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Cathodic Protection Performance Improvement of Metallic Pipelines based on Different DC Compensation Methods

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ABSTRACT

Nowadays, natural gas in the Middle East has been discovered in extremely many quantities, and it is considered the most vital natural resource. Sometimes, the natural gas pipeline is constructed in the desert and paralleled with the high voltage overhead transmission lines (HVOHTLs). An induced AC voltage has appeared on the pipeline due to interfering with the HVOHTLs. Mainly, hydroxide potassium polarization cell (KOH-PC) has been applied to discharge this voltage to the soil within a safety limit. But, the mitigation units have negatively impacted cathodic protection (CP). The DC voltage of the pipeline is initially compensated using externally supplied impressed current cathodic protection (IMCP) units. In many cases, the external power sources have continuity and stability issues. Therefore, this paper presents different strategies as a promising solution to be utilized in reducing the disturbance of the external power sources. The first strategy is exploiting the induced voltage via converting it as DC form by using the controlled rectifier circuit and reapplying on the pipeline as a cathodic protection voltage. The second strategy involves a photovoltaic (PV) system, which integrates into the pipeline. This paper also explores the superiorly of the fuzzy system with different compensation strategies in managing the DC voltage along the pipeline to guarantee better CP performance under any disturbance in the impressed current stations. From the comparative analysis, it is observed that the behavior of the various strategies in compensating the DC voltage deterioration is reasonable. The obtained results reveal that the robustness of the fuzzy logic controller in mitigating the induced voltage and has capable of compensating the cathodic protection disturbance.

1. Introduction

Corrosion is the degradation of a metal as a result of electrochemical reactions. Furthermore, AC corrosion is caused by interference between the pipeline and nearby power transmission lines. Coatings and cathodic protection are the primary methods for preventing AC corrosion in underground pipelines (CP). Coatings are typically designed to form an electrically insulating material on the pipeline's surface. Electrochemical reactions are inhibited by these coatings, which have high electrical resistance. Cathodic protection is a corrosion-prevention technique that involves applying an external current to a corroding metal surface. Current leaves the auxiliary anode (also known as a 'sacrificial' anode), travels through the corrosion cells' cathodic and anodic areas, and then returns to the DC source. Cathodic protection can be accomplished in two ways: impressed current (IC) and sacrificial anode (SA). The first technique does not require a power supply to impress current from the sacrificial anode to the cathodically protected area. Therefore, the anode metal's potential must be higher than the cathode metal's according to the galvanic series. The second method is confirmed as a vigorous technique usually utilized in the pipeline's corrosion prevention. DC power supply is utilized to impress the demanded current. A rectifier (if AC power is available) or a diesel generator is used to provide DC power.

1.1. Literature review

NACE recommends a cathodic potential of -850 mV vs $Cu/CuSO_4$ electrode (CSE) as the standard CP criteria for protecting the buried steel structures [1]. In [2], the CP criteria are insufficient to offer adequate corrosion protection for buried pipelines in the presence of AC

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interference. The CP level has a significant impact on the AC corrosion process, according to laboratory and field data. Extreme CP increases the AC corrosion rate and should consequently be limited. Increasing the CP appears to be the incorrect response to a potential AC corrosion issue [3]. The CP requirement isn't valid for AC densities greater than 70 A/m^2 [4]. Further, due to battery heating, appropriate consideration of temperature effect must be taken in insulation design of cable. The excessive temperature causes serious concerns for safety issues mainly for the insulation property of the cable [5]. A fuzzy incremental controller was also designed to regulate corrosion in underground metallic pipes, and its performance was compared to that of the traditional proportional-integral (PI) controller. The single-phase AC is varied by the fuzzy incremental controller output. For corrosion control, varying AC is rectified, filtered, and supplied into a pipeline [6]. The solar power system was used to demonstrate intelligent cathodic protection of buried pipes in [7]. Maximum power point tracking (MPPT) controller is developed to optimize the power provided by the solar array. In addition, Perturbation and observation, as well as Conductance incremental (C.I) algorithms, are used to adjust the buck converter's output voltage in response to variations in solar radiation and sunny hours during the day. In addition, an Adaptive Neuro-Fuzzy Inference Systems (ANFIS)-based identification model was built. The ICCP system was controlled using a conventional Proportional-Integral-Derivative (PID) controller and a fuzzy controller [8]. In [9], a fuzzy logic method was developed to compensate for the fluctuations and dynamic changes in the environment. FLC-controlled TR units have been constructed and thoroughly tested in two separate application regions along the Iraq-Turkey crude oil pipeline. The method was developed by combining a fuzzy logic expert system (FLES) with data from on-site investigations to enable unprecedented control over pipe corrosion rates for estimating the possibility of corrosion thinning and corrosion cracking [10]. In addition, this system was utilized to assess the possibility of corrosion thinning and corrosion cracking. The suggested model was designed to analyse the pipeline failure probability using Fuzzy Fault Tree Analysis (FFTA) based on expert expertise. The suggested FFTA framework was utilized to make risk management choices for oil and gas pipelines, which were hit by various natural catastrophes [11]. An analytic model based on the type-2 fuzzy logic controller (T2-FLC) was designed to evaluate the chance of corrosion failure for oil and gas pipelines [12].In [13], a methodology was suggested to reduce the quantity of investigation corrosion rate data and forecast underground pipelines corrosion rates using a combination of six soil factors (moisture content, pH, resistivity, redox potential, sulfate, and chloride concentrations). Simultaneous PLC-based Fuzzy-PID controller is designed to automatically manage the petroleum product flow rate via monitoring the different pressure signal ranges in the long transmission concrete pipes. A SCADA screen monitors real-time pressure and flows data to offer immediate trends through data recording. In addition, a PLC-based Fuzzy-PID controller was designed to improve the functioning of control valves in the pipeline transport system to eliminate environmental disruptions such as leakage, damage, and explosion [14].

1.2. *Research objective and scope*

AC mitigation techniques, as previously stated in [15–20], play an important role in reducing the induced voltage to a suitable grounding system, but they would have a detrimental influence on cathodic protection. The position and number of KOH-PCs are also crucial in decreasing the DC-CP voltage and mitigating pipeline voltage. Furthermore, numerous catastrophes may occur as a result of interference between metallic pipelines and high-voltage overhead transmission lines; hence, this paper aims to investigate various DC compensation algorithms as a possible approach for attaining optimal DC CP distribution. To implement such a methodology of DC compensation strategies, the Fayum gas pipeline, located in Egypt, is selected as a case study. The first strategy is built based on the exploitation of unwanted mitigated induced voltage (UMIV) to maintain DC voltage within desirable limits. This aim is achieved by using an integrated circuit that can control the discharged energy to the soil through the KOH-PCs and utilize it in improving the cathodic protection via the conversion of excessive induced voltage to DC voltage, which is injected into the pipeline. This conversion is implemented by using the controlled rectifier circuit. This solution reduces the overall installation cost of the disturbing external power supply. An attractive alternative from a techno-stable standpoint is to use photovoltaic systems (PVS) to compensate for the DC voltage disturbance issues along the pipeline to reduce the corrosion activity. To reflect the superiority of the proposed model, two performance criteria have been investigated. The first shows the total energy saved by the electric utility per year, while the second shows the total energy released to the soil each year. Furthermore, at both pipeline terminals, a fuzzy logic system is used to regulate the output of the auxiliary distribution and main impressed current stations. Furthermore, a fuzzy system was used to evaluate comparative cathodic protection performance utilizing two models of KOH-PCs: KOH-25 cells and KOH-50 cells with various DC compensation procedures to obtain a global maximum CP.

The contributions of this work are briefly summarized as follows:

1 DC voltage has been studied for the pipeline using different DC compensation strategies.
2 An integrated system has been investigated to exploit the harmful induced voltage or external PV system for compensating the cathodic protection disturbances.
3 The influence of different DC compensation methods in the case of using various KOH-PCs' models with and without fuzzy controller on the DC voltage is studied.
4 Comparative analysis of the UMIV results with PVS results in terms of saving and discharging energy per year is introduced.

The rest of the paper is organized into different sections, in which the problem statement, the induced voltage mechanisms, and AC corrosion control are presented in Section 2, the suggested solution to enhance the cathodic protection performance of the pipeline is presented in Section 3, the system description is presented in Section 4, results obtained are presented and discussed in Section 5, and, finally, conclusions and future works are presented in Section 6.

2. Problem Statement

This section provides a detailed description of the causes of induced AC voltage on the pipeline owing to transmission line interference. Besides, the electrical modeling of the impressed current system and the polarization cell is illustrated. The development of sophisticated CP is carried out dependently on the fuzzy system. Different fuzzy system schemes for dynamic controlling the AC and DC voltage are presented.

2.1. *Induced Voltage Mechanisms*

Electromagnetic interference (EMI) between HVOHTLs and metallic pipes poses a substantial hazard to surrounding electrically conductive pipelines, posing a high-level threat to the pipeline's operational security. If pipes are located near HVOHTLs without being connected to a mitigation device to reduce the induced voltage, metallic pipeline corrosion can arise. These scenarios can be more problematic in HVOHTL fault situations when the amount of induced voltage by conductive forms on unmitigated metallic pipes can reach thousands of volts [21]. The capacitive, inductive, and conductive forms of induced AC voltage are considered regarding the circuit configurations [22]. Capacitive coupling only impacts overhead pipes at power frequency. As a result, the soil's transversal electric field is almost non-existent. Furthermore, the conductive coupling will occur only when a power line fault to the ground or lightning impact upon HVOHTL occurs. This mechanism is a rare occurrence that lasts barely a fraction of a second.

On the other hand, corrosion has a long-term effect, so that the effect of conductive coupling can be disregarded [23–24]. The inductive coupling is the only coupling, which has a substantial impact on the pipeline's corrosion. Because the pipeline understudy installs on the underground, this study solely looks at inductive coupling under normal conditions. A variety of approaches may be used to compute the induced AC voltage along the pipeline. This analysis employs the methodologies described in [25–26], and perfect agreement between measurement and calculation results is obtained. The pipeline electric circuit is depicted in Figure 1 and is based on the lossy transmission line theory.

The pipeline may be separated into small sections mathematically, with uniform grounding factors like soil resistance and pipeline coating resistance in each part. The pipeline is split into 77 sectors in this analysis; each section is characterized as a π-circuit, with each section's length equal to the tower span of the power line. The pipeline to ground voltage may be smoothly computed and measured at the end of each section. The induced AC voltage is calculated based on the producing electrical field (E_i) at each sector. The ground surface per unit length (Z and Y) determines the pipeline impedance and admittance, respectively. The standard earthing components, such as soil resistance and pipeline casing resistance, are also represented as (R_L). The corresponding electrical design for the pipeline is shown in Figure 1[27]. Eq. (1) may be used to calculate the produced voltage at each sector. The complete computation of the generating electrical field (E_i), series impedance (Z_i), and shunt admission (Y_i) is introduced in [19–20]. The following formula is used to calculate the induced voltage induced at each π- pipeline segment [27]:

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

Where E_i denotes the electromotive field 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).

2.2. AC Corrosion Control

Corrosion of metallic pipes can take numerous forms, including mechanical and chemical corrosion. Mechanical corrosion is the first type of corrosion that occurs when a pipeline is damaged by overpressure, overheating, or underheating. The last process occurs when a pipe is covered with low-vigor chemical compounds, causing a galvanic cell to form [28–29]. The rate of hardness and metal corrosion is influenced by several factors related to the nature of metals and their surroundings. A faster rate of corrosion occurs in metals containing impurities and unevenly spaced physical stressors. Temperature, moisture, and soil resistivity are all factors that impact the corrosion rate [29]. The AC corrosion is a mixture of the corrosion forms. If the interference effect exists and causes a voltage on the pipeline, corrosion will occur. The chemical vigour of the coating substance, which functions as an anode, is increased by this voltage. As a result, the rate of corrosion accelerates [30]. The AC corrosion must assess based on several factors, including the AC interference evaluation on a buried pipeline, the electrical configuration of the AC power line, the separation interval between the transmission line and pipeline, coating insulation properties, and soil resistivity [28,31]. AC corrosion assessment must be accomplished by using AC and DC measurements, according to ISO 18086 [32]. The AC voltage reading from a pipeline is sent to a reference electrode located at a distance. The maximum AC voltage is adjusted at 15 V during an example period (e.g., 24 h), according to [3]. The performance of the CP system is influenced by AC interference, which causes the DC CP voltage to deviate from the design value [3–4]. For pipelines, the industry-recommended CP standard is -0.85 V (CSE) [21]. Furthermore, in the absence of AC interference or at a low AC density, such as less than 20 A/m^2, a CP voltage of -0.95 V (CSE) can accommodate complete protection. When the AC density is more than 20 A/m^2, the CP voltage should change negatively to prevent AC corrosion of pipes. As a result, the prevailing DC voltage of the pipeline should be within acceptable limits (-0.85 to -1.5 V). Corrosion prevention methods are essential to avoid pipeline damage and the associated alteration costs. Some systems used to prevent corrosion include chemical treatments, coatings, and injected electric current. Sometimes, the use of the coating provides a continuous layer of electrically insulating material that covers the protected metallic surface. The purpose of a coating is to isolate the metal from direct contact with the surrounding electrolyte and provide a high electrical resistance to prevent electrochemical reactions from occurring fast [33]. As a result, the primary purpose of a coating on a cathodically shielded pipeline is to reduce the amount of exposed metal surface area. As a result, the required current to deliver metal cathodically protected will reduce.

Cathodic protection is an effective method of using the metal as an electrochemical cell cathode for decreasing metal surface corrosion [34–35]. As a result, cathodic protection, in combination with protective coatings, is the primary strategy for corrosion control. CP may reduce the corrosion rate, and a correctly handled system can safeguard a structure throughout its structure life [30]. The corrosion rate reduction is achieved by shifting the metal potential negatively via two methods. The first method utilizes an external power supply, where it is related to an impressed current system. The second is a sacrificial anode. In the impressed current system, the power supply unit is the rectifier, which injects a current into the pipeline, which causes high potential distinctions between the anode and the structure [36]. The galvanic contact between the sacrificial anode material, such as zinc or magnesium, and the pipeline is utilized to deliver the required current in CP for the sacrificial anode process [37]. Galvanic protection has the advantage of not requiring an external power source, but its current capacity is limited by the mass of the sacrificial anode and its usage. As a result, impressed current cathodic protection (ICCP) utilizes to protect buried pipelines [38]. In an impressed current system, corrosion control can achieve from an external current source linked to the underground pipeline. Mostly, the current source is typically a transformer-rectifier (TR) unit that provides a low DC (direct current) voltage. The

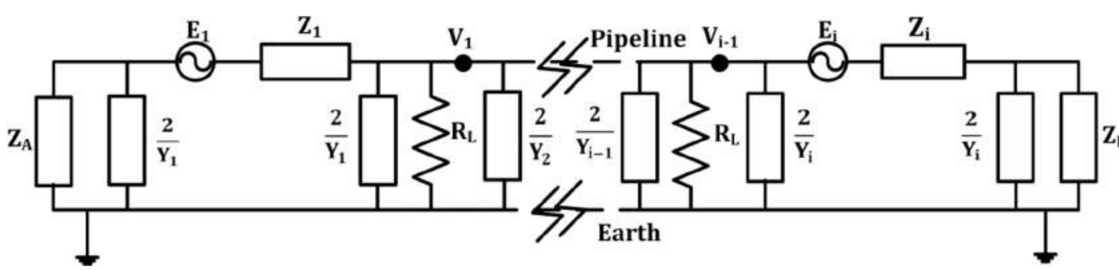

Figure 1. Electrical equivalent circuit for a pipeline with several segments.

impressed current cathodic protection system is depicted in Figure 2, where the DC is delivered into the pipeline from an external DC source (usually a power rectifier). The positive side of this source is solidly connected to a group of graphite anodes. These anodes deliver a DC through the soil to the pipeline, where the negative side of the DC source is connected to the pipeline. The rectifier is the most common power source in ICCP systems. In this study, there are two ICCP stations at both ends of the pipeline, where the transformer rectifier is used to step down the AC input from a grid to normal voltage and then rectified this by the controlled rectifier circuit.

2.3. Induced AC voltage mitigation based on polarization cells

Unwanted AC voltage can threaten persons nearby and cause pipeline corrosion owing to AC corrosion. The process of grounding the pipeline at strategic sites has been established to ensure that both steady-state and fault AC voltages are kept below safe limits. One of the most difficult aspects of these systems is to provide adequate grounding without damaging the cathodic protection (CP) system, which is used to keep pipelines from corroding. Some of the methods for reducing induced AC voltages along gas pipelines include cancellation wires, gradient control wires, insulating junctions, and polarisation cells (PCs). On the other hand, the polarisation cell is the most practicable mitigating approach.

The potassium hydroxide polarisation cell, which contributes to the overall efficacy of AC voltage mitigation devices, is briefly discussed in this section. Any mitigation technique's main objective is to minimize the induced AC pipeline voltage. This voltage can be reduced to an acceptable level by connecting the pipeline to a suitable low impedance grounding system at appropriate points. The impact on the performance of impressed current cathodic protection (CP) systems is the most challenging aspect of any mitigating strategy. As a result, mitigating strategies for reducing induced AC pipeline voltage without affecting the cathodic protection system are indeed being developed. The polarisation cell, for example, is an electrochemical switch that shunts the detrimental generated voltage into the soil. It's made up of a lot of stainless steel or nickel plates that are submerged in a 30% potassium hydroxide solution. The properties of these cells are detailed and calculated in [19–20]. As demonstrated previously, the number of plates on the KOH-PC has an impact on the CP's overall performance along the pipeline. As a result, the suggested model is essentially focused on increasing the CP potential by employing the induced AC voltage that arose on the pipeline as a result of transmission line interference as an alternative power input to impressed current devices. The suggested model is based on fuzzy logic and can regulate and change the injected current into the pipeline to produce an optimal DC voltage distribution. Furthermore, the suggested fuzzy logic system is implemented with two different DC compensation techniques with various models of KOH-PCs, the first has 25 layers (KOH-25 cells), while the second has 50 layers (KOH-50 cells).

3. Proposed Solution

One of the most challenging aspects of a buried pipeline is providing good grounding without compromising the cathodic protection system used for corrosion management. As a result, it offers an integrated system that uses either the damaging induced AC voltage or an external DC power source to protect pipelines against AC corrosion while also correcting for DC CP voltage degradation. The block diagram of the proposed control system for controlling the induced voltage and also improving the CP effectiveness is shown in Figure 3, where two main ICCP stations at both ends of the pipeline, and distributed local FLC at the highest AC voltages points. As shown in Figure 3 (a), the system constructs from a thyristor equipped in series with a KOH-PC to control the flow of the induced voltage into the soil, as well as the KOH-PC unit connected in parallel with the controlled rectifier circuit. This system installs at each point on the highest pipeline's induced voltage. The function of the controlled rectifier circuit is to convert the induced voltage on the pipeline to DC voltage for injecting the pipeline again within the desired DC voltage with reducing grid energy consumption.

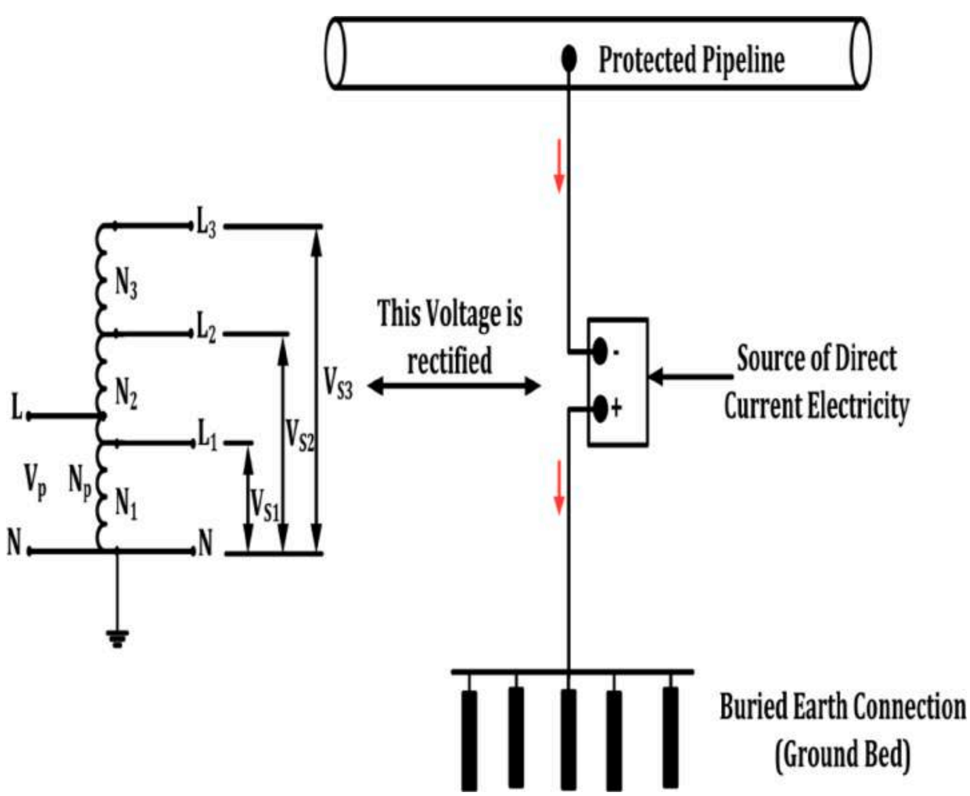

Figure 2. The construction of impressed current cathodic protection unit (ICCPU) system.

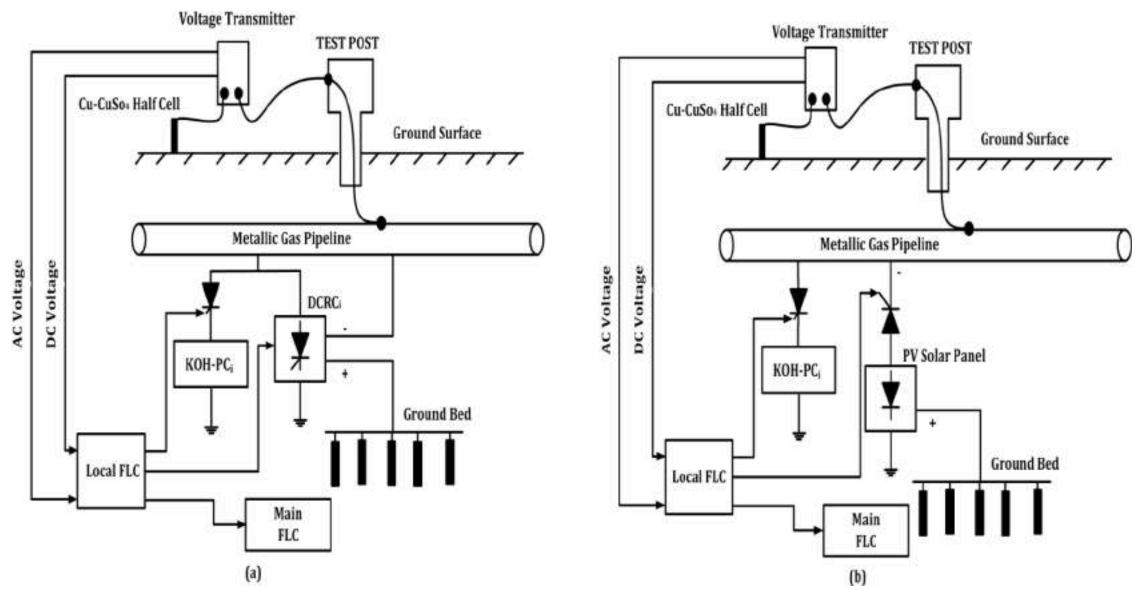

Figure 3. Detailed description of the proposed system layout in the case of (a) the UMIV, and (b) the PVS.

The negative terminal of a controlled rectifier circuit is linked to the pipeline's body, and the positive terminal is attached to the ground beds.

The suggested model structure is inserted into the pipeline and functions simultaneously to mitigate the generated voltage and compensate for the mitigation units' reduction in DC CP potential. The PV solar panel is employed instead of a regulated rectifier circuit, as shown in Figure 3 (b). The PV solar panel is employed as the distributed cathodic protection integrated system (DCPIS). The PV solar panel is linked in parallel with the KOH-PC unit. A thyristor is also used in series with a solar system to manage the DC voltage flow into the pipeline. A PV solar panel's negative terminal is connected to the pipeline's body, while the positive terminal is connected to the ground beds. Furthermore, each system has its controller, which regulates the amount of energy given and released. Each local controller should be able to manage the firing angle of the KOH- PC's primary switch as well as the impressed current injected. The fuzzy system provides a data control to the KOH-PCs' thyristor to lower the injection of polarisation cell on the pipeline when the AC voltage exceeds a threshold value (15 V). A digital voltmeter is located between the pipeline and the transportable Cu–$CuSO_4$ electrode, which is then delivered to the local FLC through a voltage transmitter for AC and DC measurements. Then, depending on the condition of DC voltage on the pipeline, each local FLC changes the firing angle for either the distributed controlled rectifier circuit or the PV solar panel. The status of DC voltage is then sent from each fuzzy controller to the main controller, which regulates the direct voltage on the pipeline. Furthermore, the main fuzzy controller must be able to handle all distributed fuzzy controllers, and the main fuzzy logic controller is used to accomplish total cathodic protection along pipelines by coordinating distributed and main ICCP stations. In addition, the main controller must be able to operate all distributed controllers and recalculate the new firing angles for the MICCPUs, KOH-PC switch, and DCPISs. The link between the different fuzzy controllers and the main fuzzy controller is shown in Figure 4.

3.1. Methodology

The flowchart of the suggested technique employed in this study is shown in Figure 5. This technique involves data collecting from pipelines and electrical lines, soil resistivity as well as both induced AC and DC voltages. Also, Figure 5 shows the procedures of the implementation strategy for improving cathodic protection performance along the gas pipeline by implementing DC compensation solutions.

The soil resistivity is measured after the data from pipes and transmission lines has been obtained. Along the pipeline, the induced AC and DC voltages are measured or calculated. This voltage is compared to the 15 V AC voltage limit and the -0.85 to -1.5 V DC voltage restriction. If both AC and DC voltages are within threshold limits, the control system will take no action. If both AC and DC voltages exceed the limit value at any time, several steps are recommended to bring these voltages back to the limit. In these procedures, the firing angle of the KOH-PC is lowered, indicating that the produced AC voltage is dissipated into the soil at a higher rate. On the other hand, the firing angle of the IMCP units is increased, either by exploiting the AC induced voltage or by using a PV system, which means that the distributed IMCP units, as well as the main impressed current stations (MICs), will be out of service until the CP potential and induced AC voltage reaches the desired limit. If the AC

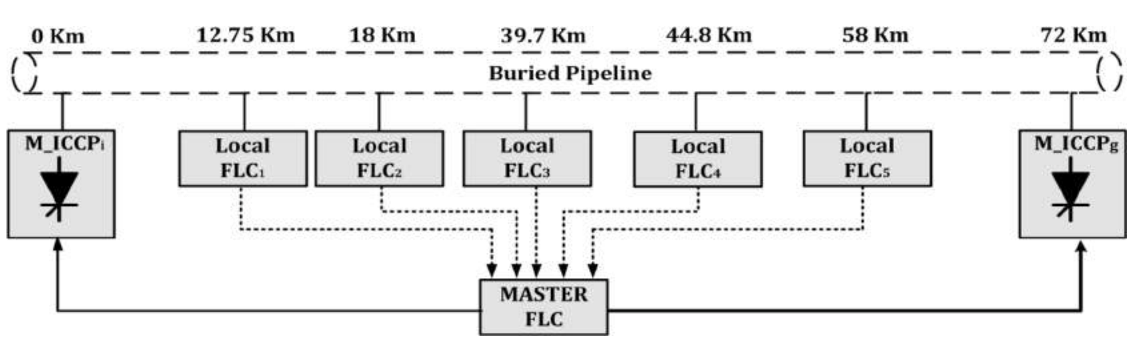

Figure 4. The suggested model's full characterization on the pipeline.

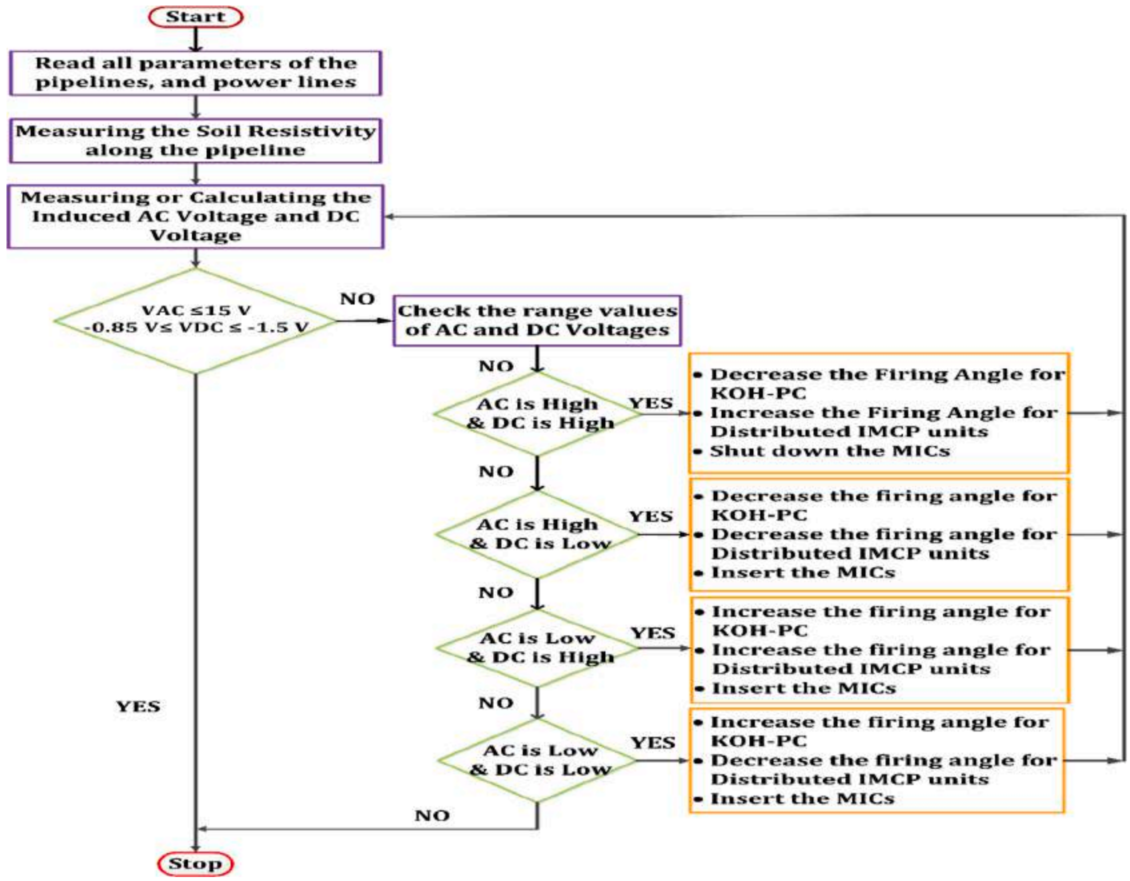

Figure 5. Flow chart for verifying the proposed strategies in recompensing the DC voltage.

voltage is higher than the threshold value and the DC voltages are lower than the limit value at any moment. A KOH-PC should be inserted to lower the induced voltage, and both distributed IMCP and MICs units should inject to raise the CP potential. If the AC voltage is less than the threshold value and the DC voltages are more than the limit value at any moment. In this case, there is no need to connect any KOH-PC at any point, and the injected current from both the distributed IMCP and the MICs units is minimized. Furthermore, no distributed impressed current unit needs to be connected. If the AC and DC voltages are less than the limit value at any moment, various measures to increase the DC voltage to the limit value are recommended. The firing angle of the KOH-PC in the UMIV method is increased to reduce the dissipation of the induced AC voltage to the soil and increase its usage in the rectification process. In addition, the firing angle of the controlled rectifier is reduced to increase the injected current on the pipeline. The firing angle of the thyristor will be reduced in the PVS technique to increase the injected current on the pipeline from the PV solar panel. Furthermore, reducing the firing angle of the central controller rectifier circuit increases the impressed current from the main ICCP.

3.2. Applying fuzzy logic system for an adaptive CP

In this study, fuzzy logic controller is applied to control either the discharging energy into the soil or the injected energy on the pipeline. Two performance criteria have been investigated to show the superiority of the fuzzy controller with different DC compensation methods. The first one demonstrates the total saved energy from the electric utility per year, while the second describes the total discharged energy to the soil per year. The fuzzy logic controller is used in this section to construct a relationship between AC and DC voltages under various scenarios and then take the appropriate action. In actuality, the AC and DC voltages vary over time, as well as these voltages are affected by the variation of the soil ingredients, operational temperature, and line currents. The fuzzy logic controller will develop to solve these difficulties. A fuzzy logic controller must create the relationship between the AC and DC voltages to establish the precise modifications in the pipeline's operating conditions. As a result, the membership functions play a significant role in determining the criticality of CP's performance. The two variables (AC and DC voltages) are inserted as the input of the local fuzzy system, as illustrated in Figure 6 (a). To improve the efficiency of cathodic protection performance, two-input and three-output local fuzzy logic systems have been created. As indicated in Figure 6 (b), the input variables are V_{AC} and V_{DC}, while the output variables are α_{KOH_i}, α_{CRC_i} or α_{TH_PVSPi}, and DC_{st}. In addition to the main fuzzy system, local fuzzy system is located at five places with the largest induced AC voltage. The main fuzzy system gets the DC voltage status at each point and performs the appropriate action to bring the dc voltage back to the target level. This is performed by raising or lowering the injected direct current from the main ICCP stations at the pipeline terminals. To compensate for the CP voltage along the pipeline, the fifth-input and one-output main fuzzy schemes are developed. The DC voltage state (DC_{st}) is the input parameter from each local fuzzy system. The firing angle is the output variable, and it is sent to a single-phase completely controlled rectifier circuit of the two main impressed current station. The master fuzzy controller is employed in this study to adapt the firing angle to the MICCPU station's-controlled rectifier input, which is represented by α_{MCRC_i}. The DC voltage state of each local fuzzy controller (DC_{st}) is the input parameter, and the fuzzy output is the firing angles to two MICCPUs (α_{MCRC_i}) at the pipeline terminals, as illustrated in Figure 6 (c). The details of twenty and forty-five rules are constructed for local and main fuzzy logic controllers, respectively, as illustrated in Tables 1 and 2. There are 243 linguistic rules in the rule base (3 DC status$_1$ × 3 DC

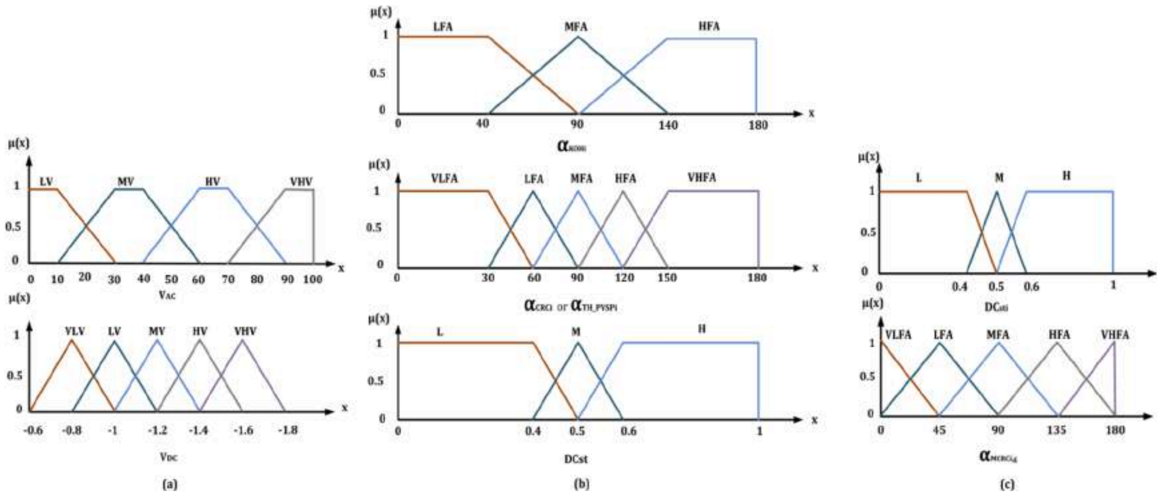

Figure 6. (a) Fuzzy sets for input variables; V_{AC}, and V_{DC},(b) Fuzzy sets for output parameters; α_{KOH}, α_{CRCi} or α_{TH_PVPSi}, and DC_{st}, and (c) The MF for main Fuzzy logic system.

Table 1
The local fuzzy system rules

No.	V_{AC}	V_{DC}	α_{KOH}	α_{CRC} or α_{TH_PVSP}	DC_{st}
1	LV	VLV	HFA	VLFA	L
2	LV	LV	MFA	LFA	M
3	LV	MV	LFA	MFA	H
4	LV	HV	LFA	HFA	H
5	LV	VHV	LFA	VHFA	H
6	MV	VLV	MFA	LFA	L
7	MV	LV	MFA	MFA	L
8	MV	MV	MFA	HFA	M
9	MV	HV	LFA	VHFA	H
10	MV	VHV	LFA	VHFA	H
11	HV	VLV	LFA	VLFA	L
12	HV	LV	LFA	LFA	M
13	HV	MV	LFA	MFA	H
14	HV	HV	LFA	HFA	H
15	HV	VHV	LFA	VHFA	H
16	VHV	VLV	LFA	VLFA	M
17	VHV	LV	LFA	LFA	M
18	VHV	MV	LFA	MFA	H
19	VHV	HV	LFA	HFA	H
20	VHV	VHV	LFA	VHFA	H

Table 2
The main fuzzy system rules

Rule No.	DC_{st1}	DC_{st2}	DC_{st3}	DC_{st4}	DC_{st5}	α_{MCRCi}
1	L	L	LMH	LM	LMH	VHFA
2	L	L	LMH	H	LMH	HFA
3	L	MH	LMH	LM	LMH	VHFA
4	L	MH	LMH	H	LMH	HFA
5	M	L	LM	L	LMH	VHFA
6	M	L	LM	MH	LMH	HFA
7	M	L	LM	MH	MH	VHFA
.	…	…	…	…	…	…
41	H	MH	L	MH	MH	LFA
42	H	MH	MH	L	L	LFA
43	H	MH	MH	L	MH	MFA
44	H	MH	MH	MH	L	VLFA
45	H	MH	MH	MH	MH	LFA

$status_2 \times 3$ DC $status_3 \times 3$ DC $status_4 \times 3$ DC $status_5$). These rules can be simplified to acceptable rules for computing simplicity. The alternation of the input fuzzy collections decreases the number of rules significantly, especially in rule bases with a large number of input variables, allowing the output to be specified regardless of the value of the input variable. There are 45 rules in all that illustrate the relationship between D_{st}, and α_{MCRC_i}. Finally, the lingual variable LM, MH, LMH of an input variable in a rule denotes that the input variable has no value; the output is specified regardless of the input variable's value.

4. System description

The case study is applied to gas buried pipeline located in Fayum-Egypt. The actual project is the Fayum, where three transmission lines are erected in parallel with or passing through the natural gas underground pipeline feeding the Fayum area via a 72-kilometer steel pipeline, as illustrated in Figure 7. This figure also shows the variation in soil resistivity over the pipeline's length.

4.1. Characteristics of the pipeline understudy

Fayum natural gas pipeline has an inner diameter of 16 inches (0.4064 m). High-density polyethylene (HDPE) with a resistance of $10^6/m^2$, a relative permittivity of 5, and a thickness of 4 mm is used to paint it. The International Standards of the Institution of Gas Engineers and Managers (IGEM) and the Egyptian Petrochemicals Holding Company Specifications for the pipeline transmission of the natural gas code prescribe a laying depth of the natural gas pipelines 1.5 m [39–40]. As shown in Figure 7, the resistivity of pipeline surrounding soil varies between 2500 Ω.m in some locations and 100 Ω.m in others along the pipeline route. The pipeline pathway runs parallel to or crosses the above-mentioned overhead transmission lines at various points. These distances range in size from 35 meters to several kilometers.

4.2. Characteristics of the transmission lines understudy

In Egypt, three high-voltage transmission power lines were constructed in parallel to or crossing natural gas buried pipeline supplying Fayum area. These lines are El-Kurimate–Cairo power line, Samaloute–Cairo power line and Dimo-6th of October power line. The 124-kilometer El-Kurimate-Cairo transmission line has a rated capacity of 575 MVA at 500 kV operational voltage. This line composes a single three-phase circuit with two earth lines, with three sub-conductors in each phase. Samaloute-Cairo is the second line, with a 1000 MVA rated capacity and a length of 209 km at 500 kV operational voltage. Furthermore, the Samaloute-Cairo tower is built similarly to the El-Kurimate-Cairo TL. The Dimo-6th October TL is the last power line, with a voltage of 220 kV and a length of 90 km. This line composes two circuits with one earth line, each circuit carrying 158 MVA rated power and two sub-conductors in each phase. Table 3 summarises the data from these

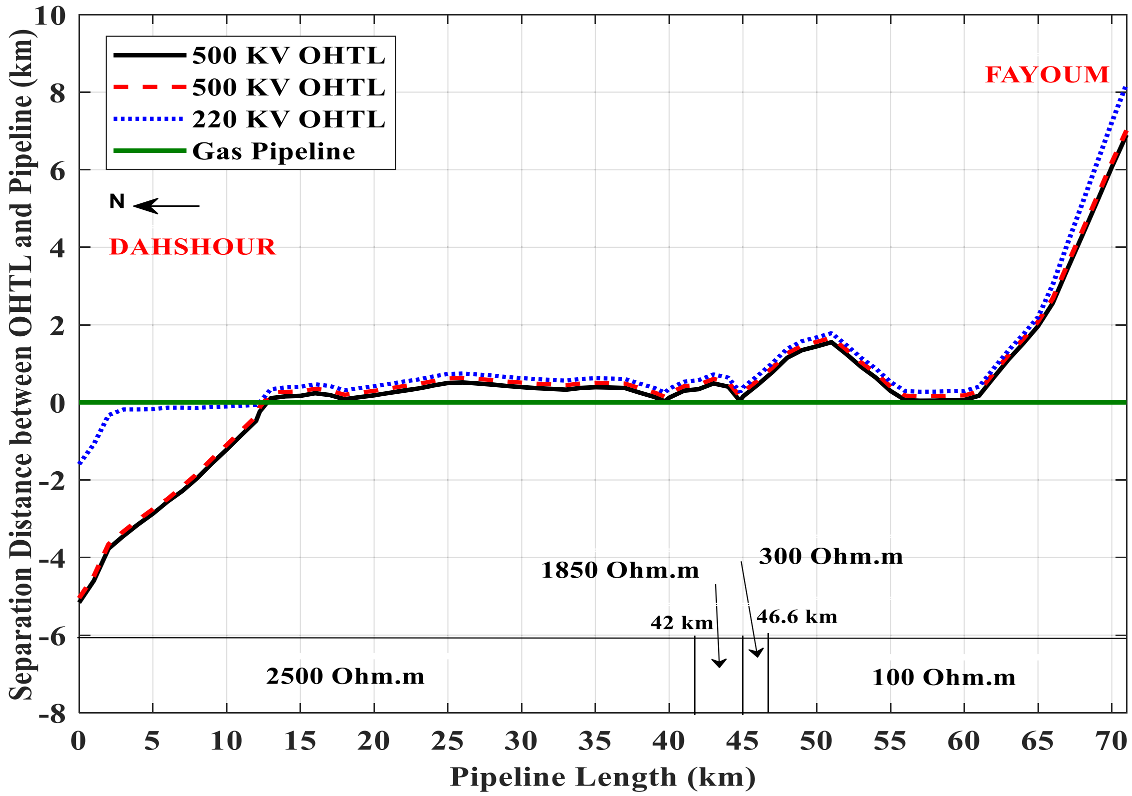

Figure 7. Pipeline-transmission line arrangement for Fayoum Gas Co.

Table 3
Detailed transmission line data utilized in the computation [19–20]

Items	Value		
Rated Capacity in (MVA)	575	1000	158/circuit
Operating Voltage in (kV)	500	500	220
Transmission lines length in (km)	124	209	90
No. of power circuits	1	1	2
No. of conductors per phase	3	3	2
Line diameter in (mm)	30.6	30.6	27
Separation distance between conductors in (cm)	47	47	30
Towers span in (m)	400	400	360
Line vertical height in (m)	19.1	19.1	15.7
No. of overhead earth lines	2	2	1
Earth line height in (m)	30	30	41.8
Earth line diameter in (mm)	11.2	11.2	13.6

three lines. The El-Kurimate-Cairo and Samaloute-Cairo transmission lines are shown in Figure 8 (a), as well as the Dimo-6th October transmission line are shown in Figure 8 (b). Using the Alternative Transient Program (ATP) platform to calculate the line current, simulation of power lines under normal operating conditions is carried out. Under normal conditions, the rated currents for the El-Kurimate-Cairo, Samaloute-Cairo, and Dimo-6th October TLs are 664 A, 1150 A, and 486 A, respectively.

4.3. PV panel specifications

In the simulation, we use the BP3270T from the BP solar company. The PV capacity has been allowed to vary from 10 kW to 300 kW. Table 4 also illustrates the PV Module specifications under standard test conditions (Irradiation = 1 kW/m, T=25°C and A.M = 1.5).

The pipeline is electrically modeled, in addition to the transmission line, polarization cell models, photovoltaic solar panel, and cathodic protection system. The overall equivalent electrical circuit is investigated in the MATLAB/Simulink platform. Therefore, different scenarios are simulated to study the induced voltage and DC CP performance along the pipeline. Firstly, to reduce the induced voltage to a safe limit, the effect of changing the KOH-PCs' parameters is introduced on both induced voltage and CP performance. Besides, the variation in the firing triggers of the main impressed current stations' rectifiers is introduced to know its effect on the DC voltage distribution. Secondly, different DC compensation strategies are utilized to compensate for the disturbance of cathodic protection. The first strategy is exploiting the induced voltage via converting it as DC form by using the controlled rectifier circuit and reapplying on the pipeline as a cathodic protection voltage. The second strategy involves a photovoltaic (PV) system, which integrates into the pipeline. Besides, this study introduces a comparative analysis of different DC compensation methods in the case of using various KOH-PCs' models with and without fuzzy controller on the DC voltage. This analysis is built based on the terms of saving energy from the utility and discharging energy into the soil per year to provide the guidelines for deciding which one of these models is more suitable for maintaining the DC cathodic protection voltage within safe limits.

4.4. Configuration of the system under study

Figure 9 depicts the sample study of a pipeline system comprising a controlled rectifier circuit that connects in parallel with the KOH-PC. In addition, thyristor is connected between the pipeline and the KOH-PC to manage the energy released into the soil. This system is installed at every point where the induced voltage of the pipeline is the maximum. Besides, each system has its controller, which regulates the amount of energy discharged. To improve cathodic protection efficacy, some of this energy is changed from alternating to direct form. At the same time, the remaining energy is directed into the ground via the earthing grid. The negative end of a controlled rectifier setup connects to the buried pipeline, while the positive terminal links to the soil beds, as indicated in Figure 9. To obtain accurate results, the KOH-PC is modeled based on the electrical circuit representation of all its parts. This cell mainly contains

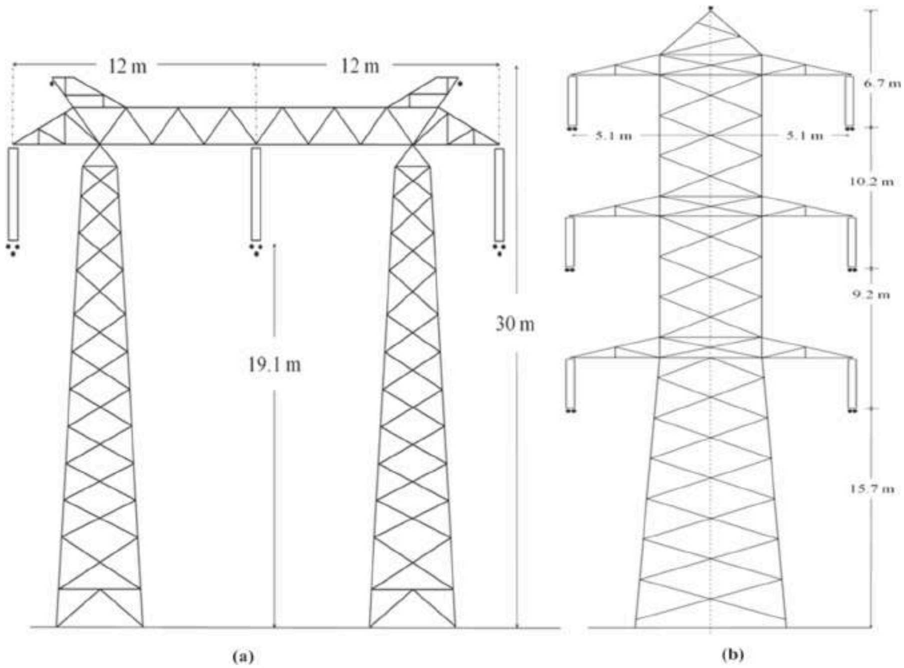

Figure 8. The overhead high-voltage transmission line towers.

Table 4
PV Module Specifications [41]

PV Model Specification	BP3270T
Manufacturer	BP solar
Maximum Power (P_{max})	280 W
Cell Type	polycrystalline
Cell Arrangement	72 cell (6×12)
Dimensions	1986×1000×50 mm
Open Circuit Voltage (V_{oc})	44.3 V
Optimum Operating Voltage (V_{max})	36.3 V
Short Circuit Current (I_{sc})	8.46 A
Optimum Operating Current(I_{max})	7.71 A
Module Efficiency Under STC	14.1 %
Power Tolerance	± 5 W
Nominal Voltage	24 V
Limiting Current	8.46 A
Nominal Operating Cell Temperature	47°C± 2°C
Temperature Coefficient Of I_{sc}	0105 % /°C
Temperature Coefficient Of V_{oc}	-0.360 % /°C
Temperature Coefficient Of P_{max}	-0.45 %/°C
Maximum System Voltage	600V/1000V

two terminals, each terminal has a group of stainless-steel plates. The upper terminal plates are connected to the pipeline and have the pipeline voltage. Besides, the lower terminal plates are connected to the earth and have approximately a zero voltage.

Finally, Figure 10 shows the equivalent circuit of the KOH-25 cells as illustrative example. Moreover, the function of this polarization cell is to dissipate severe induced AC voltages to ground. Therefore, this research looks into developing an integrated system to use the discharged energy to compensate for cathodic protection problems, with a portion of that energy being converted to DC and returned to the pipeline as a cathodic protection voltage. This research also guides determining which of these techniques is better for minimizing induced voltage and enhancing cathodic protection distribution during typical transmission line operating circumstances by comparing several KOH-PC models with different DC compensation methods. In this study, a fuzzy controller is used to control the discharged energy with KOH-PCs' models. Each local controller should be able to manage both the firing angle of the main KOH- PC's thyristor and the injected DC voltage level that is applied by the anodes to safeguard the pipeline. The induced AC and DC voltage are collected by each local controller. The main controller, which controls the main impressed current stations, receives the status of DC voltage from each local controller. In addition, the main controller must be able to operate all distributed local controllers and recalculate the new firing angles for the main impressed current stations, KOH-thyristor, PC's and distributed controlled rectifiers.

Figure 11 depicts the main impressed current cathodic protection system with manual and automated firing angle adjustments. The rectifier is the most common power source in ICCP systems. Electric power is converted from high-voltage alternating current (AC) to low-voltage direct current (DC) in this system. Rectifiers are frequently supplied with technology that allows them to alter the DC output voltage in tiny increments across a wide range. As a result, changing the duration of the gate pulse that fires the thyristor can change the waveform of the output dc voltage. When the firing angle delay is zero, the output voltage equals the average output voltage produced by an unregulated rectifier. It should also be noted that the dc voltage can be continuously modified by changing the time of the gate pulses. Furthermore, the output is blocked for one-third of each half-cycle since the gate pulse is delayed by one-third of a half-cycle. The positive terminal of the controlled rectifier is linked to an auxiliary anode positioned a short distance from the pipeline, while the negative terminal is connected to the pipeline body. Each anode is defined by a dependent source of current, which depends on the DC voltage output value. Each anode is connected in parallel, and the total current is the sum of the drawn current from each anode. In this study, there are two ICCP stations at both ends of the pipeline, where the AC input is rectified by the controlled rectifier circuit. On the other hand, the distributed cathodic protection integrated system uses either the induced voltage, which is converted to DC form using a controlled rectifier circuit and then applied to the pipeline as a cathodic protection voltage or a photovoltaic system, which does not require a connection to the utility grid to sustain the CP performance. Figure 12 depicts the second DC compensation technique, which incorporates a photovoltaic system on the pipeline.

As shown in Figure 12, the PV system and the KOH-PC unit are connected in parallel. The arrangement of the PV modules is (5 string in parallel and 2 modules in series) which can be fit in compensating the cathodic protection disturbances. A thyristor is installed between the pipeline and the KOH-PC to control the discharged energy into the soil

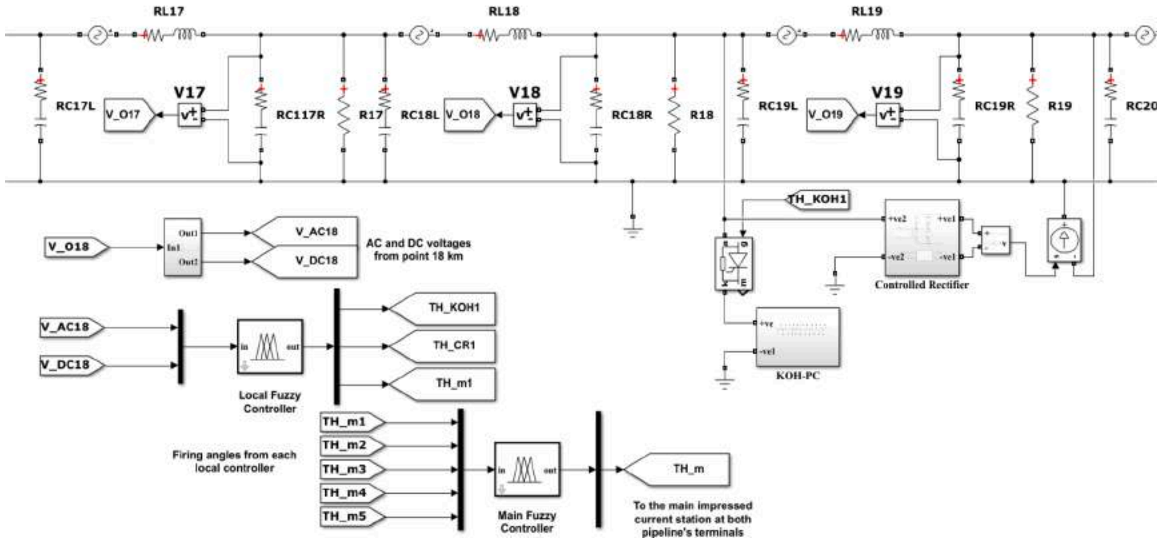

Figure 9. MATLAB simulation model of the system under study in the case of the UMIV at point 18 km.

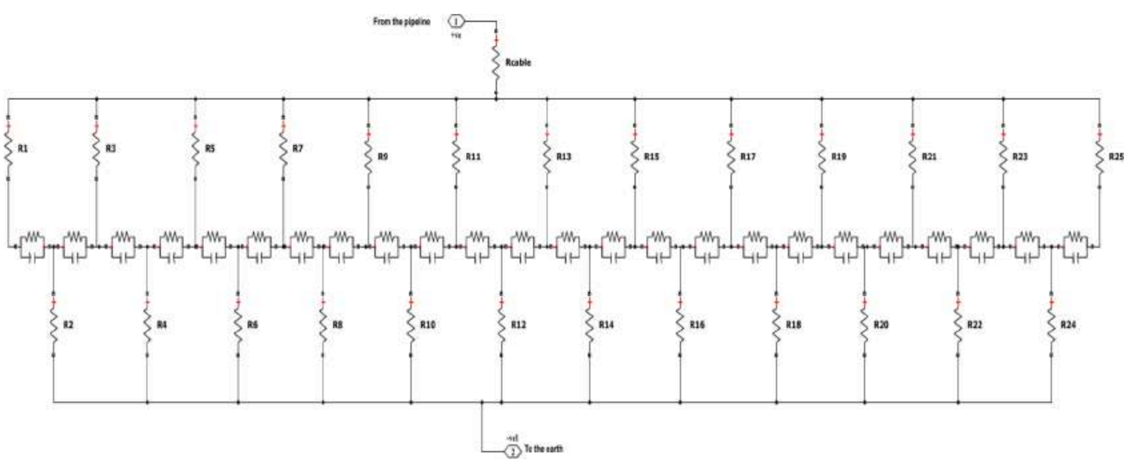

Figure 10. Simulation model of the KOH-PC under study.

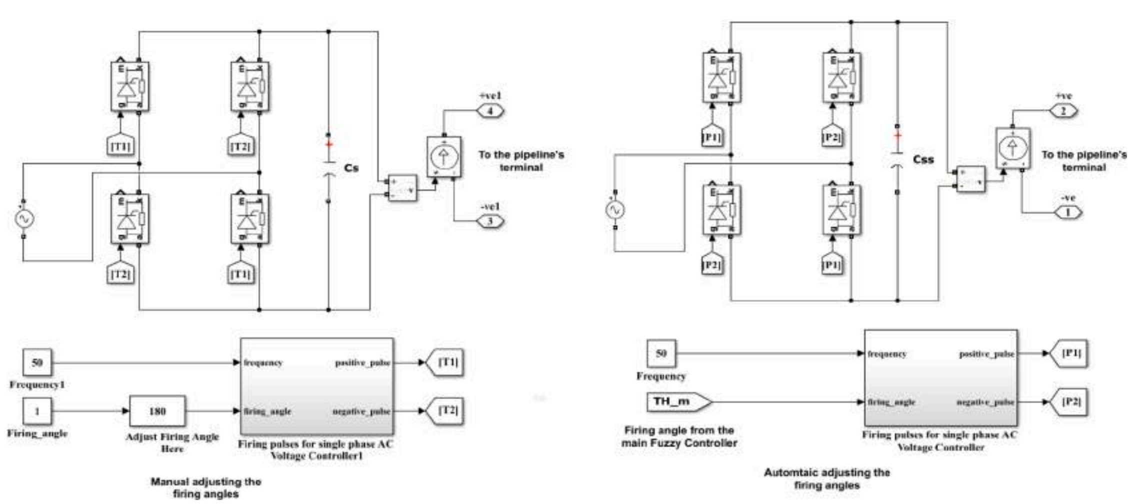

Figure 11. Schematic diagram of the main impressed current station with manual and automated firing angle adjustments.

until the AC voltage is less than a threshold value (15 V). A thyristor is also utilized in series with a solar system to regulate the DC voltage flow into the pipeline. The negative terminal of a PV solar panel is linked to the body of the pipeline, while the positive terminal is attached to the ground beds. Finally, this work also focuses on the superiorly of the DC compensation methods in managing the DC voltage along the pipeline to

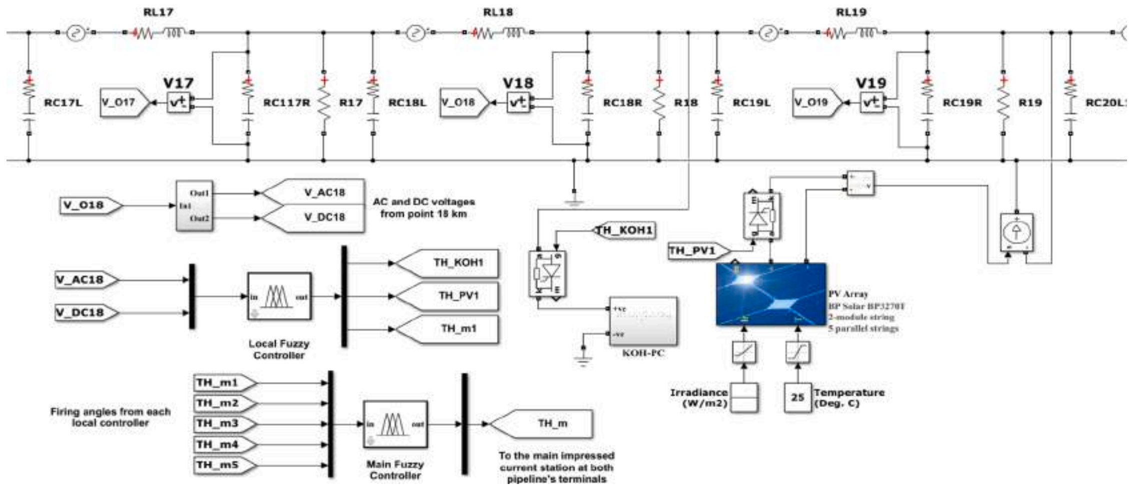

Figure 12. MATLAB simulation model of the system under study in the case of the PVS at point 18 km.

guarantee better CP performance under any disturbance in the impressed current stations. The main objective of this simulation is to select the most feasible system configurations. There are two strategies cases of DC compensation studied by the MATLAB/ Simulink platform.

Scenario 1: exploiting the induced voltage via converting it as DC form by using the controlled rectifier circuit and reapplying on the pipeline as a cathodic protection voltage without installing the disturbing external power supply.

Scenario 2: incorporating a PV system to compensate for the DC voltage disturbance issues along the pipeline to reduce the corrosion activity.

5. Results and discussion

To analyze the induced voltage generated on the pipeline by interfering TLs and the cathodic protection performance, the equivalent electrical circuit of the buried pipe is investigated on the MATLAB/ Simulink platform. The circuit's parameters are computed using MATLAB code, and the results are then handled using Simulink software. The induced AC and DC voltages may then calculate easily using the Simulink program's results at the end of each pipeline segment. A UMIV and PSPV are two DC compensation techniques for reducing DC voltage disturbances. As a result, main scenarios involving two primary DC

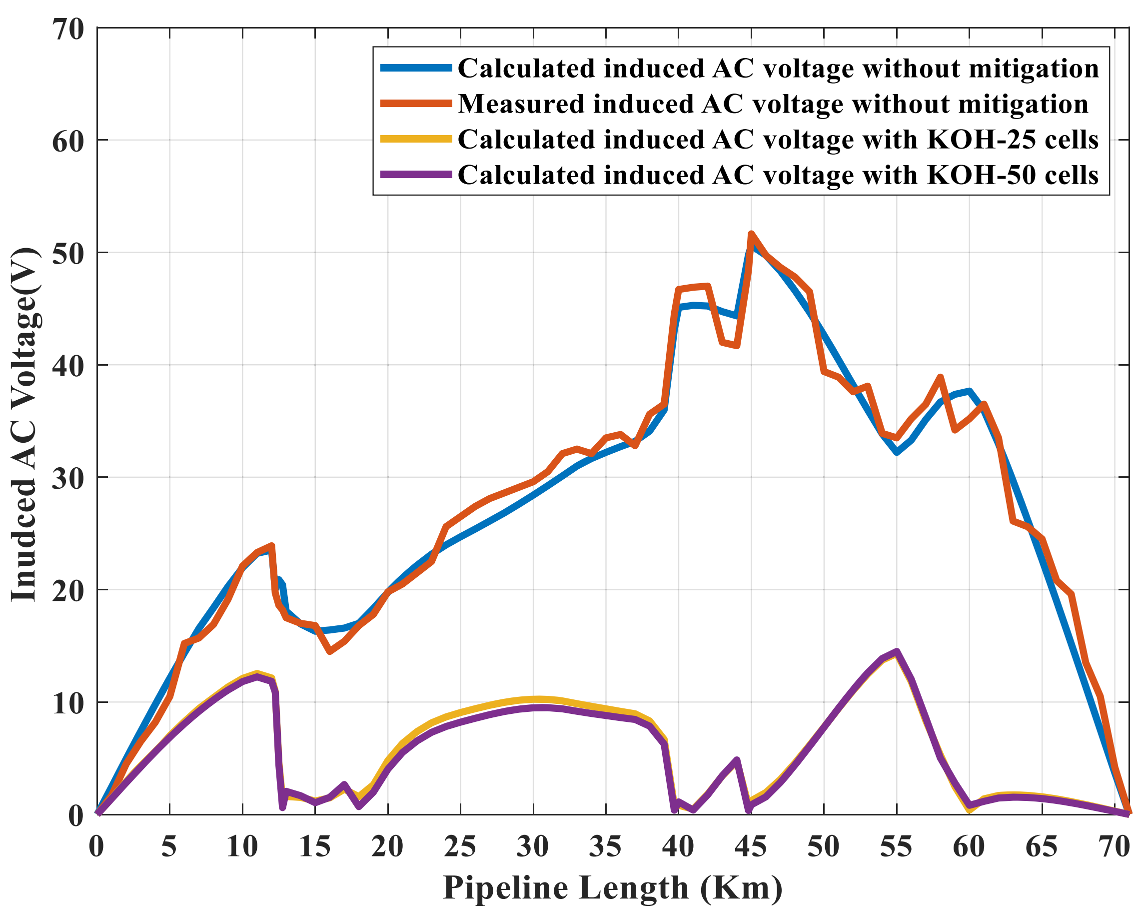

Figure 13. The calculated induced AC voltage before and after installing the different plates of KOH-PCs.

compensation approaches and various polarisation cells are simulated. The results demonstrate the impact of different DC compensation scenarios on the induced AC voltage and the cathodic protection performance. A fuzzy controller may use to accomplish two main goals. The first goal is to employ mitigated induced voltage, which involves converting a portion of the voltage to DC and reapplying it to the pipeline as a cathodic protection voltage. The second aim is the improvement of the DC cathodic protection disruptions via utilizing a photovoltaic solar panel as an alternative external DC source.

Figure 13 shows the measured and calculated induced voltage along the pipeline during normal operation, using Figure 1 to determine the voltage. The pipeline points have maximum induced voltage values at different locations. These are due to the pipeline and transmission line having the shortest separation gap. It can be seen in this figure that the induced voltage rises as the distance between the pipeline and the transmission line decreases. It is shown that the calculated voltage agrees well with the measured voltage at the field site. However, due to the difficulty of accurately evaluating transmission line operating conditions and the pipeline's surrounding environment, there are minor differences between them. Figure 13 also shows the predicted induced voltage on the pipeline after installing the various polarization cell types. These polarization cells are located at several sites along the pipeline, including 12.75, 18, 39.7, 44.8, and 58 kilometers from the pipeline's start, where the maximum induced voltage is produced. After installing the KOH-PCs, one can note the highest induced AC voltage along the pipeline does not exceed 15 V. (RMS). The highest produced voltage for the KOH-25 cells and KOH-50 cells is 14.32 V and 14.5 V, respectively. Furthermore, it is shown from this figure that the KOH-PCs models have the best performance in terms of reducing induced voltage.

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. The computed DC CP voltage along the pipeline is shown in Figure 14. Furthermore, the CP values have high values at the beginning and end of the pipeline, and then decrease to the lowest value in the center. The CP potential fluctuates between -1.5 and -1.445 V_{DC}, with a value of roughly -1.5 V_{DC} at the pipeline line terminals and -1.445 VDC in the center of the pipeline owing to the longest distance from the main ICCP stations. For steel pipes buried in the earth, the proposed effective cathodic protection potential varies from -0.85 V to -1.5 V_{DC}. This effective potential range can protect the pipeline from AC corrosion. The influence of various polarization cell types on the CP voltage distribution along the pipeline is also shown in Figure 14.

As shown in Figure 14, for KOH-50 cells and KOH-25 cells, the center pipeline DC voltage is -0.767 V and -1.374 V, respectively. As a result of the increased plate number in polarization cells, which produces an increase in the electrical paths to the soil, the KOH-50 cells have the lowest CP performance owing to the CP voltage being near to the minimum permitted limit of CP voltage (-0.85 V_{DC}) defined by the NACE standard. On the other hand, the KOH-25 cell lowers the CP voltage from -1.445 V to -1.375 V. In the case of KOH-25 cells, the drop in CP voltage is smaller than in the case of PC-50. The KOH-25 cells have a favorable impact on voltage dissipation, and it does not attract a lot of direct currents. It is noted that when the number of KOH-PC plates increases, the direct current drainage to the soil will steadily rise. As a result, in comparison to KOH-25 cells, the DC voltage in the case of KOH-50 cells is the most critical owing to the increase of the polarization cells' plate number, which produces an increase in the electrical routes to the soil.

Also, the effects of various firing angles of the main impressed current stations on the magnitude of the cathodic DC voltage along the length of the metallic gas pipeline are shown and discussed. Figure 15 shows how to change the triggered angles of a regulated rectifier and its effect on dc voltage cathodic protection. As a result, altering the time of

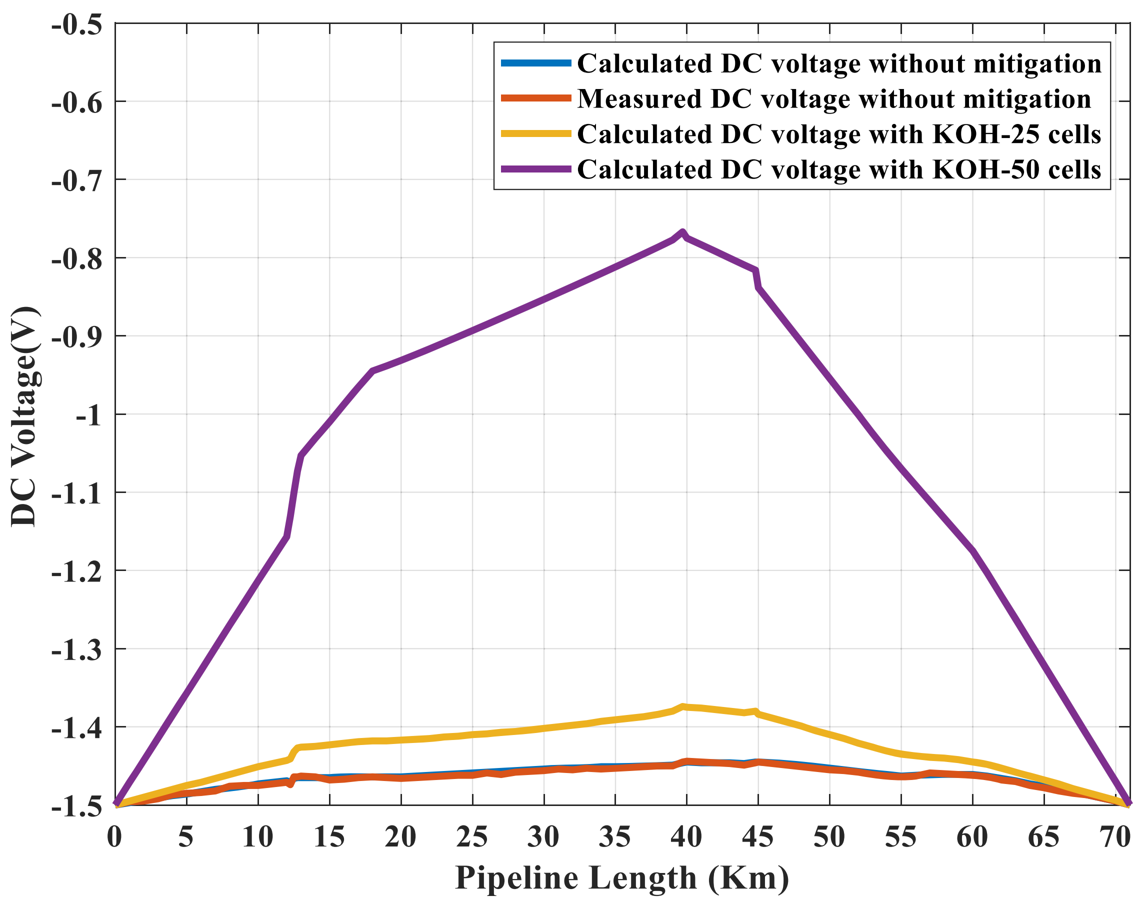

Figure 14. DC voltage cathodic protection before and after installing the different plates of KOH-PCs.

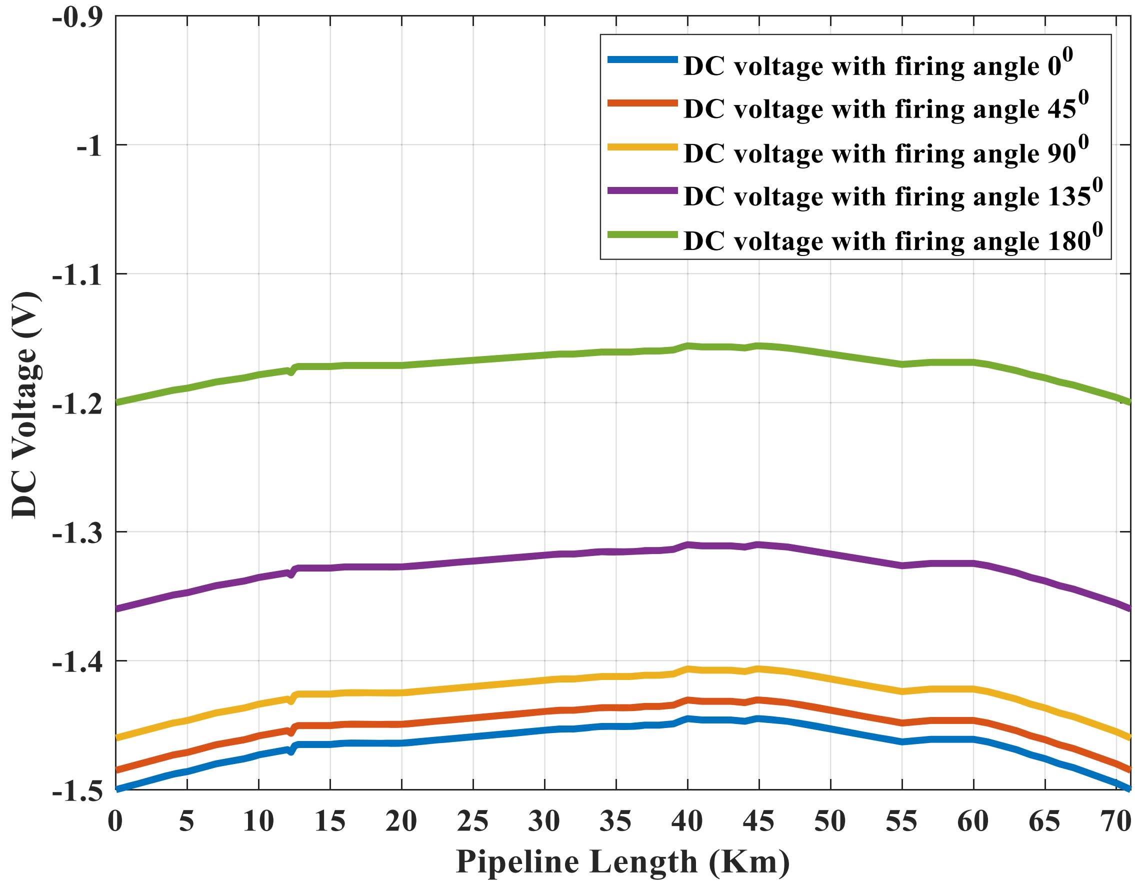

Figure 15. DC Voltage Cathodic Protection for different triggering angles before installing the KOH-PCs.

the gate pulse that fires the thyristor may vary the output dc voltage waveform. The output voltage equals the average output voltage produced from an unregulated rectifier when the firing angle delay is zero. Also, it is noted that by altering the time of the gate pulses, the dc voltage may be continually adjusted. Furthermore, because the gate pulse is delayed by one-third of a half-cycle, the output is blocked for one-third of each half-cycle. When the firing angle is reduced, the DC potential shifts to the negative. As a result, the higher the triggering angle, the higher the DC potential in a positive direction, which creates a dangerous condition for cathodic protection. The DC voltage at the pipeline line terminals also decreases as the triggered angle changes, from -1.5 V_{DC} to -1.02,-1.05, and -1.12 V_{DC} for 45^o, 90^o, 135^o, and 180^o, respectively. It is observed that when the firing angles of the main impressed current stations increase, the DC CP voltage rises. The DC voltage distribution is not influenced by changing the firing angles; it simply rises or decreases its values.

The sites of auxiliary distributed ICCP stations are chosen based on the predicted induced voltage. These locations are 12.75, 18, 39.7, 44.8, and 58 km, respectively. At these specified locations, the induced AC voltage becomes high, which causes the pipeline can be more susceptible to corrosion than at other points. Before installing the polarization cells, three scenarios are performed by modeling and simulating alternative injecting DC techniques for cathodic protection. The injecting DC variant of the layout in these figures offers the following scenarios:

1 Without five local auxiliary distributed ICCP stations
2 With five local distributed ICCP stations, which are based on the induced voltage along the pipeline as the source for its.
3 With five local distributed ICCP stations, which are based on the extracted power from an external power source (PV solar panels).

The main aim of this study is to increase CP performance along the pipeline as well as mitigate the induced AC voltage within a desirable limit. As a result, the grid power supply cannot be the sole source of impressed current system stations. Consequently, an alternate power supply is required. The induced AC voltage can use as a source of ICCP stations in this suggested model, whereas at the same time as a result of reducing the induced voltage. Besides, the use of PV solar panels as a source of cathodic protection is discussed. Figure 16 depicts the dc voltage distribution based on the various scenarios. Due to the abundance of DC sources throughout the pipeline, DC potential is moved negatively in the second and third scenarios, as depicted in this figure.

The DC voltage on the weakest DC voltage value that occurs in the middle of the pipeline will increase from -1.445 V to –1.564 V and –1.616 V in the second and third scenarios, respectively, as illustrated in Figure 16. The performance of the model employing induced voltage as a DC voltage source is superior to that of an external PV solar panel, as shown in this figure. However, the highest DC CP voltage levels disband their coatings throughout the pipeline. The effective value of DC potential recommended for totally cathodic protection of steel pipeline buried in the soil must be varied between -0.85 and -1.5 V, according to experiments. If the dc voltage is more than -1.5 volts, the pipeline enters an over-protection zone, which disbands the coatings. If the DC voltage is less than -0.85 volts, it enters the under-protection zone, resulting in corrosion. Furthermore, these scenarios do not manage the issue of hazardous induced voltage along the pipeline. However, using the induced voltage, where a portion of the voltage is converted to DC and reapplied on the pipeline as a cathodic protection voltage, is an efficient means of mitigating the induced voltage. Figure 17 shows the predicted induced voltage along the pipeline before the polarization cells are installed. From this figure, the highest induced voltage value is 19.58 V at point 23 kilometers along the pipeline. According to the NACE

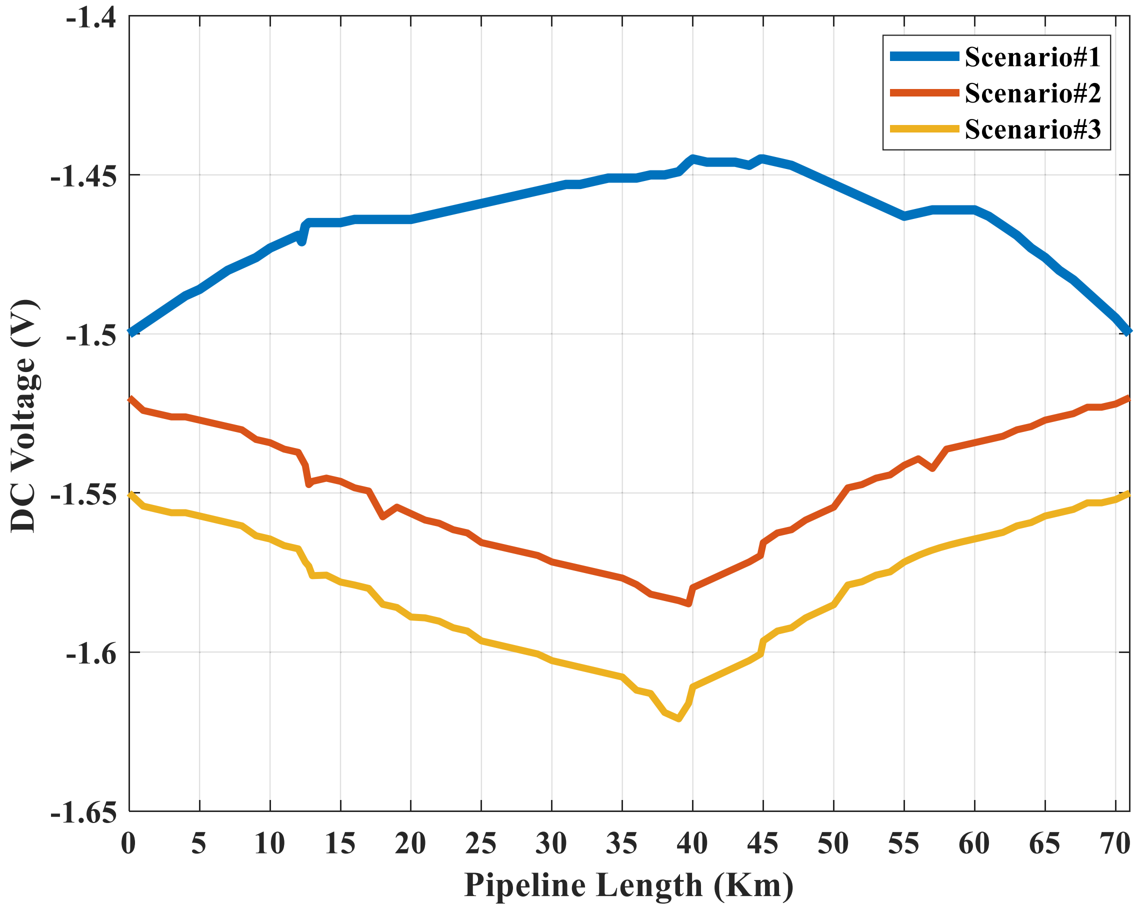

Figure 16. DC voltage cathodic protection for different scenarios.

standard, this value exceeds the permitted limit of 15 V (RMS). Because this generated voltage might endanger workers or hasten the corrosion of pipeline metal, the use of a mitigation unit becomes inevitable and necessary.

As seen in Figure 16, the DC voltage rises due to too many DC external sources throughout the pipeline. As a result, the maximum CP performance owing to the CP voltage exceeds the NACE standard's minimum allowable limit of CP voltage (-1.5 V_{DC}). The excessive DC CP voltage causes the coating disbandment. Limiting the DC CP voltage to acceptable limits is suggested from a pipeline safety point of view. Because the pipeline operator is usually aware of the DC voltage level on the pipeline, it's a good way to consider mitigation units while analyzing the risk of pipeline safety hazards. For two DC CP compensation techniques, four scenarios are implemented in this work by modeling and simulating different polarization cell models. The effect of polarization cells models vary with two DC compensation techniques for the layout in these figures includes the following scenarios:

1 Using the KOH-25 cells with the utilization of the dissipated induced voltage.
2 Using the KOH-50 cells with the utilization of the dissipated induced voltage.
3 Using the KOH-25 cells with the utilization of the PV Solar panel.
4 Using the KOH-50 cells with the utilization of the PV Solar panel.

Figure 18 illustrates the impact of several polarization cell types on the DC CP voltage distribution along the pipeline using two DC compensation strategies. In the case of KOH-25 cells at 39.7 km, the DC voltage improves from -1.374 V without DC compensation techniques to –1.406 V and -1.409 V when employing unwanted induced voltage and PV solar panels, respectively. Furthermore, In the case of KOH-50 cells at 39.7 km, the DC voltage improves from -0.767 V without DC compensation techniques to -0.870 V, and -0.923 V when utilizing UMIV and PVS, respectively. Furthermore, when the PVS is employed as an alternate DC source in KOH-25 cells, the DC voltage is enhanced by 2.55 % compared to 2.33 % when the UMIV is used. When the PVS is utilized as an alternate DC source for KOH-50 cells, the DC voltage improves by 20.34 %, compared to 13.43 % with the UMIV. This percentage implies that the amount of enhanced DC voltage based on the PVS is more than the induced voltage utilized. As a result, the problem of CP performance degradation is no longer an issue, especially with KOH-PC. As a result, the suggested system may provide the optimum DC voltage distribution, especially when using KOH-50 cells. The CP voltage readings along the pipeline will surpass the NACE standard's minimum permissible limit of CP voltage (-0.85 V_{DC}). Furthermore, the obtained results show that the use of induced voltage in compensating the DC voltage reduction gives a satisfactory result, which results in a highly efficient reduction in power energy extracted from ICCP stations and the elimination of the need for auxiliary distributed ICCP stations along the pipeline. To summarize, the provided energy from the primary ICCP units to the pipeline is around 30 MWh each year. Using KOH-25 cells and KOH-50 cells, the total discharged energy per year is 11.427 and 15.814 MWh, respectively. In the case of PV solar panels, the energy saved is larger than that achieved via induced voltage. In the instance of KOH-25, the saved energy is approximately 3.205 MWh when utilizing PV solar panels and 2.586 MWh when using induced voltage. Furthermore, the saved energy in the case of PV solar panels and employing induced voltage is around 1.568 MWh and 1.364 MWh, respectively, in the case of KOH-50 cells.

As a result, a fuzzy logic controller must be implemented to control the yearly saving energy and discharged energy. Therefore, the

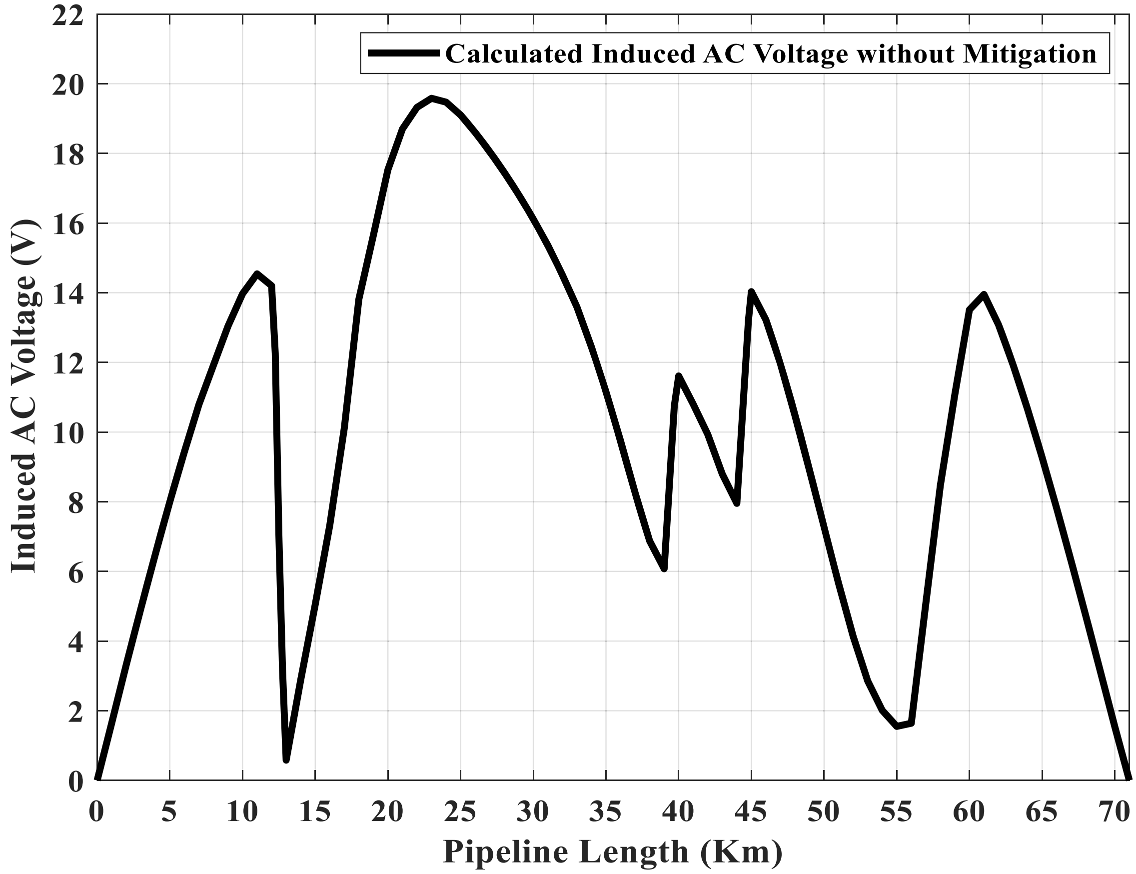

Figure 17. The calculated induced voltage along the pipeline without installing the polarization cells in the second scenario.

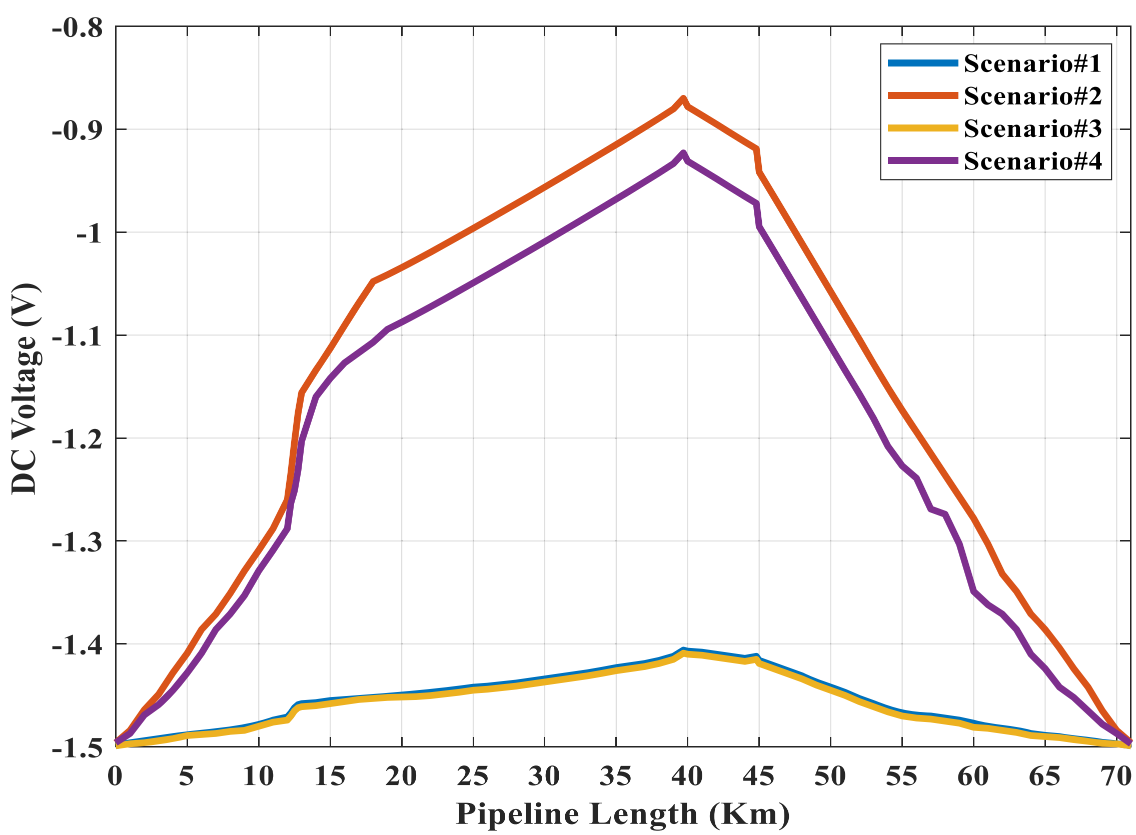

Figure 18. DC voltage cathodic protection for different scenarios without Fuzzy controller.

suggested model relies on two DC compensation methods; using the dissipated induced voltage into the soil and utilizing an external PV solar panel to ensure adequate CP performance. This suggested approach can reduce the energy consumption from the main ICCP at both pipeline terminals. Figure 19 shows the induced AC voltage utilizing various DC compensation methods with different polarization cell types, including KOH-25 cells and KOH-50 cells with a fuzzy controller.

As shown in Figure 19, the mitigated voltage with a fuzzy controller in the possibility of utilizing the undesirable induced voltage is more than that in the case of the PV solar panel, as shown in this figure. When the mitigated induced voltage and the PV solar panel are used with the KOH-25 cells, the predicted mitigated AC voltage values are 11.95 and 13.03 V at point 54 km, respectively, compared to 14.32 V without the controller. Furthermore, while using the mitigated induced voltage and the PV solar panel, the predicted mitigated AC voltage values for KOH-50 cells are 12.31 and 14.20 V at point 54 km, respectively, compared to 14.5 V without the controller. As a result, when comparing the FLC controller's performance with any polarization cell model in mitigating the induced voltage to the performance without a controller, one can conclude that the FLC controller's performance with any polarization cell model in mitigating the induced voltage is the proper option. On the other hand, Figure 20 depicts the variation of DC compensation methods with various polarization cell models and the fuzzy controller. As shown in Figure 20, the DC voltage in the case of KOH-25 cells will enhance from -1.374 V without a controller to -1.413 V and -1.418 V at the pipeline's weakest point (39.7 km) via using the induced voltage and PV solar panels, respectively. Using the induced voltage and a PV solar panel, the DC voltage in the case of KOH-50 cells will enhance from -0.767 V without a controller to -0.9641 V and -0.9961 V, respectively. Based on the obtained results, the amount of compensated DC voltage in the PV solar panel is higher than that in the other DC compensation technique. As a result, the polarization cell's negative influence on the DC distribution is eliminated. Moreover, the induced voltage mitigation and DC voltage improvement processes may coordinate without using an auxiliary DC source. Therefore, the DC voltage reduction compensation obtained from utilizing all DC compensation techniques with various polarization cell types is superior to that obtained using only mitigation units. As a result, the AC interference problem caused by the mitigation unit's influence on CP performance is reduced, and overall DC cathodic protection along the pipeline is enhanced. Finally, the results of the first suggested model, the usage of undesirable induced voltage, show that the FLC controller performs the best in fulfilling two goals: the first is to minimize induced voltage, and the second is to enhance DC potential.

Tables 5 and 6 show the induced AC and DC voltages calculations, respectively, using various DC compensation techniques. Table 5 shows that in the case of the UMIV, the suggested FLC controller with KOH-25 cells may reduce the induced voltage from 49.79 V to 1.544 V at the highest induced voltage point (44.8 km). Furthermore, the PVS's reduced induced voltage at point (44.8 km) is 1.683 V. On the other hand, the mitigated induced voltage achieved by the FLC controller with KOH-50 cells is higher than that obtained by the FLC controller with UMIV, i.e. ($V_{FLC\_KOH\text{-}25\text{-}cells}$ =1.544 V and $V_{FLC\_ KOH\text{-}50\text{-}cells}$ =0.944V). Furthermore, the mitigated induced voltage achieved by the FLC controller with KOH-50 cells is higher than that obtained by the FLC controller with PSPV, i.e. ($V_{FLC\_ KOH\text{-}25\text{-}cells}$ =1.683 V and $V_{FLC\_ KOH\text{-}50\text{-}cells}$

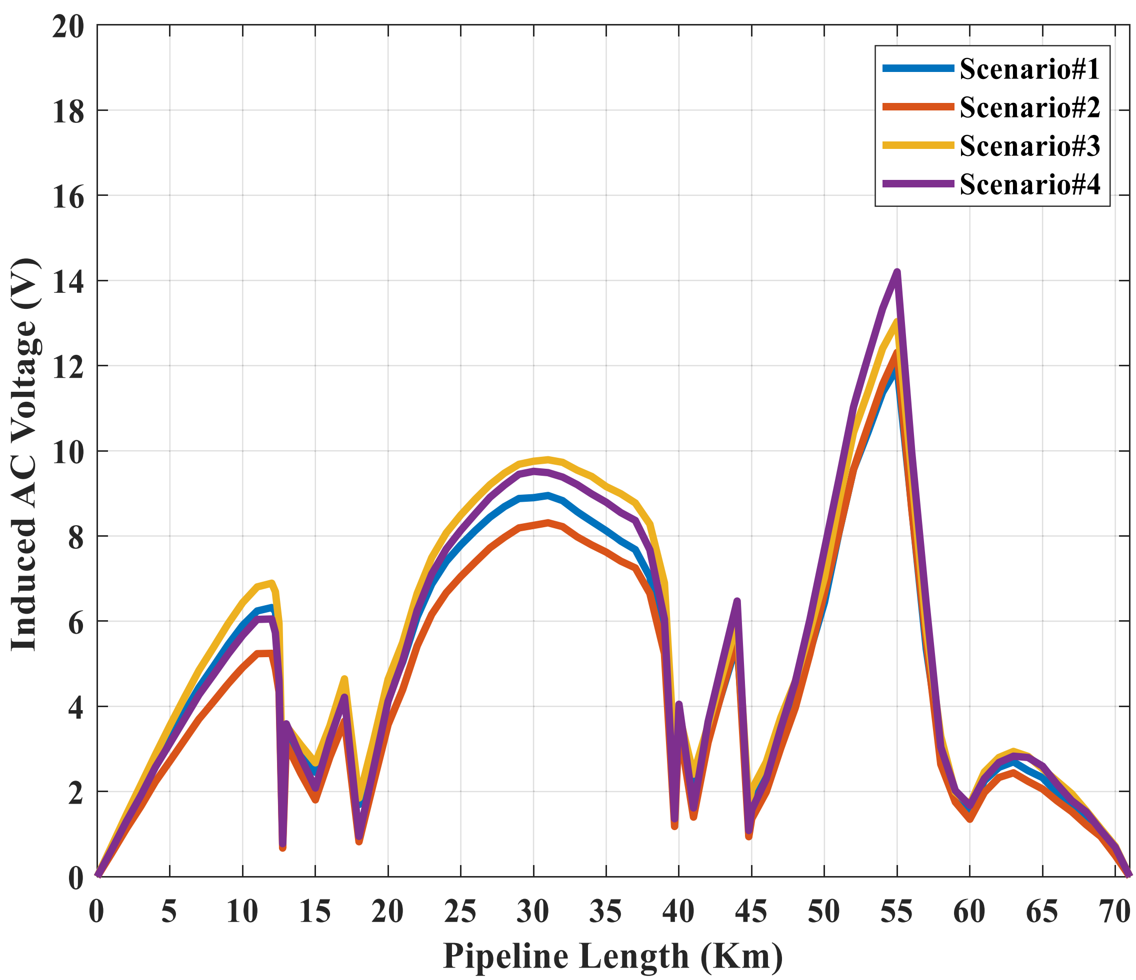

Figure 19. Mitigated induced voltage cathodic protection for different scenarios with Fuzzy controller.

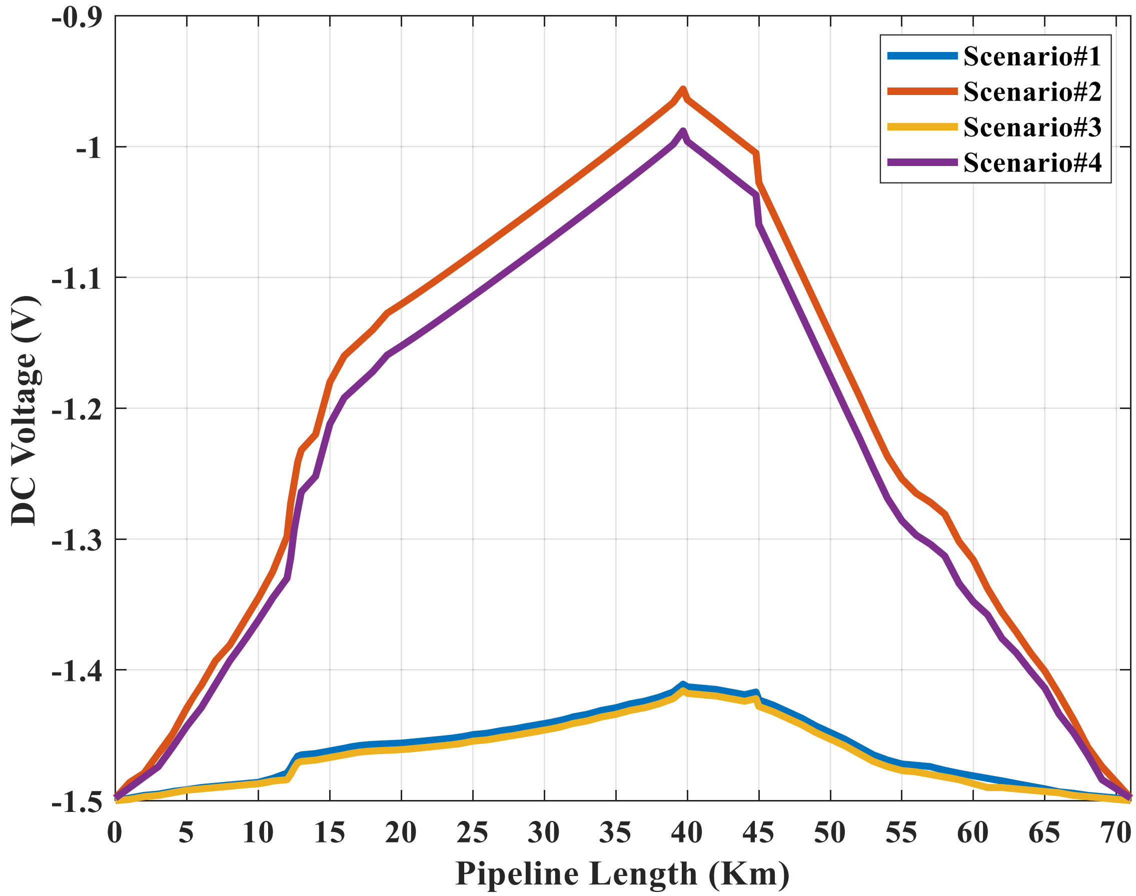

Figure 20. DC voltage cathodic protection for different scenarios with Fuzzy controller.

Table 5
Induced AC voltage calculations with different DC compensation methods

Point (km)	Without Mitigation	Without DC compensation methods		UMIV				PVS			
		KOH-25 cells Without Controller	KOH-50 cells Without Controller	KOH-25 cells Without controller	FLC	KOH-50 cells Without controller	FLC	KOH-25 cells Without controller	FLC	KOH-50 cells Without controller	FLC
12.75	20.43	1.353	0.611	1.353	1.761	0.611	0.793	1.353	1.920	0.611	0.914
18.00	17.1	1.582	0.6992	1.582	1.695	0.6992	0.965	1.582	1.848	0.6992	1.112
39.70	43.12	0.810	0.379	0.810	2.54	0.379	1.178	0.810	2.769	0.379	1.362
44.80	49.79	0.803	0.353	0.803	1.544	0.353	0.944	0.803	1.683	0.353	1.084
58.00	36.69	5.293	5.029	5.293	3.027	5.029	2.641	5.293	3.301	5.029	3.045

Table 6
DC voltage calculations with different DC compensation methods

Point (km)	Without DC compensation methods		UMIV				PVS			
	KOH-25 cells Without Controller	KOH-50 cells Without Controller	KOH-25 cells Without Controller	FLC	KOH-50 cells Without Controller	FLC	KOH-25 cells Without Controller	FLC	KOH-50 cells Without Controller	FLC
12.75	-1.427	-1.073	-1.459	-1.465	-1.176	-1.241	-1.462	-1.471	-1.231	-1.264
18.00	-1.418	-0.945	-1.452	-1.458	-1.048	-1.142	-1.453	-1.462	-1.107	-1.172
39.70	-1.374	-0.767	-1.406	-1.411	-0.872	-0.956	-1.409	-1.418	-0.923	-0.996
44.80	-1.382	-0.816	-1.416	-1.421	-0.942	-1.005	-1.419	-1.428	-0.995	-1.059
58.00	-1.443	-1.133	-1.472	-1.477	-1.257	-1.281	-1.477	-1.482	-1.303	-1.313

=1.084V).

As shown in Table 6, in the case of KOH-25 cells, the DC voltage will improve from -1.374 V without a controller at the weakest point (39.7 km) to -1.406 V and -1.411 V with an induced voltage DC source in the absence and presence of the fuzzy controller, respectively. In the case of KOH-50 cells, the DC voltage will enhance from –0.767 V without a controller at the weakest point (39.7 km) to -0.872 V and -0.956 V without and with the fuzzy controller, respectively. When the induced voltage utilizes as an alternative DC power supply without an FLC controller with KOH-25 cells and KOH-50 cells, the DC voltage is enhanced by 2.33 % and 13.68 %, respectively. When the induced voltage utilizes as an alternative DC power source with FLC controllers using the KOH-25 cells and KOH-50 cells, the DC voltage is enhanced by 2.69 % and 24.64 %, respectively. This percentage indicates that the fuzzy controller improves DC voltage more than that without a controller. As a result of the mitigation unit's installation, the problem of CP performance deterioration is no longer a concern. As indicated in Table 6, using the KOH-25 cells, the DC voltage will be increased from -1.374 V without a controller at the weakest point along the pipeline (39.7 km) to -1.409 V and -1.418 V with a PV solar panel in the case of without and with FLC controller, respectively. In the case of KOH-50 cells, the DC voltage will be enhanced from –0.767 V without a controller at the weakest point along the pipeline (39.7 km) to -0.923 V and -0.996 V with a PV solar panel in the absence and presence of an FLC controller, respectively. When the PV solar panel is utilized as an alternative DC power supply without an FLC controller with KOH-25 cells and KOH-50 cells, the DC voltage is enhanced by 2.55 % and 20.34 %, respectively. When the PV solar panel is utilized as an alternative DC power source with FLC controllers with KOH-25 cells and KOH-50 cells, the DC voltage is enhanced by 3.20 % and 29.86 %, respectively. In the case of PVS with the fuzzy controller, this percentage demonstrates that the enhanced DC voltage is more than that in the case of UMIV with the fuzzy controller. Furthermore, it is found that combining the UMIV with various polarization cell models yields promising results in the compensation of the DC CP potential. In comparison to PV solar panels, one can see that using harmful induced voltage as a DC source for enhancing DC voltage distribution is the most cost-effective alternative. Moreover, it is necessary to install panels along the pipeline in the PV solar panel configuration. Furthermore, the locations of the auxiliary distributed ICCP are independent of the induced voltage values generated throughout the pipeline.

To sum up, using different polarization cell models, the suggested model with the FLC controller can successfully sustain the cathodic protection disturbance. On the other hand, the suggested FLC controller can precisely manage the amount of DC voltage injected from either the induced voltage rectification process or the PV solar panel. As previously stated, the major goal of the proposed model is to improve cathodic protection performance. This aim is achieved by either employing mitigated induced voltage or an external PV solar panel to reduce DC voltage disturbances caused by the mitigation device. Generally, a fuzzy controller can successfully manage the prevailing DC voltage on the pipeline. In addition, the FLC controller with KOH-50 cells provides optimistic results in improving the DC voltage compared to that without a controller. Finally, the suggested model can implement, where it either allows the dissipated generated voltage into the ground or injects it back into the distributed controlled rectifier circuit. At the same time, the suggested model can regulate the amount of direct current injected into the pipeline from the PV solar panel. As a result, the suggested model is robustly effective in improving the DC CP distribution when there is a DC voltage disturbance. Furthermore, in the event of a planned or forced outage of main impressed current stations, this proposed model can sustain DC deterioration.

Table 7 shows the comparison between two main DC compensation methods in terms of energy-saving and energy discharging per year to demonstrate the efficacy of the proposed approach. The annual energy supplied to the pipeline from the major impressed current units is around 30 MWh. With KOH-25 cells and KOH-50 cells, the total discharged energy per year is 11.427 MWh and 15.814 MWh, respectively. In the case of KOH-25 cells, the PVS with fuzzy controller provides acceptable results in terms of energy-saving, where the saved energy is about 4.647 MWh compared to 4.212 MWh for the UMIV. Furthermore, with PVS and the UMIV, the saved energy for KOH-50 cells with FLC is around 3.923 MWh and 3.897 MWh, respectively. From the author's perspective, the obtained results show that the two main DC compensation systems offer an admiringly efficient in saving the extracted energy from the main impressed current stations. But, the UMIV improves overall CP performance without requiring the installation of an auxiliary DC source along the pipeline. In the case of FLC, the energy-saving is more than that obtained without a controller. Furthermore, the use of the UMIV to compensate for the reduction in DC voltage is reasonable. As a result, the AC interference problem and the mitigation unit's negative influence on the CP performance are no longer an issue.

As previously stated, the essential aim of the proposed model is to reduce the negative impact of AC interference on the cathodic protection efficacy. This aim is accomplished by using either the mitigated induced voltage or an external photovoltaic solar panel in enhancing the DC voltage disturbance. Finally, the obtained results demonstrate the effectiveness of the proposed control system in sustaining the reduction in cathodic protection owing to the installation of a polarization cell by removing the negative impact of mitigation units on cathodic protection. After examining the AC and DC voltage results, it is noted that all suggested DC compensation techniques reduce the overall degradation in the main impressed current system's efficiency during any interruption. In addition, as compared to different DC compensation systems, the UMIV allows very efficient use of discharged energy for compensating cathodic protection disturbances, where a portion of this energy is converted to DC and reapplied on the pipeline as a cathodic protection voltage. As a result, the UMIV provides a very efficient reduction in power drawn from the main impressed current stations at the termination of the pipeline without needing an additional distributed power source. A comparative performance assessment of the applied fuzzy controller is implemented to clarify the performance of the suggested model in achieving the improvement of DC potential. On the other hand, the suggested fuzzy controller enhances the DC CP potential reduction more than that obtained without it. Furthermore, the influence of polarization cell plate variation on DC voltage distribution is removed, and the effect of any interruption on CP devices is regulated. As a result, the controller is crucial in either using the high induced voltage along the pipeline in the rectification process or managing the injected current from the PV solar panel to optimize the CP performance, particularly with a mitigation unit.

Table 7
Annual saving energy (SE) and dissipating energy (DE) with different DC compensation methods

DC compensation methods	Controller	KOH-25 cells		KOH-50 cells	
		SE_{year}	DE_{year}	SE_{year}	DE_{year}
UMIV	Without	2.586 MWh	08.841 MWh	1.364 MWh	14.450 MWh
	With FLC	4.212 MWh	07.215 MWh	3.897 MWh	11.917 MWh
PVS	Without	3.205 MWh	08.222 MWh	1.568 MWh	14.246 MWh
	With FLC	4.647 MWh	06.780 MWh	3.923 MWh	11.891 MWh

6. Conclusion and extensions

This paper presents the design of an integrated system capable of sustaining the DC voltage disturbance. This is accomplished by employing either undesirable induced voltage or external solar systems that serve as a backup DC power supply. In addition, the suggested system strikes a compromise between high efficiency in reducing induced voltage and maintaining DC CP disturbance under all situations. To forecast precision CP performance before and after utilizing the fuzzy system, several designed scenarios of DC voltage compensation with different polarization cell models are employed. Furthermore, the suggested algorithm's effectiveness is assessed using two criteria: the total energy discharged from the pipeline to the soil per year and the total energy saved from the utility per year. This study addresses the cathodic protection disturbance problem by presenting a safe DC voltage compensation approach for increasing DC voltage within permitted limits while reducing energy consumption from both pipeline terminals' main impressed stations as well as optimizing discharged energy. In the case of different polarization cell types, a comparison of alternative DC compensation schemes without and with fuzzy controllers is shown in terms of total saved and discharged energy per year. The FLC controller is more efficient with the two DC compensation strategies than without the controller, according to the simulation results. In the case of KOH-25 cells, the PVS with fuzzy controller achieves satisfactory results in terms of energy savings, with 4.647 MWh saved against 4.212 MWh for the UMIV. Furthermore, for KOH-50 cells with FLC, the saved energy with PVS and the UMIV is approximately 3.923 MWh and 3.897 MWh, respectively. The obtained results, in the author's opinion, reveal that the two main DC compensation methods are astonishingly efficient in preserving the extracted energy from the main impressed current stations. By comparing UMIV to PVS, the efficacy of UMIV as a DC compensation tool is confirmed without the need for an external DC source to be installed along the pipeline. Furthermore, using a fuzzy system enhances the CP system's flexibility and provides a better alternative for cathodic protection while reducing AC interference. As a result, the results show that the fuzzy system's sensitivity to changes in pipeline operating conditions is significant and that the cathodic protection voltage may be adjusted continuously. As a result, the AC interference problem and the negative impact of the mitigation unit on CP performance are no longer a priority. Finally, the recommended techniques will be validated for their efficacy in improving the DC-CP voltage profile. In the future, it will be necessary to implement hybrid power systems with various controllers to save the energy extracted from the two main impressed current stations. In addition, more sophisticated controllers based on deep learning or reinforcement learning will develop. It will also be critical to enhance the polarization cell's performance by using an optimal metaheuristic to optimize the polarization cell's parameters. In addition, novel optimization algorithm topologies will develop to prevent AC corrosion. To coordinate among the impressed current units, modern communication systems such as 4-G or 5-G will use.

Author Statement

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

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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