

# Real-time remote monitoring and control system for underground pipelines

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## ABSTRACT

Underground pipelines suffer from corrosion in soil layers, and this corrosion is accelerated with the increasing of soil thickness due to more water contained. Cathodic protection (CP) is one of the most common methods for controlling corrosion of metals. Its popularity returns to the fact that CP system is simple, cheap, and suitable for many industrial applications. The drawback of the available CP systems is the need to go to the site for gathering data using classical instruments and methods, which is tedious, dangerous, uneconomic, and inaccurate. The main objective of this paper is to present a real-time remote monitoring and control (RT-RMC) system for any CP platform. The work started with implementation of an industrial-like CP prototype to realize the desired task. The implemented CP system consists of two famous CP methods, the sacrificial anodes (SACP) and the impressed current (ICCP). After that, the RT-RMC system is implemented with two techniques, global system for mobile communications (GSM), and web of things (WoT) to facilitate monitoring and control tasks. Experimental results are obtained for voltage and current measurements with different environments, disturbance, and pipe coatings.

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## 1. INTRODUCTION

Pipelines are the main, global, and distinguished tools for transporting water and petroleum products. They are usually suffering from some natural phenomena (e.g., corrosion) or some external effects (e.g., cross pipelining, vehicular movement, and acidity). Classical methods of pipelines monitoring involve intermittent appraisal of pipelines status using field visits or some not real-time surveillance devices. High cost, planning complexity, and the absence of suitable access routes are some main drawbacks for these monitoring approaches. Usually, operators prefer the real-time monitoring of pipelines to be restricted to control rooms in a particular location.

Today, there is about 2.5 million kilometers of hydrocarbon pipelines [1] need to be strongly protected to avoid damage, which costs millions of dollars. Previous research papers had concentrated on the development of intelligent pipeline inspection gauges (pigs) to achieve monitoring [2]. These pigs cost about \$56,000/km of pipeline [3], the matter that led to 25% of the world's pipelines to be 'un-piggable'. Piggings systems are very messy, labor-intensive, and may not satisfy health, safety and environment (HSE) parameters since they are run during pipelines' operation.

The use of global system for mobile communications (GSM), internet of things (IoT), and web of things (WoT) are proposed as a replacement to realize real time monitoring of a pipeline from anywhere and

anytime. WoT is an ecosystem of services that orchestrating different types of services in an agile manner, leading to services with more human-centric and smartness. The inclusion of services from sensors and actuators makes WoT differs from classical web.

Damages caused by corrosion and other natural events generate standard range voltages and currents that propagate through the fluid in the pipeline. Detection and measurement of these voltages can be carried out at points remotely distant from the site using GSM or WoT or both. These measured voltages contain information about the status of the pipelines and the location of the damage along the pipeline.

Several methods for monitoring are issued by researchers and had been given in their manuscripts. The oil and gas sector are slow in applying IoT techniques despite having pipelines and drilling rigs for tens of years. Recently the extraction industry started to apply IoT [4]. This change is due to energy cost that must be considered in recent times, and due to the coronavirus disease (COVID-19) pandemic. Petrol companies are trying to reduce costs via the use of integration and automation. Wireless techniques became a good choice for petroleum companies to minimize human errors and obtain real-time readings from the several instrumentations available along the petroleum pipeline [4]. IoT can also be used in pipeline monitoring and control, where it can drive actuators (e.g., fans) and send an alert to a mobile phone to avoid a major disruption or damage of a pipeline or its power supply [5].

Joshi [6] expressed that without IoT, organizations would need to depend on people to do routine checks and measurements. The IoT framework helps in reducing manual checks because of its capability to screen pipelines continuously (24/7/365). Another benefit of IoT in pipeline observing as expressed in [6] is the productive administration of laborers. Cheddadi *et al.* [7] presented an IoT framework to assemble and screen continuously electric and environmental information of a PV solar station. The ESP32 DEVKIT V1 was utilized as the microcontroller, and information is sent to the cloud through implicit Wi-Fi. Ferraris *et al.* [8] developed a measuring system able to continuously monitor the system protection state and maintaining it in a safe condition. The proposed system attached a controller that can adjust the sacrificial anode current, hence increasing its life and keeping its protection effect. Islam *et al.* [9] presented an IoT framework for efficient monitoring and effective control of various aquatic environmental parameters. The proposed system was implemented as an embedded system using sensors and an Arduino. Different sensors, including pH, temperature, turbidity, and ultrasonic are placed in the site and each of them is connected to the main microcontroller.

Wang *et al.* [10] combined a long-distance pipeline CP method and GSM technology. The system realized automatic pipeline testing and transmission of test data and had succeeded in solving transmission of test data at the area having no GSM signals. Luo [11] designed and developed a pipeline inspection system based on smartphone integrated with GPS/GPRS technology with its system architecture and function modules. Irannejad and Irannejad [12] designed a device for remote sending the CP information of oil and gas pipelines and applied it to supervisory control and data acquisition (SCADA) system via GSM. This device had been designed and tested in a local oil pipelines and telecommunication system. Al-faiz and Mezher [13] developed a SACP system that remotely monitored the oil pipelines and reduced the incidence of corrosion. The proposed system integrated the technology of wireless sensor networks (WSN) to collect potential data and realized remote data transmission. Liu *et al.* [14] proposed a system that used WSN with the internet. The comparisons of many wireless communication technologies had been discussed with their transmission range, processing, transmission rate, and quality. Among them, the GSM/GPRS found to be the most attractive technology to be used due to the merits of having a spread coverage in the whole world. Eze *et al.* [15] proposed an architecture for WSN with enhanced power consumption and data transmission rate for pipelines. The requirements and components of motes, different threats to pipelines and methods of detecting such threats were presented. Fournier and Michalon [16] developed an image-based surveillance technique, designed for monitoring, reporting, warning, and alarming purposes from any abnormal activities detected at the locations near the underground pipeline's sites. The basic traceability algorithm of the online aircraft monitoring relies on the image recorded previously taken from the previous flights and compared with every new monitoring. Zakharov *et al.* [17] presented a satellite-based monitoring for image processing automated algorithm and software for detecting and controlling the intended target. This technique could make an archive for storing data, which could be used later by the pipeline operators. Kassim and Lazim [18] established design requirements of a good algorithm tracking system and designed a prototype automatic adaptive solar photo voltaic (PV) module connected through IoT, wireless connection to a webpage and information transferred via Android phone.

The competitive advantage of the proposed work of our paper and its contribution to industry lies in its ability to perform real-time wireless readings of CP system parameters to detect damage location using a combination of voltage/current propagation, set of sensors, a wireless data transmission system, and an internet of thing (IoT) platform to connect with a web server. With this system, the transmission of damage data captured by sensors to the control and monitoring center (CMC) is achieved wirelessly, making the monitoring of pipelines in real-time from any geo-location in the world possible. This proposed system is an

inexpensive device since it uses commercial-of-the-shelf (COTS) modules, and it is an easy to deploy using existing local infrastructure. The CP system site is connected to the CMC via GSM and Internet. The CMC monitors and controls all peripherals of the CP system, maintains a log of alerts, displaying sensors' information, and control some relays for "fans" and "CP type selection". This system can be embedded in a SCADA system to satisfy pipeline surveillance.

The paper is structured as follows: section 2 covers the materials and methods used in building the whole system. Section 3 contains the experimental results. Section 4 focuses on the main conclusions and some future works.

## **2. MATERIALS AND METHODS**

### **2.1. Cathodic protection (CP) system**

CP is one of the most common methods for controlling corrosion for underground or submerged metallic pipelines. Sir Humphry Davy was the first in applying and suggesting the idea of cathodic protection when applied it to protect ship's hull. The corrosion rate of metals was reduced after applying CP. CP systems are used worldwide because its effectiveness in protecting structures like pipelines, tanks, and bridge decks. At the pipe surface and under the condition of corrosion, anodic and cathodic regions are formed and the current flows inside the pipe at the cathodic sides which results in corroding anodic areas while maintaining cathodic areas without corrosion. CP forced the whole metal structure (being protected) to become a cathode by applying an external direct control (DC) current to each point at the pipeline surface making the potential of the pipe with more negativity leading to minimum corrosion rate. There are two methods of cathodic protection systems [19]:

#### **2.1.1. Sacrificial anode cathodic protection (SACP)**

The anode, connected directly to the structure, is sacrificed to protect the intended structure. There are many advantages for this system such as: no need for external power supply, uniform current distribution, easy to install and doing maintenance, and minimized cost. Its disadvantages are, requiring large number of anodes, working in low resistive environments only, short lifetime for anodes, and higher cost per unit Ampere. In this paper, a magnesium anode is used which has a potential of -1.55 V or -1.75 V when measured with respect to Cu/CuSO<sub>4</sub> electrode and suitable for both soil and water environments. Most frequently, magnesium sacrificial anodes are used as temporary protection of underground pipelines during the construction and installation phase, prior to energizing a permanent impressed current cathodic protection (ICCP) system.

#### **2.1.2. Impressed current cathodic protection (ICCP)**

The required protection current impressed using an external power source is placed between the anodes and the structure being protected. The DC current is forced to flow from the anode to the structure to satisfy protection. The advantages of this method are providing a range of voltages and currents, working in low and high resistivity environments, suitable for uncoated structures, economically suitable when installed on existing structures or replacing anodes, and suitable for applications need high currents. Its major disadvantages are, interference, high cost for maintenance, overprotection may occur, and probability of premature breakdown. In this paper, a high silicon-cast iron, Ferro silicon (Fe-Si), and anodes are used. Instead of building sacrificial anode cathodic protection (SACP) temporarily during construction and then building permanent ICCP system, the proposed work of this paper builds the two systems together at the same time with ICCP electrically separated and SACP is electrically connected temporarily for protection. After finishing of the construction phase, the SACP is electrically disabled and ICCP is electrically connected as permanent protection. This is done with "Relays" remotely controlled from the CMC. The new added benefit of this work minimizes cost, time, and efforts. The schematic diagram of the proposed CP system setup is shown in Figure 1.

### **2.2. Field installation**

In this section, the field work including materials selection, drilling process, welding process, and electrical connections are explained. Studying the effect of interference, soil resistivity, soil temperature, conductivity and potential difference between the pipe and soil is essential for any CP system engineer to reveal and control the reasons of corrosion. The electrical design of the CP system should follow the procedures and standards of National Association of Corrosion Engineers (NACE) [20] to obtain exact results and avoid performance degradation. In addition, supplying a protection of an acceptable level and a minimum cost (for installation, maintenance, and power consumption) must be achieved. Tables 1 and 2 show the characteristics and dimensions of the pipeline and anodes used in SACP and ICCP systems

respectively. The rectifier used in this system has 9 V supply with a maximum current of 1.5 A. The detailed design equations for the various parameters needed for the CP system design can be found in [21]–[25].

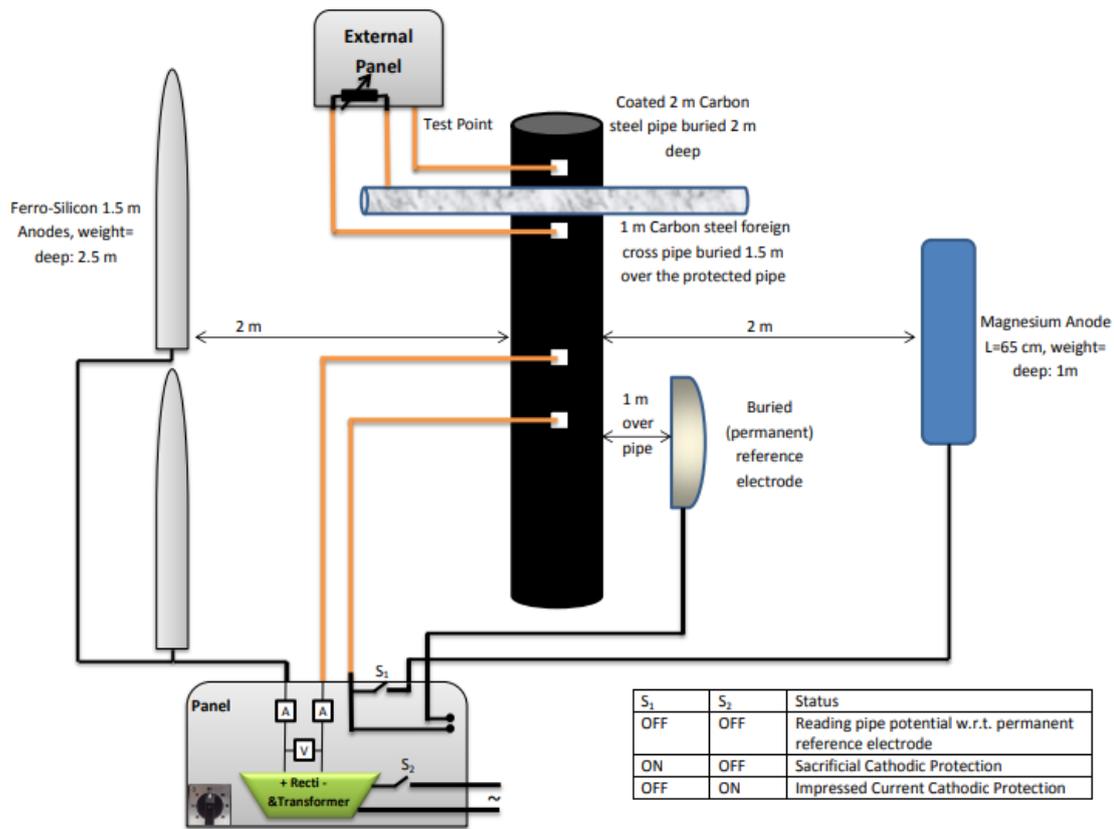


Figure 1. The schematic diagram of the entire CP cell

Table 1. Pipeline and Magnesium anode’ characteristics of SACP system

Pipe length (ft)	Pipe diameter (inch)	Pipe thickness (inch)	Coating quality (%)	Required current density (mA/ft <sup>2</sup> )	Soil resistivity (W-cm)	Anode weight (lb)	Anode length (ft)	Anode diameter (ft)
6.39	10.75	0.365	80	2	656.84	24	1.91	0.374

Table 2. Pipeline and Ferro-Silicon anodes’ characteristics of ICCP system

Pipe length (ft)	Pipe diameter (inch)	Pipe thickness (inch)	Coating quality (%)	Required current density (mA/ft <sup>2</sup> )	Soil resistivity (W-cm)	Anode weight (lb)	Anode length (ft)	Anode surface area (ft <sup>2</sup> )
6.39	10.75	0.365	80	2	656.84	110	1.91	4

The materials prepared for burying contains the carbone steel pipe that needs protection, Mg anode used for SACP, two parallel-connected Ferro-silicon anodes used for ICCP, and DC power supply needed with ICCP as shown in Figure 2. The distance between the anodes and the structure being protected is estimated to be 2m, and the depth of burying is nearly 2 m. The CP system test mechanism depends on the pipe-to-soil voltage, which is measured with a reference electrode (RE) permanently buried 1m adjacent to the pipe being protected as shown in Figure 3. There are five test points (TPs) distributed and welded 40cm distant along the surface of the pipe. Exothermic welding is the process of connecting test leads wires, bond wires, galvanic anode leads, and rectifier negative terminal to the surface of the pipeline. For insulation with high electrical resistance, a mixture of cold curing material of polyurethane resin is used for cable joints due to its good anti-corrosion properties. Figure 3 also shows the wire routing from the underground pipeline to the indoor and outdoor panels. The indoor panel contains transformer/rectifier unit, a selector switch, amper/voltage analog gauges, and a small panel for the remote monitoring and control (RT-RMC) system as shown in Figure 4.

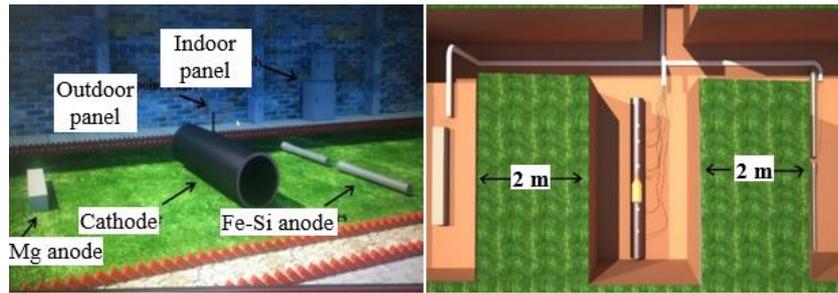


Figure 2. Materials' distribution of the whole CP system

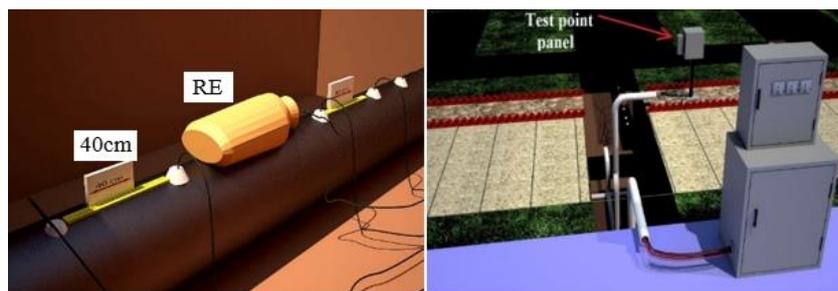


Figure 3. Permanent RE, welded TPs, and indoor and outdoor panels

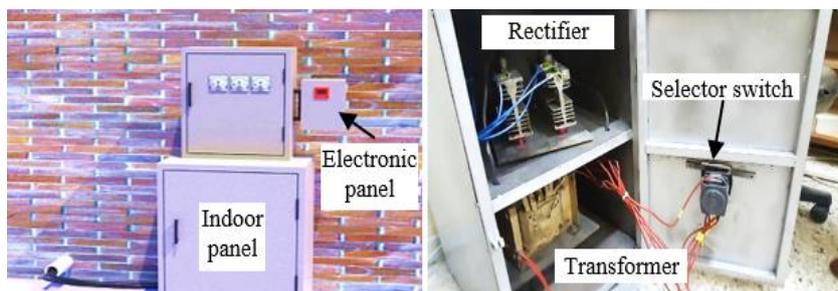


Figure 4. The indoor panel contains power unit and monitoring unit

### 2.3. RT-RMC system

To overcome the old classical manual offline measurement and surveillance methods used to pursue CP cells and to move towards automation, the work of this paper introduces two RT-RMC platforms. The first platform is based on GSM technology and the second is based on WoT. The proposed system has also some control capabilities to control electrical fans for panels and a selection capability for selecting the desired protection method: SACP or ICCP.

#### 2.3.1. GSM technology

GSM shield is used in this project to support the SMS sending functionality. The voltage and current return from the CP cell are the main parameters that need to be monitored for the system operator. These parameters are sent as SMS messages via GSM SIM900 module to the operator mobile phone. This technique is beneficial when there is no internet service, or the operator is far away from the control center. The messages have been sent in the form, #ON1 for ICCP cell readings or #ON2 for SACP cell readings as shown in Figure 5. The hashtag, #, is used to clarify that the message is received from the system and not from an intruder or unauthorized persons. The measured data readings can also be monitored remotely on a human machine interface (HMI) designed using C# for that purpose as shown in Figure 6. To add another monitoring facility, a 16×2 LCD display is connected to the main microcontroller, Arduino UNO, to provide a local monitoring on the indoor panel as shown in Figure 7, which displays the whole electronic diagram for the designed microcontroller-based system. The measured readings (analog voltage/current) must be

converted to digital before sending to the Arduino microcontroller. This is done using voltage and current sensors shown in Figure 7. Additional facility has been added to the proposed system, that is, a soft changeover is used to switch between SACP and ICCP using 4-channels relay module displayed also in Figure 7. The mechanism for “Relay” switches operation is explained in the table included in Figure 1.



Figure 5. Phone-based CP data monitoring

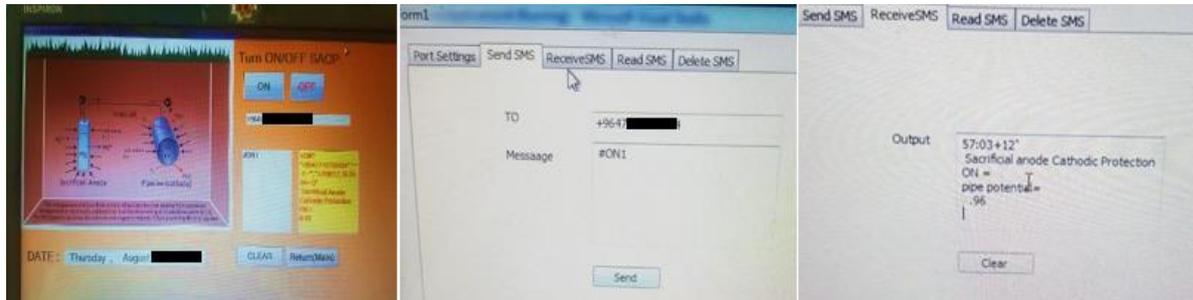


Figure 6. HMI for data logging and monitoring

### 2.3.2. Web of things

Different methods from various points of view had been presented to support the development and spreading of IoT [18]. One of these methods is viewing IoT as WoT where the free web applications are adopted for data sharing and embedded device's interoperation. By inserting smart things into existing web, the standard web services are enhanced with physical world services. WoT's idea presents a new technique for limiting the gap between virtual and physical worlds. In this paper, open platform and prototype are developed for our CP application. Arduino Uno microcontroller board with Ethernet shield is used as a client server and connected to the Internet via a router as shown in Figure 8. Using a web architecture as a basic platform, web servers directly provide web services on the world wide web. WoT has a flat architecture as compared to the traditional client-server model. Indirect integration is used to integrate the sensor nodes to the web, in which an intermediate proxy (smart gateway) is placed between the sensors and the web. The smart gateway abstracts the suitable protocol and APIs of the sensor node and provide uniform accessible web. A prototype with smart gateway to directly integrate voltage/current sensors into the web is presented. To use a web browser to effectively query and manage the sensors/actuators, the gateway is programmed to have a web server supporting http protocol. The implemented applet for efficient and real-time data aggregation and exchange is shown in Figure 9. The workflow for the proposed real-time system is shown in Figure 10.

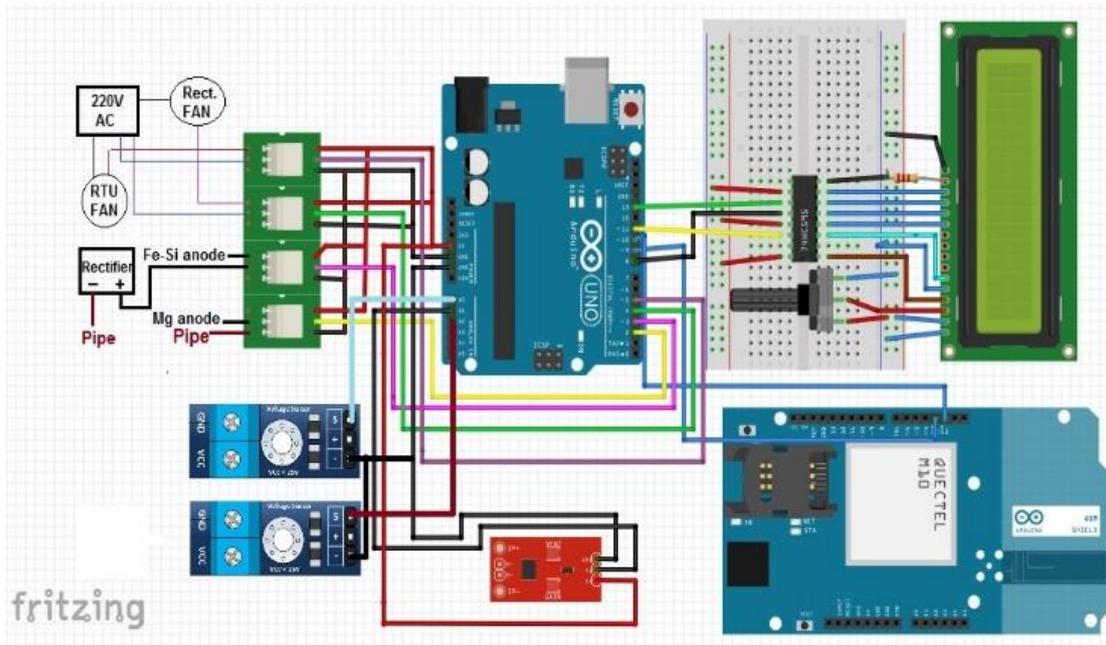


Figure 7. Electronics diagram of the overall RT-RMC unit

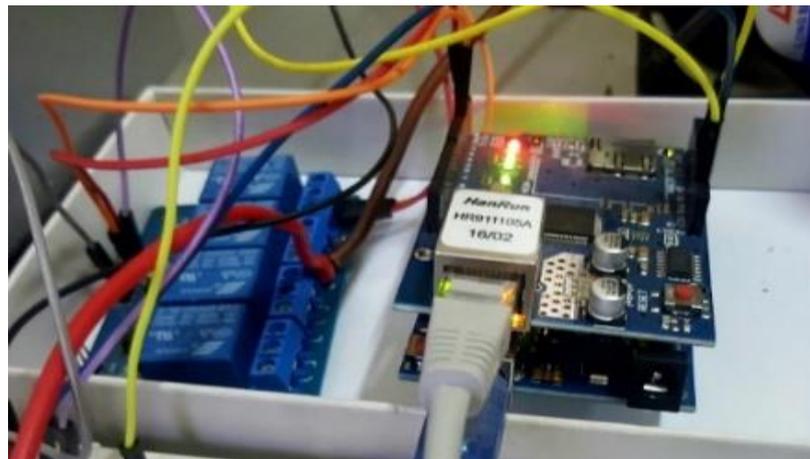


Figure 8. Ethernet web server

Catholic protection wireless mo x +

localhost/All/index%20(4).html

### Monitoring/Control System for Underground Pipelines

Sacrificial Anodes Method		Impressed Current Method	
Real-time pipe voltage (V)	-1.2	Real-time pipe voltage (V)	Unknown
Status	On	Status	Off
<input type="button" value="Fan On/Off"/> <input type="button" value="Connect"/> <input type="button" value="Disconnect"/>		Real-time current (A)	Unknwon
		<input type="button" value="Fan On/Off"/> <input type="button" value="Connect"/> <input type="button" value="Disconnect"/>	

Figure 9. Applet for RT-RMC unit

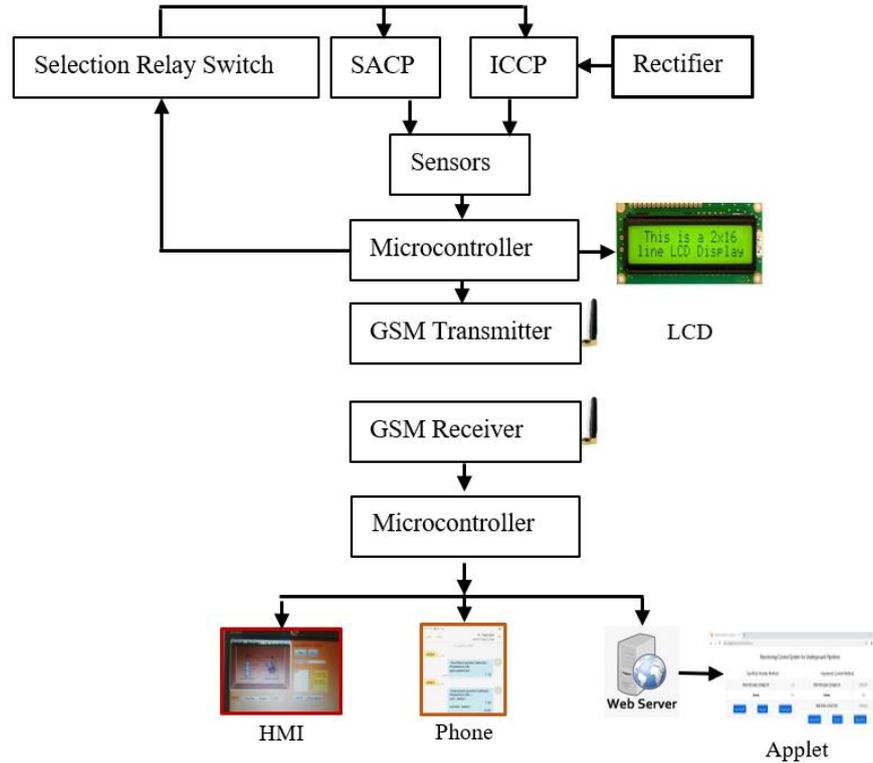


Figure 10. Workflow of the proposed real-time system

**3. EXPERIMENTAL RESULTS**

Using the characteristics and dimensions in Tables 1 and 2 and the design equations in [21]–[25], the designed parameters for the SACP and ICCP Systems are given in Tables 3 and 4. It is important to consider that the coating material plays a significant role on the lifetime of pipelines. It can reduce corrosion and current required for protection and then avoiding continuous coating maintenance. For the work of this paper, a new polymer material is developed to improve the protective requirement over conventional commercial coatings. The composition of this new polymeric material is beyond the scope of this paper since it will be introduced as a patent. Table 5 shows the required current and potential to satisfy full protection using the new polymeric material as compared to the normal one which depends on the wrapping-tape layer with primer material.

Table 3. SACP system design parameters

Required current (A)	Anode resistance ( $\Omega$ )	I anode (A)	Number of anodes	Expected lifetime (Years)	Expected polarized potential (V)	Lifetime (Years)
0.007	2.18	0.415	1	15	-1.2	15

Table 4. ICCP system design parameters

Required current (A)	Anode resistance (W)	Required voltage (V)	Number of anodes	Expected lifetime (Years)	Expected polarized potential (V)	Lifetime (Years)
1.5	3.9	9	2	25	-1.5	15

Table 5. Voltages and currents required for normal and invented coatings

Coatings	SACP				ICCP	
	Pipe potential (V)		Pipe potential (V)		Needed voltage (V)	Current demand (A)
	TP1	TP2	TP1	TP2		
Pipe with normal coating	- 0.85	-0.84	-1.5	- 1.49	2	0.5
Pipe with new polymer coating	- 1.2	- 1.19	-1.6	-1.5	1.5	0.3

The required voltages and currents are much lower in case of using our new polymer coating than that when using the commercial coating. This significant difference leads to increasing in pipeline lifetime to about 25 years instead of 15 years with the normal coating. The recorded parameters require to take the soil temperature and conductivity into consideration to get accurate results. Table 6 shows the current density and protection voltage with temperature and conductivity were taken into consideration. Whenever the conductivity is increased, the impressed current for protection is increased correspondingly.

Table 6. Current density and protection voltage vs soil temperature and conductivity

Soil Temperature (C°)	Conductivity (mg/l)	Supply Voltage (V)	Current Density (A)	Protection Voltage (V)
29	765	2	0.3	-1.3
33	1503	4	0.5	-1.3
36	1550	6	1	-1.3
40	1560	8	1.5	-1.3

Underground pipelines are usually suffering from some external effects such as foreign pipeline crossing, in which a foreign pipeline intersects the main structure leading to some interference. This disturbance is taken into consideration during the installation process of the CP cell of this work as shown in Figure 1. The proposed solution to this problem is to use a “bonding resistance” connected between the structure being protected and the foreign pipe at the intersection point [26]. The variable bonding resistor is adjusted empirically to make the foreign pipe potential meets a steady value when measured with respect to Cu/CuSo<sub>4</sub> RE positioned near the point of intersection. The obtained value of the resistor is approximately 1.4 as shown in Figure 11.



Figure 11. Variable bond resistor measurement

#### 4. CONCLUSION AND FUTURE WORK

A real-time remote monitoring wireless communication system was developed for transmission of measured CP voltages and currents wirelessly based on GSM and WoT platforms. Test rig was built with SACP and ICCP with water as the transport liquid to prove the efficacy of the developed monitoring system. The system is not only used for monitoring, but also for some control commands to actuate fans used for cooling inside panels. The system has the following facilities: local monitoring on an LCD, remote monitoring HMI, remote monitoring based on SMS to a mobile phone, and internet-based monitoring with web browser using a WoT platform. This low-cost pipeline monitoring system performs real-time damage detection based on “Test points” measured voltages, determining location based on “Test point number”, and allows operators to view the results of the measured parameters in real time on a smart phone or even on a computer system from any geo-location worldwide. The polymer coating of the pipe presented in this paper will be introduced as a patent since it has a new composition, results in getting larger lifetime and lower current for protection. As a future work, a PLC can be used instead of Arduino to get a heavy-duty monitoring system. Also, an Andriod app can be designed for monitoring and some analytics for predictive maintenance, which is a condition-based maintenance process that uses data analytics to indicate the possible equipment failure time for scheduling maintenance. Proper maintenance scheduling helps to avoid unplanned or sudden equipment failure.

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