Improved impressed current cathodic protection systems by incorporating a pulse-feeding technique integrated with internet of things capabilities

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ABSTRACT

This paper introduces an innovative improvement to impressed current cathodic protection (ICCP) systems by integrating a pulse-feeding technique designed to address metal protection degradation during off-potential periods, a common issue in conventional systems. The proposed system enhances the overall effectiveness and reliability of ICCP, providing consistent corrosion protection for critical metal structures. A notable advantage of this method is its simplicity, utilizing a cost-effective microcontroller for pulse feeding. This approach simplifies integration processes and enhances cost-effectiveness, making it an attractive solution for improving cathodic protection system performance without substantial additional costs. The method addresses conventional ICCP weaknesses by applying a high-frequency pulse current during off-potential periods. This reduces excessive negative charge buildup on metal surfaces during interruptions, boosting the system's effectiveness and stability. Research laboratory experiments were conducted using pulse width modulation (PWM) on an ATmega328P microcontroller to demonstrate the method's effectiveness. Additionally, an IoT-monitored ICCP system was developed using an ESP32 microcontroller and the Blynk application. Results highlight the superiority of a 50 kHz pulse feeding frequency in preventing corrosion compared to lower frequencies. Overall, this advancement significantly enhances ICCP systems, providing improved corrosion protection and durability in harsh environments.

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1. INTRODUCTION

Corrosion poses a persistent threat to metallic assets across various industrial sectors, necessitating robust defense mechanisms to protect against structural deterioration [1]–[3]. Cathodic protection systems have evolved significantly to safeguard critical infrastructures, including underground oil and gas pipelines, submerged structures, and storage tanks, from the deleterious effects of corrosion [4]. Employing either impressed current or sacrificial anode methods, cathodic protection alters the electrochemical processes on metal surfaces, serving as a pivotal defense mechanism against corrosion [5]–[7]. Impressed current cathodic protection (ICCP) is a well-established method for safeguarding steel structures, particularly in buried and submerged oil and gas pipelines, from corrosion [8]–[11]. This system involves the use of sacrificial anodes connected to an external power source, such as a transformer-rectifier unit (TRU) linked to alternating current (AC) power. The TRU in ICCP systems regularly switches on and off to counteract the effects of internal resistance (IR) voltage drop caused by solution resistance [12]–[14]. This voltage drop significantly impacts electrochemical measurements, making it crucial to address these effects when interpreting electrochemical data. The complementary nature of sacrificial anode cathodic protection (SACP) and ICCP further enhances the effectiveness of corrosion protection strategies. SACP is known for its cost-effectiveness and ease of installation but is limited by a short lifespan, limited current capacity, and lack of control [15]–[17]. Conversely, ICCP provides adjustable, regulated current output, a long lifespan, and high capacity, though it is more expensive and demands significant maintenance and installation costs. Additionally, the impact of IR drops on electrochemical experiments is profound and must be carefully considered [18].

To mitigate IR drop, the current interruption method, known as instantaneous off-potential, is employed. However, Malek *et al.* [19] highlighted that this standard procedure in ICCP can lead to more severe issues, making it difficult to protect metals from corrosion. During current interruptions, positive charges act as corrosive agents, reabsorbing the metal surface and re-inducing corrosion reactions. This process deteriorates the protective potential over time, accelerating rust formation and compromising the effectiveness of the ICCP system. Despite these challenges, ICCP circuits using direct current schemes have largely remained unchanged. Most corrosion engineers continue to use the same approach with different setting parameters, resulting in limited references for substantial improvement. Despite the widespread use of ICCP, researchers are increasingly exploring pulsed current cathodic protection (PCCP) to overcome ICCP's limitations like IR drop and uneven current distribution. By optimizing pulse parameters, PCCP aims to enhance corrosion protection efficiency and extend the longevity of metallic structures in challenging environments. Several researchers have begun exploring pulse cathodic protection as an alternative [20]–[26]. Experiments have been conducted to replace direct current with current/voltage pulse feeding, though results have been mixed and further research is ongoing [19]. George's experiments [27] on pulse width modulated signals found limited effectiveness, particularly on small surface areas, indicating that modulated signals may not significantly improve ICCP efficiency. Xu *et al.* [28] reported that the influence of pulse protection parameters on potential distribution was unclear, suggesting that better protection could be achieved by optimizing anode distance, high frequency, and moderate duty cycle. Furthermore, Studies suggest that PCCP might be more effective than ICCP for reducing corrosion in buried oil and gas structures with the right parameters [25]. While some research shows potential benefits, these findings are not yet widely reported or commercially validated, and other studies find no significant advantage. Despite mixed results, research continues to explore pulse current techniques to enhance ICCP system efficiency and reliability in corrosive environments.

Addressing these challenges, this study proposes advancements in conventional ICCP systems by implementing pulse-impressed current cathodic protection (PICCP) with a high-frequency pulse current approach during off-potential periods, aiming to significantly improve corrosion prevention effectiveness. This study aims to evaluate the enhancements in PICCP by investigating the impact of pulse feeding in the ICCP system. Corrosion prevention tests are conducted on steel samples in a 3.5% NaCl solution using an Arduino circuit generating pulse square waveforms. Moreover, integrating an internet of things (IoT)-based monitoring and control system enhances real-time data collection, analysis, and remote access for corrosion protection management, promising significant strides in corrosion prevention strategies for crucial metallic infrastructures.

2. METHOD

The selected mild steel samples for this corrosion study are highly susceptible to corrosion. Before the experiments, the steel bars were thoroughly cleaned using alcohol to remove surface oil, grease, or oxide. Flat mild steel bars measuring 21 cm in length and 1.1 cm in width were used as protected metal samples. Anodes composed of 16 cm long and 0.5 cm in diameter graphite rods were positioned 4 cm opposite the steel to be protected. A 3.5% sodium chloride (NaCl) solution served as the electrolyte, prepared by dissolving 35 g of sodium chloride in 1,000 ml of distilled water. The solution was stirred for 10 minutes to ensure homogeneity. All experiments were conducted at room temperature (25 °C), maintaining the solution's pH at 7. The pulsed-impressed current cathodic protection (PICCP) system utilized a direct current (DC) power supply (SPS305B, nice power) set at a constant 2.10 V output. A solid-state relay switch with a time controller connected the DC power to the pulse generator, simulating a TRU in actual fieldwork. The system operated cyclically: ON for 4 seconds (ON-potential) and OFF for one second (instantaneously OFF-potential). A multimeter (MT-1710, Pro'skit) measured steel samples and graphite anodes immersed in the 3.5% NaCl solution.

The proposed technique setup mirrored an ICCP system, incorporating a current pulse unit activated while instantaneously OFF-potential. An oscilloscope monitored the predetermined pulse waveform. Different frequencies (1, 10, and 50 kHz) were tested to evaluate PICCP's corrosion protection abilities. An internet of things (IoT) monitoring and control system captured real-time data, analyzed through voltage and current readings across different frequencies. Figure 1 provides a camera photograph and, Figure 2 shows a schematic diagram of the experimental setup.

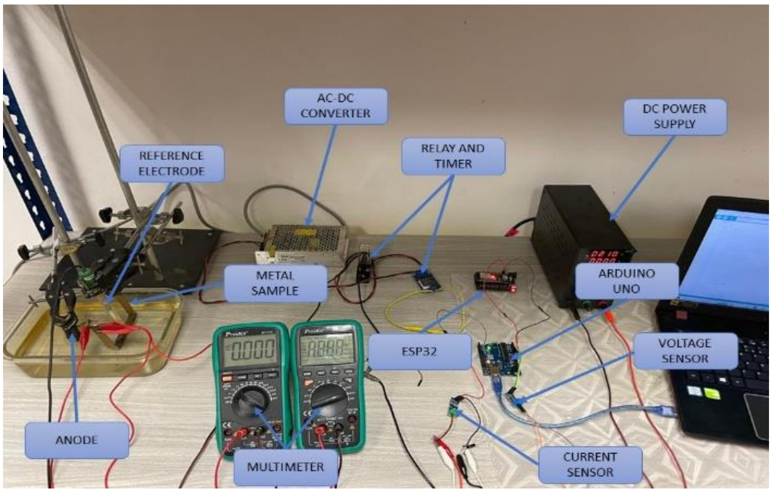


Figure 1. Camera photograph of experiment setup of the PICCP system

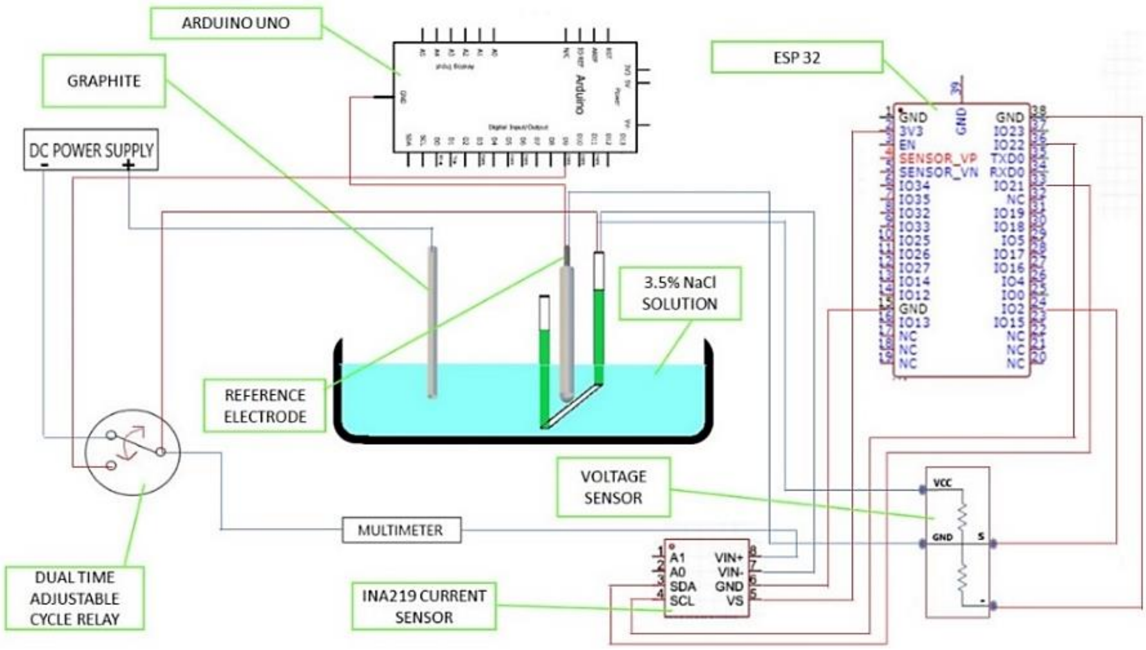


Figure 2. Schematic diagram illustrating the experimental setup

The setup included an adjustable-frequency square waveform circuit using Arduino, delivering pulsed currents of 5 V peak-to-peak at 50% duty cycle across varied frequencies. Voltage, current sensors, and an ESP32 microcontroller facilitated the corrosion protection tests for 7 days in the 3.5% NaCl solution. The IoT-based monitoring and control system integrated with Blynk and Push Safer applications ensured real-time data display and notifications for critical events. Figure 3 illustrates the project's flowchart, detailing the setup and data collection process.

Post-experimentation, the steel sample was promptly removed, dried, visually inspected, and examined under a stereomicroscope to assess its corrosion prevention effectiveness. In summary, the comprehensive corrosion study, utilizing mild steel samples under varied conditions and frequencies, provided valuable insights into the effectiveness of ICCP in preventing corrosion. The post-experimentation visual assessment of surface morphology aided in evaluating the corrosion prevention effectiveness of the steel samples.

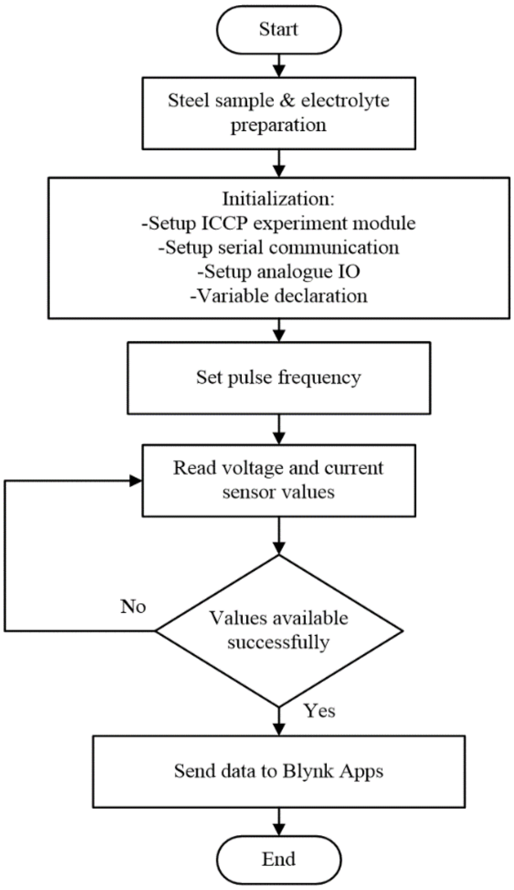


Figure 3. Flowchart for a system that uses pulses to protect the metal from corrosion, including IoT capabilities

3. RESULTS AND DISCUSSION

3.1. Cathodic protection potential analysis

The information depicted in Figure 4 was recorded utilizing an IoT-based measurement system and subsequently compared with multimeter readings obtained in voltmeter and ammeter modes. This figure illustrates the ON-potential and instant OFF-potential measurements of mild steel within a pulse-impressed current cathodic protection (PICCP) system over 7 days in a 3.5% NaCl solution. The ON-potential curve captures measurements taken during the active flow of cathodic protection current, indicating the state when the metal surface is effectively protected. These values range from -1087 mV to -953 mV vs SCE throughout the 7-day observation period. Conversely, the instantaneous off-potential curve reflects measurements immediately following the cessation of the cathodic protection current, portraying the state when the metal surface is temporarily without active protection. These values range from -992 mV to -942 mV vs SCE over the same period.

Typically, ON-potential values are more negative (cathodic) than instant OFF-potential values due to active polarization during protection. The interruption of the cathodic protection current leads to a less negative potential, trending towards a less cathodic or even anodic direction. The disparity between ON-potential and instant OFF-potential values is influenced, in part, by the IR drop, representing the voltage drop due to electrolyte resistance an essential consideration in cathodic protection systems. The curves in Figure 4 suggest a decreasing trend in potential over time for both ON-potential and instant OFF-potential, indicating potential factors such as gradual anode material consumption or electrolyte condition changes. This difference between the curves provides insights into the cathodic protection system's effectiveness, with the potential becoming less negative after current interruption. It is crucial to note that specific system behavior depends on factors like PICCP system design, anode material condition, and electrolyte environment. When interpreting potential measurements in cathodic protection systems, the IR drop should be considered to ensure accurate assessments of the protection level. Continuous monitoring, including current measurements, is essential for the comprehensive evaluation of the cathodic protection system's performance over time.

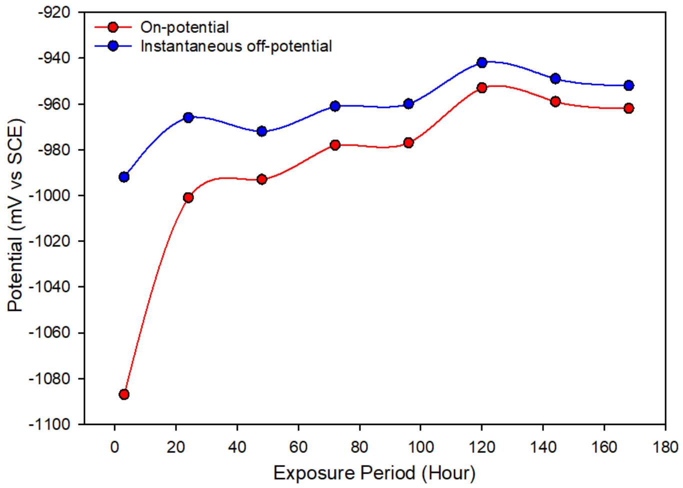


Figure 4. ON-potential and instantaneous OFF-potential readings of steel immersed in a 3.5% NaCl solution under PICCP at a 50 kHz pulse frequency

3.2. Effect of pulse frequency on PICCP

The curves depicted in Figure 5 reveal the behavior of the instant OFF-potential of mild steel in the PICCP system under different pulse frequencies (50, 10, and 1 kHz) in a 3.5% NaCl solution over 7 days (3 to 168 hours). The data were manually recorded through a multimeter using voltmeter and ammeter modes. The protected instant OFF-potential target is within the range of -778 to -1028 mV vs SCE. The curves exhibit distinct patterns associated with varying pulse frequencies, offering insights into the system's performance over time.

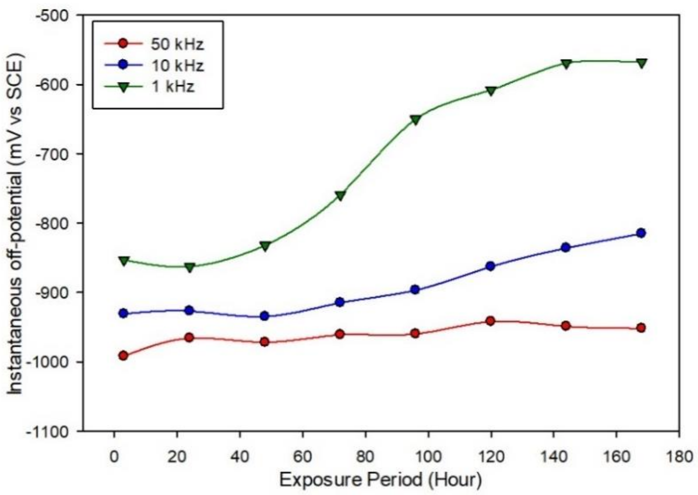


Figure 5. Instantaneous OFF-potential of steel immersed in a 3.5% NaCl solution under ICCP at various pulse frequencies

At a 50 kHz pulse frequency, at the onset (3 hours), the potential is -992 mV vs SCE, signifying a highly cathodic state. Over the next 24 hours, there's a gradual shift towards a less negative potential (-966 mV vs SCE), suggesting a slight reduction in cathodic polarization. Subsequent time intervals (48 to 168 hours) show fluctuations, potentially indicating dynamic changes in ion transport and polarization effects, demonstrating that cathodic protection could gradually strengthen in the long term. The potential stabilizes around -952 mV vs SCE after 168 hours, indicating a relatively steady cathodic protection level.

Under a 10 kHz pulse frequency, the initial potential at 3 hours is -931 mV vs SCE, indicating an effective cathodic protection state. Similar to 50 kHz, there's a gradual decrease over 24 hours (-927 mV), implying a slight reduction in cathodic polarization. Notably, ascending potential fluctuations are observed, especially between 48 and 168 hours, suggesting dynamic processes in ion transport and polarization effects, expressing that cathodic protection gradually weakens in the long run. The potential is around -815 mV vs SCE after 168 hours, although it is still within the cathodic region, indicating a level of cathodic protection that is unlikely to last for an extended period

However, at a 1 kHz pulse frequency at 3 hours, the potential is -853 mV, showing effective cathodic protection. Over the next 24 hours, a gradual decrease is observed (-863 mV vs SCE), indicating an improvement in cathodic polarization. Fluctuations persist, starting at 72 hours, suggesting relatively abrupt dynamic changes in ion transport and polarization effects, indicating that cathodic protection is greatly weakened in the long run. The potential is polarized, ascending towards the positive at around -568 mV after 168 hours, suggesting a weak cathodic protection level.

The variations in potential over time at different pulse frequencies (50, 10, and 1 kHz) reveal the dynamic interplay between ion transport and polarization effects. Higher pulse frequencies, such as 50 kHz, initially provide a more cathodic potential. Over time, a slightly horizontal trend suggests stable cathodic polarization. Fluctuations in potential may be attributed to the complex interplay of ion transport, where higher frequencies enhance polarization effects, influencing the protective capacity of the system. At 10 kHz, corrosion protection by PICCP is known to be less efficient in the long term, as indicated by slight ascending potential fluctuations starting after 48 hours of the experiment. Additionally, at 1 kHz, corrosion protection by PICCP is insufficient, leading to clearly no corrosion protection occurring. The stabilization of potential after an initial dynamic phase suggests the establishment of a potential of zero charges (PZC). PZC occurs when the surface charge becomes neutral, indicating a balance between the attractive force of cathodic protection and the repulsion force against corrosive ions at the electrode-electrolyte (metal-solution) interface. The stabilization in potential after fluctuations indicates the system's ability to maintain a protective state with a repulsion force countering corrosive influence.

Summarily, the curves in Figure 5 illustrate the dynamic behaviors of the instant off-potential under different pulse frequencies. The fluctuations and eventual stabilization provide valuable insights into ion transport, enhanced polarization effects, and the establishment of a potential of zero charges, all crucial aspects of evaluating the effectiveness of the PICCP system for cathodic protection.

3.3. PICCP current consumption

The current consumption curve in Figure 6, representing the performance of PICCP at different pulse frequencies (50, 10, and 1 kHz) over time, reveals distinctive behaviors that are crucial for understanding the system's effectiveness. Under 50 kHz Pulse Frequency, at the initial surge (3 hours), the current consumption is notably high, starting at 0.534 mA/cm². This suggests an intensified cathodic protection response during the initial phase, indicating efficient polarization and ion transport under the influence of the higher pulse frequency. Subsequently, there is a consistent decline in current consumption, reaching 0.228 mA/cm² after 168 hours. This gradual reduction could be attributed to a balance achieved in the system, indicating an optimized level of cathodic protection over an extended period. At 10 kHz, the initial current consumption is 0.284 mA/cm², indicating a lower consumption rate compared to 50 kHz. This may suggest a slightly less intense cathodic protection response, but still effective, as the system establishes its protective state. The current consumption continues to decrease over time, reaching 0.132 mA/cm² after 168 hours.

This declining trend indicates a relatively stable and less efficient cathodic protection system at the 10 kHz pulse frequency. However, the current consumption at 1 kHz is notably lower initially, starting at 0.936 mA/cm². This could indicate a less aggressive cathodic protection response at this lower pulse frequency. Surprisingly, there is a rapid decline in current consumption, reaching 0.004 mA/cm² after 168 hours. Such a significant decrease may suggest that the system adjusts to the lower current consumption by low pulse frequency, indicating insufficient corrosion protection by the PICCP system.

The observed current density curve behaviors underscore the impact of pulse frequency on the current consumption of the PICCP system. Higher frequencies initially demand more current, potentially resulting in a robust protective response. However, over time, the system stabilizes to provide efficient protection at a reduced consumption rate, as happens with the 50 kHz pulse frequency. On the other hand, the lower pulse frequencies show declining trends in current consumption, indicating the corrosion protection system's inefficiency and adaptability. The PICCP system optimizes its performance, adjusting the current density based on the applied pulse frequency. The surprisingly rapid decline in current consumption at 1 kHz suggests that the system is inefficient as a result of lower frequencies and lower current consumption, demonstrating an inability to provide adequate cathodic protection with minimal energy consumption.

PICCP systems, especially those employing low-frequency pulses, may benefit from modifications to enhance cathodic protection on steel. One approach involves adjusting the current volume or magnitude, either manually or automatically. Increasing the current volume can potentially maintain an effective cathodic protection effect on steel surfaces. This modification addresses the dynamic nature of corrosion conditions, allowing for a more robust and adaptable PICCP system. Whether done manually or through automated processes, optimizing the current volume/magnitude represents a strategy to improve the overall performance and longevity of cathodic protection systems.

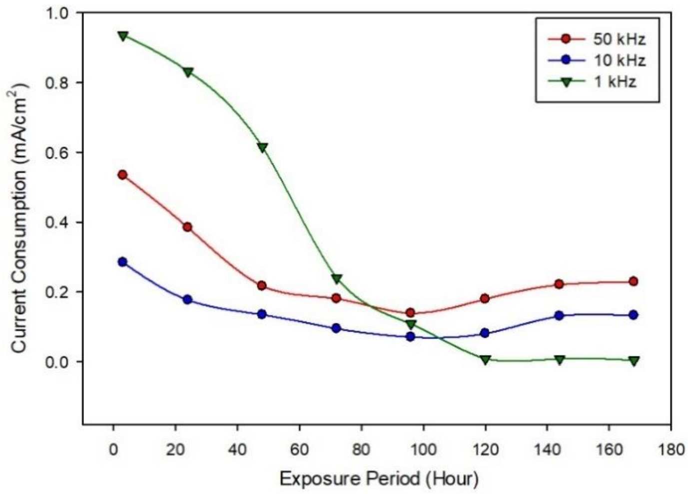


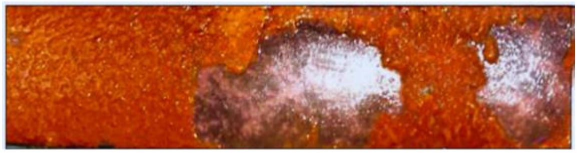
Figure 6. Current consumption of ICCP system for steel in a 3.5% NaCl solution under ICCP at various pulse frequencies

3.4. Surface morphology

Figure 7 compares the conditions of the steel surface after immersion in a 3.5% NaCl solution for 168 hours. Figure 7(a) illustrates the surface condition of steel without any corrosion protection, clearly showing a thick layer of reddish-brown corrosion products that have precipitated on the steel surface. The steel sample under pulse-impressed current cathodic protection (PICCP) with the lowest pulse frequency as shown in Figure 7(b), exhibits a surface with a thin reddish-brown layer (i.e., rust). This suggests that corrosion protection does not occur with a pulse frequency of 1 kHz, a confirmation supported by its instantaneous off-potential not exceeding -778 mV vs SCE (*i.e.*, the minimum threshold of protected potential) since the 72^{nd} hour of the immersion period. Figures 7(c) and 7(d) present noticeably different surface colors, showcasing the original surface of the steel before the experiment. This surface is well-protected from severe corrosion attacks. However, upon close observation of Figure 7(c), a very thin reddish-brown layer is revealed on the steel surface, possibly due to the ascending trend of the protection potential becoming more polarized towards the positive direction. Nevertheless, the steel sample under PICCP at a pulse frequency of 10 kHz is considered safe and protected at the 168^{th} hour, as its potential still falls within the range of -778 to -1,028 mV vs SCE. The steel sample believed to have undergone no direct corrosion is the PICCP sample with a pulse frequency of 50 kHz. Its surface appears undisturbed and shows no interaction with the corrosive salt solution, similar to its condition before the experiment was conducted.

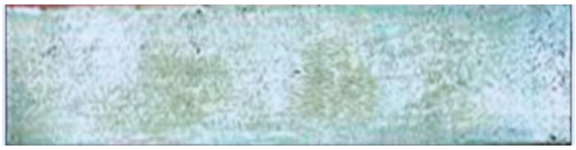
3.5. IoT-based data monitoring

The objective was to evaluate the performance of the pulse impressed current cathodic protection (PICCP) system over 7 days at various frequencies (50, 10, and 1 kHz) using an IoT-based monitoring setup. The experiment involved an ESP32 MCU, voltage and current sensors, Arduino IDE software, and the Blynk cloud application. Programming within the Arduino IDE enabled the transmission of signals between the current sensor, voltage sensor, and ESP32. Results were displayed on the Blynk app and Arduino's serial monitor, aligning with measurements obtained from a multimeter. The Blynk app interface in Figure 8 reflected current and voltage values, demonstrating drops during off potential and rises during on potential. Although Wi-Fi speed may introduce a slight delay, eventual synchronization occurs. The PICCP's current reading can be adjusted through pulse parameters like frequency, width, or duty cycle, crucial for effective protection. Adaptations can also address varying corrosion rates and environmental factors, such as soil resistivity, necessitating higher current outputs for effective corrosion prevention.



(a)

(b)



(c)

(d)

Figure 7. The condition of the steel surface after 7 days of experimentation immersed in a 3.5% NaCl solution, where (a) is without pulse feeding, and under pulse feeding at, (b) 1 kHz, (c) 10 kHz, and (d) 50 kHz pulse frequency

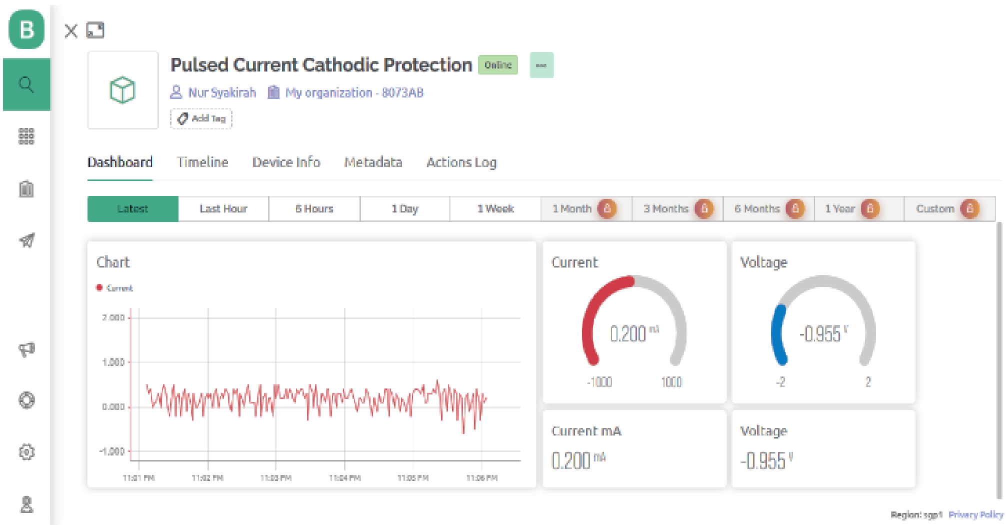


Figure 8. Blynk cloud application interface

Tables 1, 2, and 3 present voltage and current readings for various pulse frequency configurations during both active and inactive states. Based on measurements, at both 50 and 10 kHz, voltage consistently stayed within the favorable range of -800 to -1,150 mV (potential measured in mV in seawater), showcasing effective corrosion prevention and minimal surface corrosion. Conversely, at 1 kHz, less favorable outcomes were observed, with voltage readings rapidly decreasing, indicating compromised protection and the initiation of corrosion. These results underscore the critical influence of frequency on the corrosion prevention effectiveness of PICCP. While 1 kHz exhibited diminished protective capability and noticeable corrosion, 50 kHz demonstrated remarkable preservation of metal integrity. Figure 6 provides visual evidence supporting the strong corrosion protection of the metal sample at 50 kHz frequencies.

In summary, the results emphasize the criticality of meticulously choosing optimal parameters for PICCP to achieve effective corrosion prevention. The study underscores that a frequency of 50 kHz provides enhanced protection compared to lower frequencies. Moreover, the project features a practical Arduino-based monitoring system with IoT implementation for corrosion prevention in metal structures, offering valuable insights for devising corrosion prevention strategies incorporating optimized frequencies and resilient monitoring systems to ensure enduring structural strength.

Table 1. Voltage and current readings at 50 kHz in both on and off states

Hours	Current (mA)	Voltage (mV)	
		On Potential	Off-Potential
3	-0.534	-1087	-992
24	-0.384	-1001	-966
48	-0.216	-993	-972
72	-0.18	-978	-961
96	-0.138	-977	-960
120	-0.179	-953	-942
144	-0.22	-959	-949
168	-0.228	-962	-952

Table 2. Voltage and current readings at 10 kHz in both on and off states

Hours	Current (mA)	Voltage (mV)	
		On Potential	Off-Potential
3	-0.284	-948	-931
24	-0.176	-948	-927
48	-0.134	-968	-935
72	-0.094	-1010	-915
96	-0.07	-1012	-897
120	-0.08	-949	-863
144	-0.13	-982	-836
168	-0.132	-987	-815

Table 3. Voltage and current readings at 1 kHz in both on and off states

Hours	Current (mA)	Voltage (mV)	
		On Potential	Off - Potential
3	-0.936	-900	-853
24	-0.832	-896	-863
48	-0.616	-950	-832
72	-0.24	-765	-759
96	-0.108	-649	-650
120	-0.008	-609	-608
144	-0.008	-565	-569
168	-0.004	-586	-568

4. CONCLUSION

In conclusion, our investigation evaluated the effectiveness of pulse feeding in ICCP systems for preventing corrosion in steel structures, particularly during instantaneous off-potential periods. Tests were conducted using different frequencies (50, 10, and 1 kHz), with voltage and current readings monitored over 7 days. The results indicate that the 50 kHz frequency provided the most effective corrosion protection, maintaining voltage levels within the desired range and effectively preventing surface corrosion. In contrast, lower frequencies demonstrated reduced protection and early signs of corrosion. The study also introduced an IoT-based monitoring and control system, which improved real-time data collection and allowed for timely notifications for intervention. These findings highlight the importance of optimizing frequency in PICCP to prevent corrosion effectively across various industrial applications. Future research should focus on fine-tuning parameters, integrating advanced control systems like PID and ANFIS, and conducting rigorous testing in different environmental conditions to enhance ICCP with pulse-feeding techniques. This research aims to improve the technical understanding and practical use of ICCP in preventing corrosion during periods of reduced protection.

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