.352 V
KOH-PC-50	Calculated	0.611 V	0.6992 V	0.379 V	0.353 V	5.029 V
	Measured	0.810 V	1.012 V	1.231 V	0.821 V	5.68 V
Optimized KOH-PC	Calculated	0.755 V	0.682 V	0.432 V	0.325 V	4.391 V
Optimized SS-PC	Calculated	0.809 V	1.174 V	0.844 V	0.310 V	3.942 V

Table 3
Comparisons for the DC voltage points with different polarization cells models.

Point (km)	12.75	18.00	39.70	44.80	58.00
W/O PC	-1.465 V	-1.464 V	-1.446 V	-1.445 V	-1.461 V
KOH-PC-25	-1.427 V	-1.418 V	-1.374 V	-1.381 V	-1.441 V
KOH-PC-50	-1.073 V	-0.945 V	-0.767 V	-0.816 V	-1.133 V
Optimized KOH-PC	-1.440 V	-1.431 V	-1.389 V	-1.394 V	-1.445 V
Optimized SS-PC	-1.463 V	-1.458 V	-1.432 V	-1.431 V	-1.467 V

On the other hand, as shown in Table 3, the DC voltage will be improved from −1.374 V and -0.767 V, at the middle point pipeline (39.7 km), with KOH-PC-25, and KOH-PC-50, respectively, to −1.389 V, and −1.432 V with optimized KOH-PC, and optimized SS-PC, respectively. These results indicate higher effectiveness of the optimized SS-PC over other different polarization cells models. The DC voltage, using KOH-PC-25, is improved by 1.1 %, and 4.2 % when the hill-climbing optimization algorithm is implemented with KOH-PC, and SS-PC, respectively. Whereas the DC voltage, using KOH-PC-50, will be improved by 81.1 % and 86.7 % when the hill-climbing optimization algorithm is implemented with KOH-PC, and SS-PC, respectively. This percentage symbolizes that the optimization method can sustain the deteriorated DC voltage, particularly with KOH-PC-50. Moreover, it is observed that all different proposed optimized polarization cells models give promising results in eliminating the problem of the CP performance deterioration due to the use of mitigation units. Therefore, the optimized SS-PC and KOH-PC give the best cathodic protection performance. . Furthermore, the hill-climbing algorithm is more helpful for minimizing induced voltage and reducing overall degradation of the cathodic protection performance.

To sum up, the amount of deteriorated DC voltage using optimized SS-PC is less than that obtained using the optimized KOH-PC. Consequently, the problem of the negative impact of the polarization cell on the DC distribution is eliminated. Therefore, the optimization process of the polarization cells is essential in protecting the pipeline from corrosion. Consequently, it is essential to develop alternative methods to improve the polarization cell performance, especially with hydroxide polarization cells. Finally, the obtained results illustrate the efficacy of the hill-climbing optimization algorithm in sustaining the negative impact on DC voltage from the mitigation device.

5. Conclusions and extensions

This paper presents an efficient solution to the AC corrosion problem that can occur in metallic pipelines when HVOHTLs construct in parallel with it. Deterioration of the coating can occur as a result of this corrosion. The KOH-PC models with the electrical model of the buried pipeline and cathodic protection systems are presented in previous studies. Various polarization cell models, such as PC-25 and PC-50, have been introduced to study the effect of selecting the plate's numbers on both induced AC and DC voltage. In this study, the hill-climbing algorithm is used to determine the appropriate number of potassium polarization cell plates for ensuring the best DC voltage distribution. Moreover, the polarization cell performance will improve by optimizing the potassium polarization cells parameters to reduce induced voltage and improve DC voltage deterioration. It is found that the performance of the optimized KOH-PC is better than that of the various KOH-PCs' models to dissipate the induced voltage into the soil remarkably. Recently, a solid-state polarization cell is introduced due to the dilution of the KOH solution in the hydroxide polarization cell. A complete comparison has been performed using different KOH-PCs' models with solid-state polarization cells. Therefore, solid-state polarization cells will introduce more controllability than the conventional polarization cell. Consequently, it is necessary to study the variations in the numbers and configurations of the solid-state polarization cells on the induced AC voltage and DC CP performance. Besides, this paper introduces the electrical modeling of the SS-PC, in addition to its optimal design. Further, a comparative performance evaluation of various polarization cell models, such as KOH-PC and SS-PC, is implemented. The obtained results reveal the effectiveness of optimized SS-PC for mitigating the harmful induced voltage and maintaining the CP voltage within desirable limits. Consequently, the selection of suitable polarization cell configurations reduces the influence of the interfering transmission line with the pipeline remarkably. Finally, one of the most considerable challenges with AC mitigation methods is the deterioration of the cathodic protection. This problem is solved by optimizing the KOH-PC and SS-PC. Therefore, for future work, it is essential to develop the new topologies of optimization algorithms for optimizing the parameters of all polarization cells models to implement for mitigating the harmful induced AC voltage to prevent AC corrosion on the pipeline.

CRediT authorship contribution statement

Mohamed A. Mostafa: Software, Writing – original draft, Visualization, Investigation. **Mostafa Al-Gabalawy:** Conceptualization, Methodology, Data curation, Validation. **Essam M. Shaalan:** Supervision, Writing – review & editing. **Abdel Salam Hamza:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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