Adaptive pulse impressed current cathodic protection using fuzzy logic control

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ABSTRACT

Corrosion in buried metal infrastructure poses significant economic and safety risks, requiring advancements over traditional impressed current cathodic protection (ICCP). This study presents an innovative pulse impressed current cathodic protection (PICCP) system integrating high-frequency pulse feeding with fuzzy logic control (FLC) for enhanced stability and energy efficiency. Utilizing an Arduino Uno and ESP8266 for real-time IoT monitoring via Blynk, the system was tested for 14 days in humus soil (10–20 kilo-ohm·cm, pH 5–6). Results demonstrate that PICCP consistently maintained off-potentials within the safe range of –1100 to –850 mV, whereas conventional ICCP failed by the eighth day, falling below –750 mV. The adaptive PICCP system, operating between 44–52 kHz, achieved a tenfold improvement in energy efficiency, requiring only 0.74–0.80 mA compared to 9–10 mA for ICCP. These findings validate the PICCP framework as a robust, scalable solution for embedded metallic infrastructures, effectively combining automated remote monitoring with adaptive electrochemical protection.

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1. INTRODUCTION

Corrosion is still the most dangerous and expensive reason why materials fail in energy infrastructure, transportation, and process facilities. NACE International's IMPACT study indicates that corrosion incurs global costs of approximately 2.5 trillion US dollars, or to almost 3.4% of the world's gross domestic product. This means that managing corrosion is not only a technical issue, but also a public safety and macroeconomic one [1]–[4]. Best practices emphasize proactive corrosion prevention to prevent pipe leaks, service disruptions, and environmentally damaging accidents from occurring upstream. In the context of cathodic protection, a widely used criterion for steel buried in soil is a protection potential of at least -850 millivolts against a copper sulfate reference electrode measured when the system is off, as this approach minimizes the influence of voltage drop (IR Drop) in the medium [1]–[6].

Various strategies have been implemented to reduce the corrosion rate, including organic and metallic coatings, the use of inhibitors, and cathodic protection with galvanic anodes and impressed current [7]–[9]. ISO 15589-1 standard positions cathodic protection as a systemic scheme that can be realized through galvanic anodes or impressed current, with strict measurement and monitoring governance of buried pipeline structures [4], [10]. Technical literature and industry practice indicate that forced current systems are superior when large protection currents are required, the structure's surface area is extensive, or the soil has high resistivity, because the current magnitude can be precisely controlled and the protection range can cover long pipe segments from a single current source. Nevertheless, the conventional direct current approach is prone to higher energy consumption and, if not well-controlled, can lead to the risk of overprotection of the coating or hydrogenation [11]–[15]. Recent findings on pulsed current mode indicate the potential for increased energy efficiency and better protection control compared to pure direct current, making it interesting to explore further.

Most field applications of forced current still rely on direct current injection with fixed settings or periodic manual adjustments, which often leads to a delayed system response to changes in soil environment. Two directions of reinforcement that are beginning to be reported are the addition of pulse signals to the current injection and the use of intelligent control to make the response adaptive [8], [16]–[21]. Recent reviews show that pulse currents in long-distance pipelines can reduce energy consumption while maintaining protection performance, while studies on fuzzy logic-based intelligent control have demonstrated the ability to maintain protection potential within the target range and reduce power consumption in forced current systems [3], [7], [22]–[25]. However, the integration of both on a soil experiment scale with frequency settings directly linked to the system's potential measurements being off is still rarely documented, necessitating studies that simultaneously summarize the control architecture, pulse frequency validation, and energy performance evaluation.

This study aims to evaluate the efficacy of a fuzzy logic-based pulse impressed current cathodic protection (PICCP) system in maintaining the off-potential of ferrous materials within a consistent protection range of -850 mV to -1100 mV. The evaluation is carried out over a 14-day comparative study against conventional ICCP systems in humus soil media. Additionally, this study also quantifies the increased energy efficiency (44 kHz-52 kHz) acquired from implementing adaptive pulse frequency modulation to achieve current density optimization while still maintaining similar levels of corrosion inhibition.

2. METHOD

Figure 1 is the research flow of the cathodic protection system, starting with the experimental preparation stage, which includes all initial requirements before testing is conducted. Next, environmental testing was conducted to ensure the soil conditions were within the appropriate range, specifically with soil resistivity between ten thousand and twenty thousand ohm-centimeters and soil pH between five and six. After that, system testing was conducted to ensure the error rate did not exceed five percent, so the data obtained remained accurate. If all conditions are met, the experiment is conducted for fourteen days with continuous observation. After collecting the data, it was processed and analyzed to get accurate results. The last step in this process is to look at the surface of the metal sample to see how the environment and the system affect the material being tested.

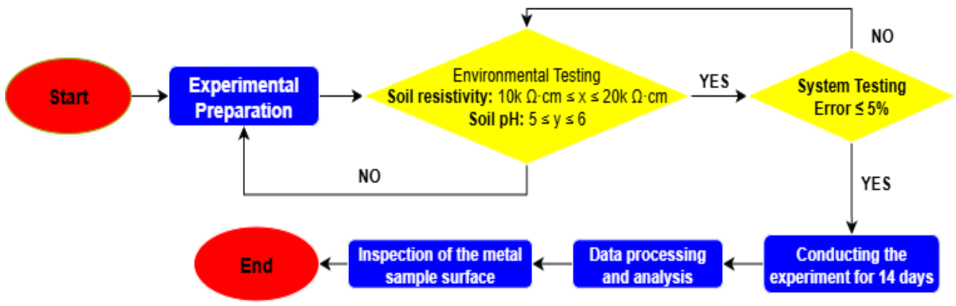


Figure 1. Research flow of the cathodic protection

2.1. Experiment preparation: material

The cathode samples used were mild steel strips measuring 30×1.5 cm. The initial surfaces were cleaned of paint residue by sanding until the metal appeared clean. The strip was then formed into a U shape for easy planting in the soil medium, with both ends left open as terminals to be connected to the negative pole of the ICCP system. On the flat side of the U shape, an open area measuring 2.5×1.5 cm was marked, and then this area, along with both terminal ends, was covered with masking tape. The entire remaining surface was coated with resin twice, with drying time between coats. The purpose of this coating is to limit the field of observation so that the effectiveness of the protection can be evaluated only on the exposed parts. Once the resin has fully hardened, the specimen is declared ready for use.

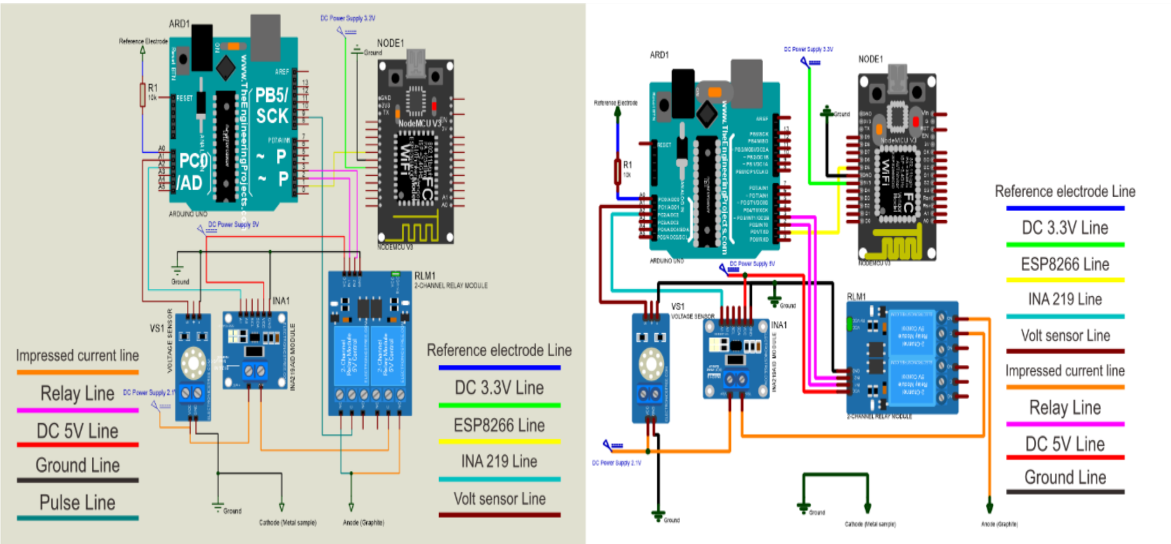
The anode employed is a graphite rod measuring 20 cm in length and 0.5 cm in diameter. Measurements were acquired utilizing a laboratory-constructed $Cu/CuSO_4$ reference electrode, fashioned from a recycled pen casing as the container and a wooden tip serving as the porous plug to facilitate ionic conduction. Copper and copper sulfate powder are placed in a container and moistened with distilled water to form a saturated solution, creating a stable potential reference for measuring the potential against the metal sample throughout the testing series.

2.2. Experiment preparation: soil

In the soil preparation, humus soil was placed in a 60×15×15 cm container as the test medium. Environmental conditions are first adjusted with soil resistivity in the range of 10 k-20 k Ω·cm and pH in the range of 5 to 6. After the initial values were achieved, the soil was allowed to acclimate naturally during the experiment to monitor the system's performance under varying conditions, especially rising resistivity, without additional intervention.

2.3. Experiment preparation: impressed current cathodic protection system

The circuit connection diagrams for the corrosion monitoring system are illustrated in Figure 2. Specifically, Figures 2(a) and (b) show the basic designs of both the PICCP and ICCP systems, respectively. Each system use an Arduino Uno as the primary controller to manage relays, measure corrosion potential using reference electrodes, and oversee voltage and current through sensors. Both systems send data to the ESP8266 IoT module, which then sends it to the Blynk server so that it can be monitored from afar. Each system's relay operates on a four-second cycle of direct current injection, succeeded by a one-second interval for measuring off potential. In the PICCP system, the Arduino executes a fuzzy logic algorithm and generates a pulsed current signal via the internal timer ICR1. This signal has an amplitude of five volts and a frequency of forty to sixty kilohertz. It is then stepped down to about two point one volts using a resistor network. A five-volt power supply powers the whole circuit, and during the four-second phase, about two point one volts are sent to the anode. The voltage sensor tells you how much voltage is being injected, and the INA219 sensor tells you how much current is flowing toward the anode as a load indicator.



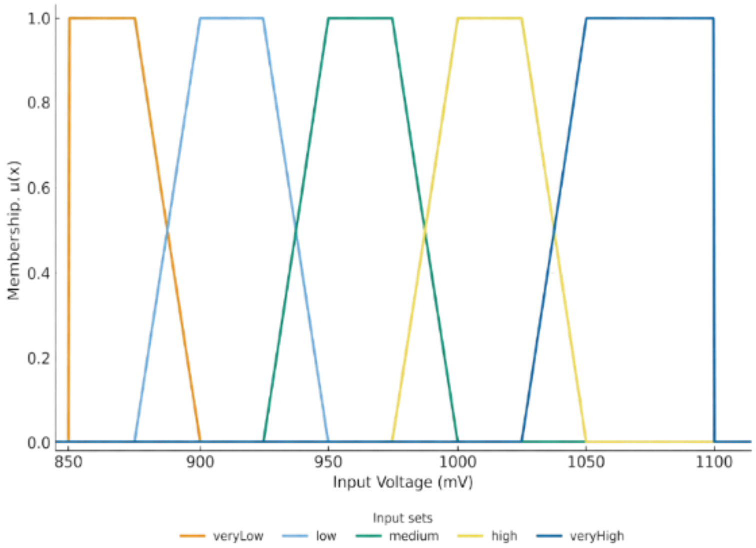
(a) (b)

Figure 2. Circuit connection diagrams of the corrosion monitoring system; (a) PICCP and (b) ICCP setup

2.4. Fuzzy logic programs and systems

The fuzzy membership functions for the PICCP system are presented in Figure 3. Figures 3(a) and (b) show the fuzzy logic configuration, which utilizes membership functions for the off-potential input and for the frequency output. In Figure 3(a), the off-potential is divided into five fuzzy sets within the range of 850 to 1100 millivolts according to reference [9], namely VL, L, M, H, and VH. In Figure 3(b), the frequency output is modified using the ICR1 setting, ranging from 260 to 400, and categorized into five bands from VHF to VLF. The relationship between input and output is established through fuzzy rule Table 1, for example, input VL produces frequency output VHF, while input VH produces

VLF. These rules form the basis for the system's decision to dynamically adjust the pulse current injection frequency based on the off-potential conditions.



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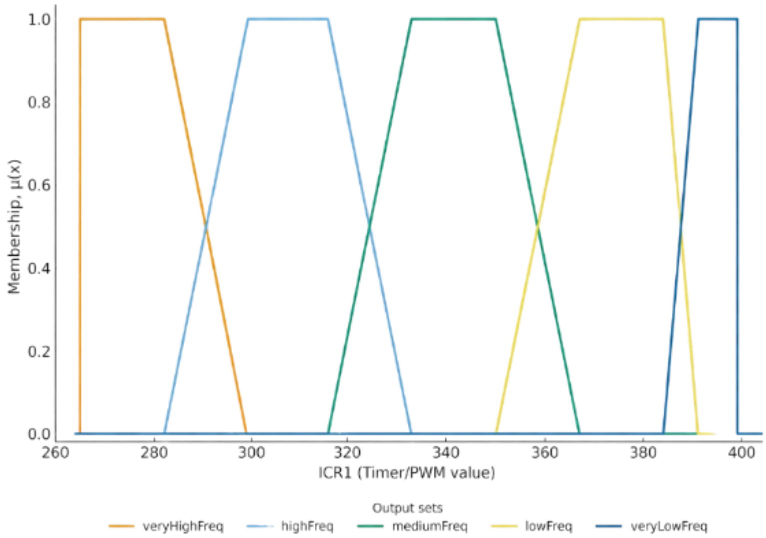


(b)

Figure 3. Fuzzy membership functions; (a) input sets and (b) output sets

Table 1. Correlation of fuzzy rule basis for transforming potential level (VL-VH) into frequency (VHF-VLF)

Membership function	Input	Output
1.	Very low (VL)	Very high frequency (VHF)
2.	Low (L)	High frequency (HF)
3.	Medium (M)	Medium frequency (MF)
4.	High (H)	Low frequency (LF)
5.	Very high (VH)	Very low frequency (VLF)

Figure 4 illustrates the fuzzy logic workflow in the PICCP system, which begins by measuring the open-circuit potential of the metal structure. To ensure the controller generates the correct hardware response, the system utilizes the mathematical relationship between the output frequency and register settings shown in Table 2, which maps frequencies from approximately 40 kHz to 60 kHz to specific ICR1 values ranging from 399 to 265.

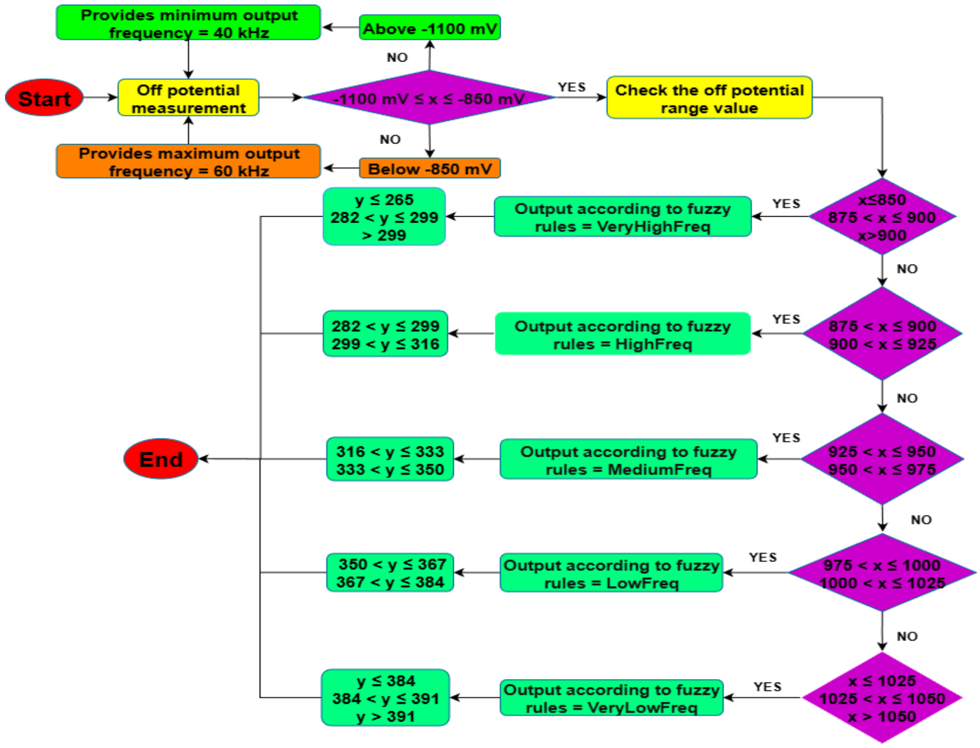


Figure 4. Flowchart of the fuzzy control system mapping input potentials to output frequencies

Table 2. The relationship between the ICR1 value and the frequency generated by the controller in the PICCP system

ICR1 value	Frequency (kHz)
265	60.4
282	56.7
299	53.5
316	50.6
333	48
350	45.7
367	43.6
384	41.7
391	41
399	40.1

During operation, the measured potential is compared to the $Cu/CuSO_4$ reference range of -1100 mV to -850 mV. If the value is outside these limits, the output frequency is immediately set to its minimum or maximum value. If the value is within the valid range, it is classified into five fuzzy categories: very low, low, medium, high, and very high. Each category has specific input limits; for example, values below -875 mV trigger a very high frequency, while values above -1025 mV trigger a very low frequency. The fuzzy rules then determine the precise output frequency, which, when cross-referenced with the ICR1 values in Table 2, allows the system to automatically adjust the current injection frequency so that metal protection remains optimal according to actual conditions.

2.5. Experiment preparation: setup

Test configuration of this study contains two schemes that are controlled by Arduino Uno as the central control unit, depicted in Figure 5. Figure 5(a) shows the setup of a typical impressed current cathodic protection (ICCP) system. A 20 cm long, 0.5 cm diameter graphite rod is employed as an anode, installed in the ground with one end exposed for cable connection. The anode is located 20 cm from the metal sample acting as a cathode. A reference electrode is positioned above the exposed site but does not contact the metal surface, allowing for local potential measurements. The notable technical differences in the depicted PICCP system in Figure 5(b). The PICCP scheme applies the pulse signal line and fuzzy logic-based control mechanism, which are not utilized in common systems. The Arduino Uno generates high-frequency pulses through internal programming on the ICR1 register for this configuration. By combining this register with a fuzzy logic controller, the system will adapt to changing the frequency of current injection. Conversely, the ICCP system presented in Figure 5(a) does not use either pulse modulation or fuzzy control and works continuously.

The experimental tests were conducted over a period of 14 days to evaluate the long-term performance of the protection systems. This testing duration was selected in accordance with the ASTM G97 standard [26], which provides an established procedure for laboratory evaluation of anode specimens in underground environments [27]–[29].

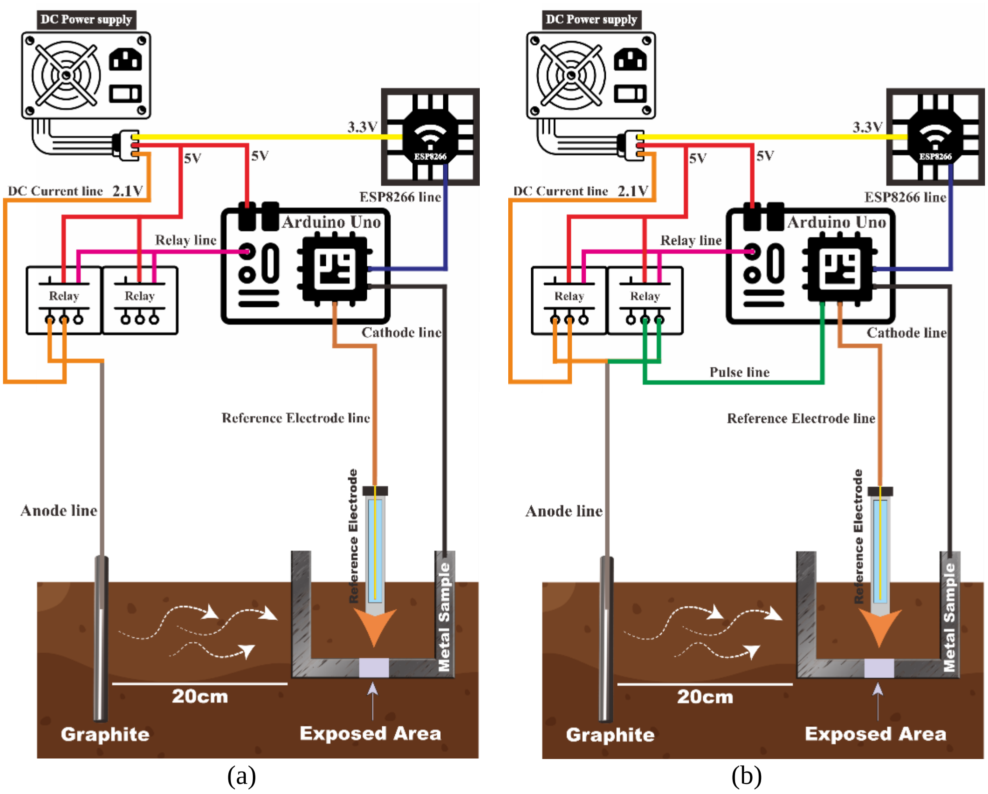


Figure 5. Experimental setup; (a) ICCP and (b) PICCP

2.6. System validation and accuracy testing

The system performance was validated using two primary sensors: a voltage sensor and a current sensor. Each sensor's accuracy was verified by comparing its readings with a calibrated digital multimeter to ensure the measured data corresponded closely to actual values. The accuracy of the fuzzy logic control was evaluated in two stages. The first stage verified the fuzzy algorithm embedded in the microcontroller by comparing the results of the fuzzification and defuzzification processes with outputs generated in MATLAB's Fuzzy Logic Designer. The second stage involved testing the defuzzified output pulse signal using an oscilloscope to confirm that both the frequency and amplitude conformed to the design specifications. The system was deemed valid when the overall measurement error remained within a ±5% tolerance.

2.7. Fourteen-day experimental operation and data analysis

The experimental system was operated continuously for fourteen days without any external intervention. During this period, the soil medium was maintained in its natural condition, allowing the setup to function autonomously throughout the test. The system automatically collected essential parameters, including off-potential, current, voltage, and frequency, which were transmitted to the Blynk IoT server for continuous monitoring and storage. This fully automated operation ensured consistent data acquisition under stable environmental conditions, providing a reliable foundation for performance evaluation.

Following the fourteen-day operation, all recorded data were exported to an Excel file for processing and analysis. Data smoothing was applied at 30-minute intervals to minimize short-term disturbances while preserving the true response of the system to environmental variations. The analysis focused on evaluating current density to determine energy consumption, off-potential to assess corrosion protection effectiveness, frequency to measure controller adaptability, and duty cycle to examine protection performance based on real-time potential readings. Collectively, these parameters provided a comprehensive evaluation of the PICCP system in terms of energy efficiency, protection stability, control responsiveness, and long-term sustainability.

2.8. Examination of the metal sample's surface

After completing the experiment, the metal samples were cleaned using a high-strength light-duty cleaner (HLDC) solution at 12 volts for 12 hours to remove corrosion residues and surface contaminants. The cleaning solution consisted of 70% distilled water, 20% citric acid, and 10% sodium hydroxide, formulated to eliminate hydrophobic impurities such as oil, dust, and fingerprints. Following this process, the samples were rinsed and wiped with acetone to remove any remaining residues, ensuring that the surfaces were clean and ready for microscopic examination. Surface characterization was conducted using a Keyence VHX-X1 digital microscope, a high-resolution inspection system capable of capturing single-frame images at 2048×1536 resolution, stage-shifted images at 6144×4608 resolution, and gigapixel mosaics up to approximately 100,000×100,000 pixels through advanced image stitching. The microscope was set to ×20 or ×30 magnification, with autofocus and depth composition enabled to capture accurate three-dimensional surface images. The lens could be tilted up to 90°, and the specimen table rotated 360°, allowing comprehensive visualization of features such as threads, welds, and sidewalls. The resulting 3D surface models, roughness data, and topographic color maps provided detailed insights into the surface morphology and corrosion behavior of the tested metal specimens.

3. RESULTS AND DISCUSSION

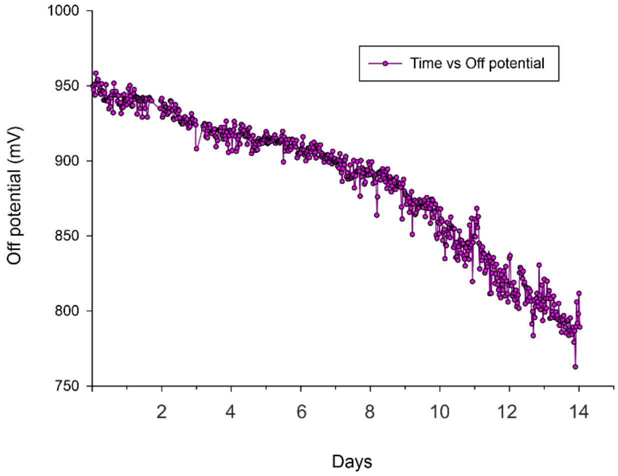
This section discusses key parameters such as off potential, current density, and frequency, that affect the performance of ICCP and PICCP systems using fuzzy logic control, designed to adapt to changing environmental conditions.

3.1. Impressed current cathodic protection performance

The performance metrics of the conventional ICCP system, focusing on protection stability and current consumption throughout the 14-day monitoring period, are summarized in Figure 6. Specifically, Figure 6(a) presents the variation in off-potential, showing a steady decline from approximately –950 mV at the beginning to about –750 mV by the end of the observation period. This indicates that the cathodic protection system initially performed effectively, maintaining adequate polarization of the metal surface. However, from around day eight onward, the off-potential approached –850 mV, signifying a gradual loss of protection efficiency. The continuous drop in potential suggests that the metal structure began to lose sufficient cathodic protection over time, potentially due to electrode passivation, soil resistance variation, or degradation in the system's current output stability.

Figure 6(b) illustrates the variation in current density of the ICCP system over a 14-day testing period. The current density remained relatively stable at approximately 9.2 mA/cm² during the first six days, after which a significant increase was observed. This rise indicates an intensified cathodic protection current, suggesting that the system was compensating to maintain adequate polarization of the metal surface. However, the abrupt increase also highlights a potential issue, as excessive current density can lead to unnecessary energy consumption or degradation of the protective film on the metal surface. Overall, the observed trend suggests that while the ICCP system effectively responded to changing conditions, the control mechanism requires optimization to prevent overprotection and ensure consistent, energy-efficient operation.

The surface morphology and topographic characteristics of the metal specimen after exposure to the conventional ICCP system are detailed in Figure 7, which includes optical imaging, 3D surface profiling, and roughness analysis. Specifically, Figure 7(a) shows micro photograph at 80× magnification, and a 500-micrometer scale shows long grooves made by mechanical preparation. These grooves act as microchannels for the electrolyte. There are reddish-brown rust spots on the surface that are tens to hundreds of micrometers wide and tend to follow the direction of scratches. This shows that a thin, scattered oxide film is forming. The lack of sharply defined pits shows that pitting is not the main problem, and the uneven discoloration shows that corrosion is still happening but is being kept in check. This pattern is common in ICCP-protected specimens, where the potential has already been moved to a safe zone, which slows down the corrosion rate. However, some active sites on the scratch line still react. This means that the whole surface needs a more uniform initial cleaning and flow control process in order to reach a stable passive state.



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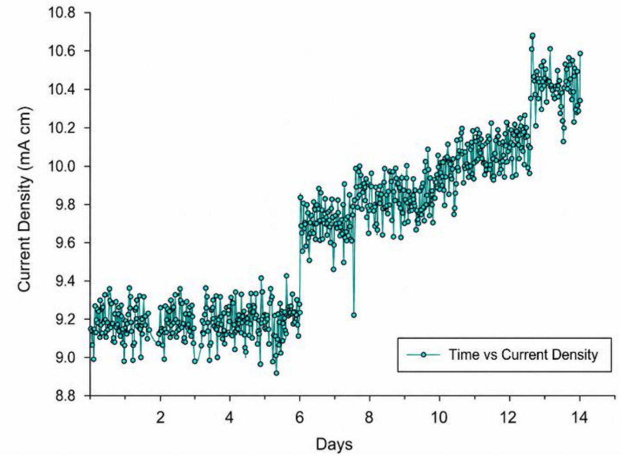
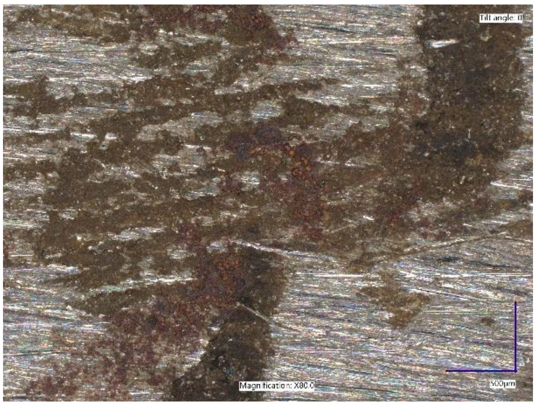


(b)

Figure 6. Variation of; (a) off-potential and (b) current density over 14 days of monitoring for the ICCP system

Figure 7(b) shows a 3D reconstruction of an area that is about 3.8 millimeters by 2.85 millimeters. The relief is wavy and has a height range of about 339 micrometers. The low ridges and shallow valleys that follow the machine's flow show that there is a mix of abrasion and thin corrosion product buildup, not aggressive local erosion. The elevation goes up toward the upper right side, which means that the current distribution changes during testing. Non-uniformity on a scale of hundreds of micrometers shows that the film and deposit are not even, which means that some areas are better protected than others. In the context of ICCP, this pattern indicates the necessity of equalizing the distance between the anode and the surface, along with more precise current regulation, to attain a more uniform electric field, thereby producing a flatter and more stable post-test morphology.

Figure 7(c) presents a three-dimensional topographic profile of the metal surface, displaying height variations of up to approximately 339 µm, with elevation increasing toward the upper right region. The right panel provides a corresponding optical image marked with a measurement line across the observation area. The surface profile graph shown below indicates height fluctuations within the range of 220–300 µm, exhibiting a relatively smooth waveform that suggests the surface morphology is predominantly wavy without sharp peaks. The coloration patterns on the 3D topographic map, along with the visible sanding traces, indicate the presence of a thin corrosion layer with non-uniform thickness across the surface. The absence of deep craters or localized pitting suggests that the surface degradation is shallow and evenly distributed. This observation aligns with the behavior of the specimen exposed to ICCP treatment, where the applied protection current effectively minimized metal dissolution but did not achieve fully uniform current distribution. In practical applications, optimizing the current magnitude or repositioning the anode could improve potential uniformity and contribute to a more stable surface profile.



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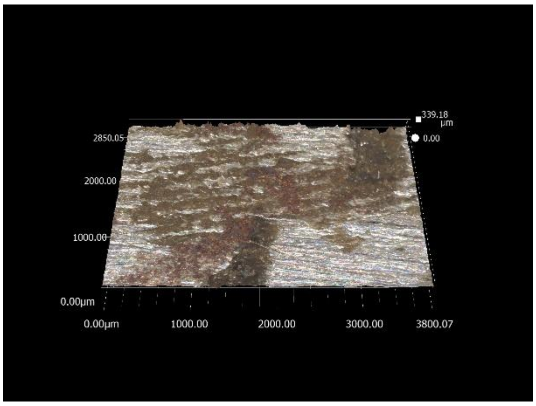

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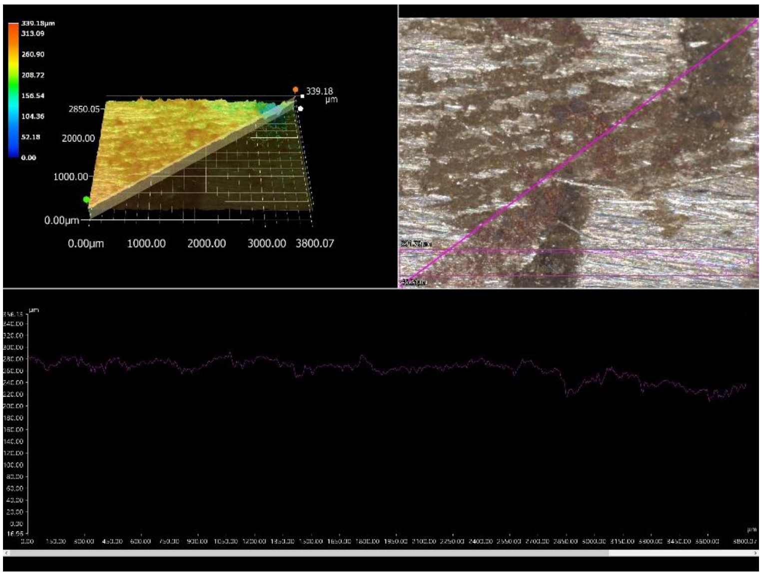


(c)

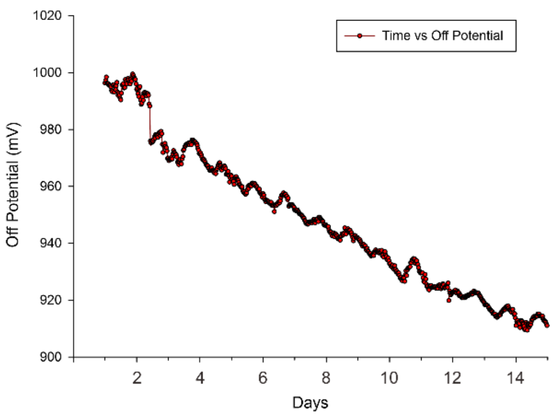
Figure 7. Surface morphology of the metal sample after exposure: (a) optical image, (b) 3D surface profile, and (c) surface roughness analysis

3.2. Pulse impressed current cathodic protection performance

The comprehensive performance metrics of the fuzzy logic-controlled PICCP system throughout the 14-day experimental period, covering protection stability, current consumption, and adaptive frequency modulation, are summarized in Figure 8. Specifically, Figure 8(a) illustrates the relationship between time and off-potential throughout the 14-day testing period. The recorded off-potential exhibited a gradual decline, decreasing from approximately –1000 mV on the first day to around –920 mV on the final day. This consistent downward trend indicates the system's adaptive response to environmental variations, continuously adjusting its parameters to maintain adequate corrosion protection. Minor fluctuations observed in the graph may be attributed to transient environmental changes or minor system perturbations that have a negligible overall impact. Nevertheless, the general stability of the decreasing trend demonstrates the system's effective regulation of current to sustain protective performance over time.

Figure 8(b) presents the variation in current density over the 14-day testing period. The current density exhibits a gradual decline from approximately 0.80 mA on the first day to about 0.74 mA on the final day. Minor fluctuations observed throughout the period may be attributed to environmental variations or transient system responses. Overall, the consistent downward trend indicates effective energy regulation by the system, suggesting that it successfully adapts to environmental changes while maintaining adequate corrosion protection for the metal surface.

Figure 8(c) illustrates the variation in control frequency over the 14-day experimental period. Initially, the system operated at approximately 44 kHz, increasing progressively to over 52 kHz by the end of the test. A significant adjustment occurred on the second day, followed by minor yet consistent fluctuations throughout the remaining days. The observed frequency increase reflects the system’s adaptive capability to compensate for changing environmental conditions, thereby enhancing the regulation of cathodic protection. The subsequent frequency stability after the initial rise indicates that the system successfully maintained optimal control parameters to ensure sustained corrosion protection throughout the experiment.



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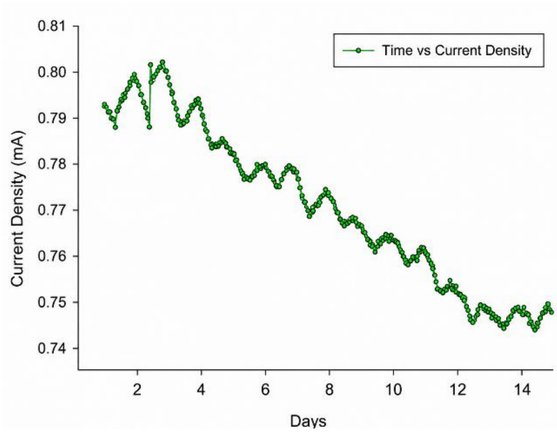

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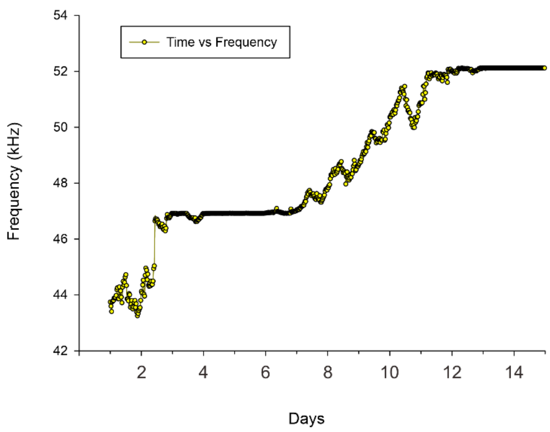


(c)

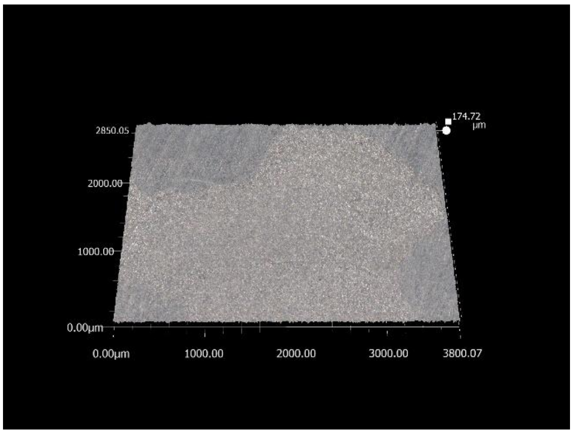
Figure 8. Variation of; (a) off potential, (b) current density, and (c) frequency over 14 days of PICCP system operation

The comprehensive surface characterization of the steel specimen protected by the PICCP system, encompassing 2D morphology, 3D model reconstruction, and topographic profiling, is presented in Figure 9. Specifically Figure 9(a) presents the surface morphology of the metal sample at 80× magnification. The surface appears generally uniform and smooth, with no evidence of deep corrosion pits or delamination of the protective layer. The presence of fine gray patterns across the surface indicates the formation of a thin oxide film, likely produced by mild electrochemical reactions during system operation. The absence of cracks or localized damage confirms that the PICCP system effectively maintained protective performance throughout the testing period.

Figure 9(b) is a three-dimensional model of the metal sample surface reconstruction based on the depth measurement data. The surface appears flat with smooth contours and uniform elevation changes up to a range of 174 µm. This condition shows that the pulsed current with fuzzy logic control was able to keep the protection potential stable, which controlled the corrosion reaction and stopped the metal surface from eroding too much. Uniformity of the area indicates the system's success in maintaining an even distribution of protective current across the entire test surface.

Figure 9(c) presents the three-dimensional topographic profile of the metal surface after treatment with the PICCP system. The surface remains relatively uniform, with a maximum height variation of approximately 174.72 µm. Minor surface fluctuations observed on the profile indicate acceptable micro-irregularities resulting from normal electrochemical reactions during protection. The uniform color distribution across the 3D map further confirms stable protection without significant crust formation or localized corrosion.

(a)



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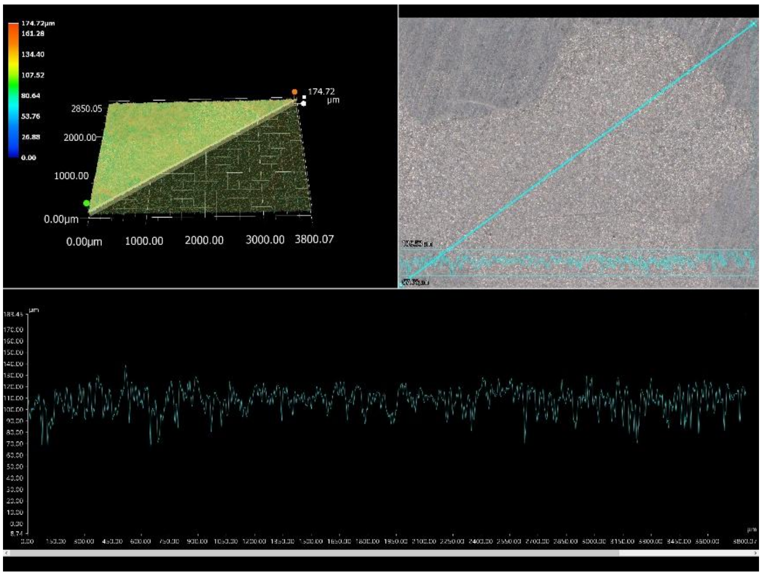


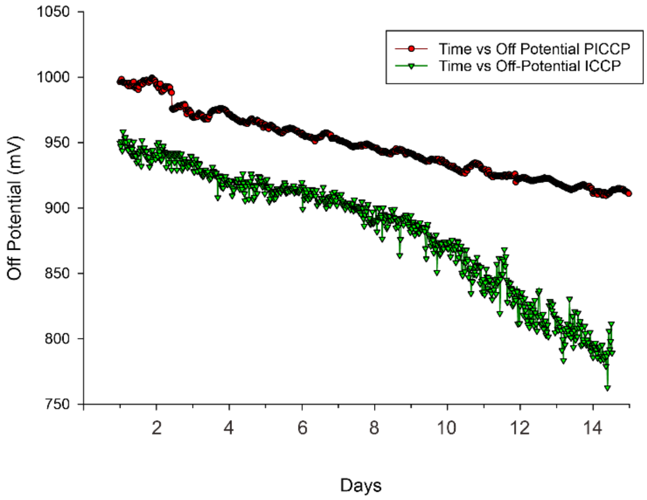
(c)

Figure 9. Surface morphology analysis of the steel specimen using an optical microscope; (a) 2D surface image, (b) 3D surface profile, and (c) surface roughness measurement

3.2.1. System performance comparison

A comprehensive comparison between the PICCP system with fuzzy logic control and the conventional ICCP system, focusing on protection stability and current consumption over the 14-day experimental period, is summarized in Figure 10. Specifically, Figure 10(a) compares the performance of the PICCP system with fuzzy logic control against the conventional ICCP system over 14 days. The PICCP system maintained the off-potential consistently within the protection range of −1100 mV to −850 mV, as indicated by the gradual and stable decline of the red curve. This demonstrates the system's ability to adapt effectively to variations in soil conditions. In contrast, the ICCP system (green curve) exhibited a sharper decline, falling below the −850 mV protection threshold, which indicates a shorter protection duration and a higher risk of underprotection leading to corrosion. These results confirm that the adaptive control strategy implemented in the PICCP system ensures better potential stability and sustained corrosion protection throughout the testing period.

Figure 10(b) illustrates the current density comparison between the ICCP and PICCP systems. The PICCP system maintained a relatively stable current density of approximately 1 mA throughout the 14 days, exhibiting only minor fluctuations. In contrast, the ICCP system operated at significantly higher current levels, ranging between 9 and 10 mA, with a gradual increase observed during the mid and final phases of the experiment. This indicates that the PICCP system achieved equivalent corrosion protection with substantially lower current consumption, demonstrating improved energy efficiency and reduced risk of overprotection. The stability of the PICCP current further reflects the effectiveness of the fuzzy logic controller in adapting to variations in soil conditions, whereas the ICCP system required higher current levels to maintain adequate protection.



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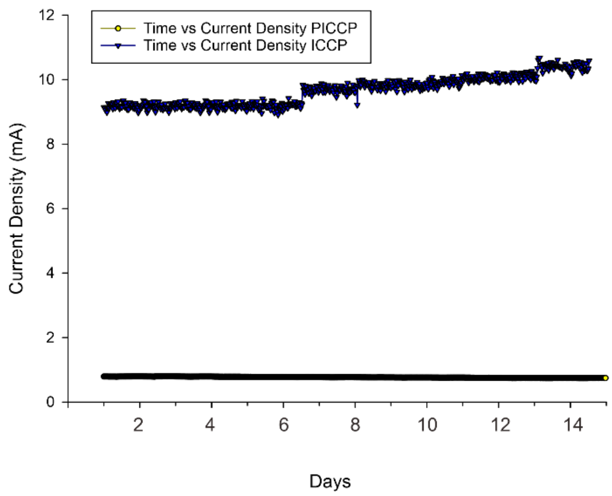

(b)

Figure 10. Comparison between ICCP and PICCP systems over 14 days; (a) off potential and (b) current density measurements

4. CONCLUSION

The results of this study confirm that the PICCP system integrated with fuzzy logic control provides superior stability and energy efficiency compared to the conventional ICCP system. Over a 14-day evaluation period, the PICCP system consistently maintained the off-potential within the optimal protection range of −1100 to −850 mV, while the ICCP system dropped below −850 mV by the eighth day, indicating insufficient protection. In terms of current consumption, the PICCP system required only 0.74–0.80 mA, significantly lower than the 9–10 mA needed by ICCP, representing nearly a tenfold improvement in energy efficiency and a reduced risk of overprotection. By integrating pulse current modulation with intelligent fuzzy logic control, the PICCP system demonstrated effective adaptability to varying soil conditions and sustained metal protection. These outcomes validate its potential as a more reliable and energy-efficient alternative for modern cathodic protection applications.

However, this study has several limitations despite its promising results. Please note that the terrain sample set was taken over a brief 14 days' timeframe and strictly from humus soil, which likely would not accurately reflect long term performance and variability of field application chemistries. Further studies are needed that analyze the longevity of the system over a wider range (in terms of soil types) and for wider parts of the world, especially considering clay or sandy soil types with different moisture differences. Moreover, incorporation of internet of things (IoT) features to allow remote real-time monitoring and other advanced optimization algorithms could further contribute to the practical implementation and intelligence of PICCP system.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors assert that the research was performed without any commercial or financial affiliations that might be interpreted as a potential conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author.

REFERENCES

[1] J. P. Broomfield, "A Historical Review of Impressed Current Cathodic Protection of Steel in Concrete," *Construction Materials*, vol. 1, no. 1, pp. 1–21, 2021, doi: 10.3390/constrmater1010001.

[2] Komalasari, Evelyn, I. D. R. Situmeang, and D. Heltina, "Cathodic protection on stuctures of carbon steel using sacrificial anode

methode for corrosion control," in *IOP Conference Series: Materials Science and Engineering*, vol. 845, no. 1, 2020, doi: 10.1088/1757-899X/845/1/012015.
[3] Z. Guo, R. Guo, and G. Yao, "Multi-factor model to predict surface chloride concentration of concrete based on fuzzy logic system," *Case Studies in Construction Materials*, vol. 17, p. e01305, 2022, doi: 10.1016/j.cscm.2022.e01305.
[4] M. Nale *et al.*, "Transient Modeling of Corrosion Protection Systems With BEM-Electrical Circuit Hybrid Model," *IEEE Transactions on Magnetics*, vol. 59, no. 5, pp. 1–5, May 2023, doi: 10.1109/TMAG.2023.3255979.
[5] G. Ramírez *et al.*, "Accident Risk Detection in Urban Trees using Machine Learning and Fuzzy Logic," *Procedia Computer Science*, vol. 203, pp. 471–475, 2022, doi: 10.1016/j.procs.2022.07.064.
[6] A. Ramírez, M. Figueroa, E. Ossandón, R. G. Martínez, M. Ángel, and R. O. Cruz, "Improved Impressed Current Cathodic Protection PID Control based on a machine learning approach," *Research Square*, pp. 1–18, 2023, doi: 10.21203/rs.3.rs-3414233/v1.
[7] M. R. Adzman *et al.*, "Improved impressed current cathodic protection systems by incorporating a pulse-feeding technique integrated with internet of things capabilities," *International Journal of Electrical and Computer Engineering*, vol. 14, no. 6, pp. 7254–7265, 2024, doi: 10.11591/ijece.v14i6.pp7254-7265.
[8] H. Eslamian, M. Javidi, M. R. Zamani, M. M. Dana, and E. Mansoori, "Effect of pulsed current cathodic protection on pipeline steel API 5L X65 corrosion mitigation: An investigation and machine learning-assisted modeling," *Corrosion Communications*, vol. 12, pp. 29–45, 2023, doi: 10.1016/j.corcom.2023.01.005.
[9] E. M. Shaalan, M. A. Mostafa, A. S. Hamza, and M. Al-Gabalawy, "Cathodic Protection Performance Improvement of Metallic Pipelines based on Different DC Compensation Methods," *Electric Power Systems Research*, vol. 210, p. 108064, 2022, doi: 10.1016/j.epsr.2022.108064.
[10] A. Mohamed and N. Martin, "Impressed Current Cathodic Protection and Environmental Impacts," in *13th Annual International Conference on Industrial Engineering and Operations Management*, Manila, Philipines, 2023, pp. 2493–2509, doi: 10.46254/an13.20230683.
[11] O. Prokhorov, V. Prokhorov, A. Khussanov, Z. Khussanov, B. Kaldybayeva, and D. Turdybekova, "Complete Integrated Automation of the Electrochemical Corrosion Protection System of Pipelines Based on IoT and Big Data Analytics," *Computation*, vol. 10, no. 7, 2022, doi: 10.3390/computation10070123.
[12] O. Prokhorov, V. Prokhorov, A. Khussanov, Z. Khussanov, B. Kaldybayeva, and D. Turdybekova, "Optimization of the Cathodic Protection System for the Main Pipelines," *Radioelectronic and Computer Systems*, no. 3(107), pp. 187–203, 2023, doi: 10.32620/reks.2023.3.15.
[13] J. P. Rico *et al.*, "Electrochemical Evaluation of the Metal-Media Interface of a Calcareous-Formed Al-Base Alloy Immersed in a Synthetic Seawater Solution," *ECS Transactions*, vol. 110, no. 1, pp. 177–184, 2023, doi: 10.1149/11001.0177ecst.
[14] M. K. Zadeh, M. Yeganeh, M. T. Shoushtari, and A. Esmaeilkhanian, "Corrosion performance of polypyrrole-coated metals: A review of perspectives and recent advances," *Synthetic Metals*, vol. 274, p. 116723, 2021, doi: 10.1016/j.synthmet.2021.116723.
[15] A. Bastari and O. Sri Suharyo, "The Comparison Study Of Cathodic Protection System Of Victim Anoda Between Zink Anoda (Zn) And Aluminum Anoda (Al)," *International Journal of Progressive Sciences and Technologies (IJPSAT)*, vol. 24, no. 1, pp. 183–193, 2020.
[16] M. A. Ali, A. Miry, and T. Salman, "Implementation of Intelligent Industrial Controller Based On Fuzzy Logic and PLC," *Al-Qadisiyah Journal for Engineering Sciences*, vol. 13, pp. 55–60, 2020, doi: 10.30772/qjes.v13i1.626.
[17] T. Hatzichristos and D. Ntzanis, "Comparison of Defuzzification Operators on Geographic Data of Ratio Scale," *Intelligent Information Management*, vol. 15, no. 05, pp. 373–389, 2023, doi: 10.4236/iim.2023.155018.
[18] M. K. Sharma, N. Dhiman, Vandana, and V. N. Mishra, "Mediative fuzzy logic mathematical model: A contradictory management prediction in COVID-19 pandemic," *Applied Soft Computing*, vol. 105, p. 107285, 2021, doi: 10.1016/j.asoc.2021.107285.
[19] E. Danish and M. Onder, "Application of Fuzzy Logic for Predicting of Mine Fire in Underground Coal Mine," *Safety and Health at Work*, vol. 11, no. 3, pp. 322–334, 2020, doi: 10.1016/j.shaw.2020.06.005.
[20] C. Joshi, R. K. Ranjan, and V. Bharti, "A Fuzzy Logic based feature engineering approach for Botnet detection using ANN," *Journal of King Saud University - Computer and Information Sciences*, vol. 34, no. 9, pp. 6872–6882, 2022, doi: 10.1016/j.jksuci.2021.06.018.
[21] J. Ma, X. Zhang, W. Yuan, and H. Zhou, "Study of cathodic protection system for oil well casings based on pulse current," in *Proceedings - 2020 International Conference on Intelligent Transportation, Big Data and Smart City, ICITBS 2020*, pp. 463–467, 2020, doi: 10.1109/ICITBS49701.2020.00100.
[22] M. Moradi, F. Bayat, and M. Charmi, "A salient object detection framework using linear quadratic regulator controller," *Journal of Visual Communication and Image Representation*, vol. 79, p. 103259, 2021, doi: 10.1016/j.jvcir.2021.103259.
[23] M. A. Abdullah, A. Q. Al-Shetwi, M. Mansor, M. A. Hannan, C. W. Tan, and A. H. M. Yatim, "Linear quadratic regulator controllers for regulation of the dc-bus voltage in a hybrid energy system: Modeling, design and experimental validation," *Sustainable Energy Technologies and Assessments*, vol. 50, 2022, doi: 10.1016/j.seta.2021.101880.
[24] J. A. Juarez-Islas and J. Genesca-Llongueras, "Development and testing of galvanic anodes for cathodic protection," *Contributions to Science*, vol. 1, no. 3, pp. 331–343, 2000.
[25] A. D. Corella and G. Wachsmuth, "Stability and genericity of bang-bang controls in affine problems," *SIAM Journal on Control and Optimization*, pp. 1–25, 2023, doi: 10.1137/23M1586446.
[26] ASTM, "G97-2013 Standard Test Method for Laboratory Evaluation of Magnesium Sacrificial Anode Test Specimens for Underground Applications 1," vol. i, no. Reapproved 2013, pp. 1–4, 2017, doi: 10.1520/G0097-18R22.2.
[27] B. Han, W. Dong, B. Fan, and S. Zhu, "Comparison on the immersion corrosion and electrochemical corrosion resistance of WC-Al2O3composites and WC-Co cemented carbide in NaCl solution," *RSC Advances*, vol. 11, no. 36, pp. 22495–22507, 2021, doi: 10.1039/d1ra03549e.
[28] H. Zhang *et al.*, "The effect of immersion corrosion time on electrochemical corrosion behavior and the corrosion mechanism of eh47 ship steel in seawater," *Metals*, vol. 11, no. 8, 2021, doi: 10.3390/met11081317.
[29] A. T. Lim and A. Ismail, "A Review Study of Critical Oxygen Content to Stress Corrosion Cracking of Stainless Steel 304," *Research Progress in Mechanical and Manufacturing Engineering*, vol. 1, no. 1, pp. 92–100, 2020.

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