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APPLICATION OF INDUSTRY 4.0 TECHNOLOGIES FOR EFFECTIVE REMOTE MONITORING OF CATHODIC PROTECTION SYSTEM OF OIL AND GAS PIPELINES – A SYSTEMATIC REVIEW

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Abstract

Implementation of Industry 4.0 technologies in remote monitoring for cathodic protection of oil and gas pipelines saves time and money, gives a real-time image of the effectiveness of the Cathodic Protection System on the Pipeline for corrosion control, even from a remote location. This paper presents a systematic review of the implementation of industry 4.0 technologies for effective remote monitoring and cathodic protection of oil and gas pipelines. Many databases, such as the Google Scholar, Scopus, IEEE Xplore, ResearchGate, ScienceDirect were used for data collection. The study revealed that modelling a real-time view of the Cathodic Protection System Monitoring functionality will give the same image one would get during the site visit and help with decision making. This collaboration is essential to industries due to issues like the covid-19 pandemic, which imposes movement restrictions, security threats in some locations and inaccessibility of pipeline's right of way.

Keywords: Virtual Reality; Real-Time Assessment; Corrosion Control; Internet of Things.

1. Introduction

The economy of Nigeria is largely dependent on the oil and gas industry. The oil and gas industries contribute about 65% of the government revenue and 88% of the country's foreign exchange. These industries make use of underground pipes to transport materials from one place to another. These materials are hazardous substances in the form of hydrocarbons in either gas or liquid form, including natural gas, crude oil, high vapour pressure products such as propane and refined products such as gasoline or jet fuel (Shipilov & May, 2006). These pipes are continuously exposed to harsh environmental conditions that result in corrosion-related damages.

In Nigeria, a significant problem is the corrosion of the external surfaces of such pipelines, which are not usually adequately safeguarded during construction (Lilly et al., 2007). Most of these metallic pipes have been in use for over five years and have experienced metallurgical defects, cracks and corrosion. The sources of these cracks can be due to randomly distributed defects induced by the manufacturing process or the degradation of carbon steels used as components of pipelines. The combined action of stress (e.g., hoop and/or residual) and natural soil environment containing varying amounts of moisture and oxygen further facilitates the crack initiation (s) and corrosion. This accelerates their propagation through the pipe thickness, which can lead to pipeline failure, damage to products, soil pollution, and subsequent environmental degradation when left unchecked.

Cathode protection (CP) is one of the most widely used methods in the oil and gas industry to prevent (or reduce) rust and corrosion of structures and metal pipelines or their associated cost (Oghli et al., 2020). Cathodic protection is a critical technology for corrosion control that can be applied to underground or submerged metallic infrastructures like pipelines. It is typically used in conjunction with coatings and can be considered as a secondary corrosion control technique.

Traditionally, the Cathodic System requires periodic inspection and thorough data analysis by specialized personnel. This is to ascertain the level of protection of the Pipeline against corrosion, introduction of foreign metallic structures, stray currents, localized coating defects, etc. This periodic inspection is associated with challenges like time-consuming, cost-intensive, and requires qualified personnel and accessibility of the pipeline right of way. Owing to the challenges associated with this periodic inspection, there have many paper studies on remote Cathodic Protection Monitoring.

This paper presents a systematic review of industry 4.0 technologies for effective remote monitoring for cathodic protection of oil and gas pipelines.

2. Methodology

This paper presents the different remote cathodic protection monitoring of oil and gas pipelines against corrosion, with a special focus on the application of industry 4.0 technologies which provides a real-time pipeline inspection and allows pipeline monitoring from outside the site with immersive experience. The research strategy adopted is presented and the results analysed.

2.1 Search strategy

An ordered and planned search was carried out to identify papers with focus on remote cathodic monitoring and other systems for inspection of oil and gas pipelines against corrosion, especially papers that applied industry 4.0 technologies in carrying out this task. The materials were gathered through web searches, different databases were accessed such as, Science Direct, Scopus, Springer, Google Scholar, IEEE Xplore, and Research Gate (Mgbemena et. al., 2020).

Materials written only in English Language with related literatures published from 2003 to 2021, were selected, so as to capture the recent trends and applications of the systems under review, and its impacts in Cathodic Protection System monitoring. Another important consideration for eligibility was the selection of papers that answered any of the following questions:

- Does the paper focus on industry 4.0 technology?
- Does the paper have a cathodic monitoring system?
- Does the proposed system help in corrosion control?
- Does it discuss the application of these systems for Corrosion Control and cathodic protection system monitoring?

All paper not published before 2003 and not written in English Language were not selected for this study.

2.2 Search Results

Materials were initially sorted out based on the title and abstract. Papers that did not contain information on cathodic monitoring of pipelines for corrosion control, and use of industry 4.0 technologies for this purpose were dropped. Only online publications written in English language and published within the period under study were used. At last, a total of 50 papers were gathered, these papers were thoroughly studied to extract its case studies and experimental descriptions.

2.3 Analysis

The whole of the papers studied in this review are presented in the table below. The table 1 below presents a broad overview of the papers reviewed.

Table 1: Analysis of 2003 – 2008 papers

S/N	Article	Author, Country and year	Journal	Objective of the paper	Number of papers studied	Duration
1	Structural integrity of aging buried pipelines having cathodic protection.	Shipilov & May (2006). Canada	Engineering failure analysis	In this paper, close attention is paid to the role of hydrogen embrittlement in pipeline safety and reliability.	101	1958-2005
2	Prolonging the lives of buried crude-oil and natural-gas pipelines by cathodic protection.	Lilly, Ihekwoaba, Ogaji & Probert (2007) Nigeria	Applied energy	Use of cathodic protection in corrosion control of external surfaces of pipelines.	21	1983-2004
4	Natural products as corrosion inhibitor for metals in corrosive media — A review	Raja & Sethuraman (2008) India	Material letters	The paper gives an account of natural products which are used as corrosion inhibitors for various metal and alloys in aggressive media	83	1935-2007
5	Consequences and standards from using cathodic protection systems to prevent corrosion	Durham & Durham (2005) USA	IEEE Industry Applications Society 50th Annual Petroleum and Chemical Industry Conference	In the paper, history of cathodic protection is traced, the design fundamentals are developed, including the three components of a corrosion system.	23	1981-2002
6	Online, real time monitoring for improving pipeline intergrity – Technology and experience	Kane & Eden (2003) USA	NACE Corrosion Conference, San Diego, California.	The paper describes the evolution in corrosion monitoring technology from off-line historical applications to online, real-time use.	50	1975-2002
7	Virtual reality Presentation for Nondestructive Evaluation of Rebar Corrosion in Concrete based on Inverse BEM	Kyung et al. (2005) Korea	Journal of Korean Society for Nondestructive Testing,	In the paper, potentials measured on a concrete surface are compensated into those on the concrete-rebar interface by the inverse boundary element method (IBEM).	13	1978-2003
8	Monitoring of Distributed Pipeline Systems by Wireless Sensor Networks	Jin & Eydgahi (2008) USA	Proceedings of the 2008 IAJC-IJME international conference	The paper describes a sensor network platform for pipeline system monitoring.	23	1970-2008

Table 2: Analysis of 2009 – 2014 papers

S/N	Article	Author, Country and year	Journal	Objective of the paper	Number of papers studied	Duration
1	Cathodic corrosion protection systems: A guide for oil and gas industries	Bahadori (2014) Australia	Gulf proffesional publishing	The work provides information concerning survey requirements to ascertain that corrosion control systems installed on buried or submerged structures are properly designed, operated and maintained.	210	1952-2013
2	The dual role of microbes in corrosion	Kip & Veen (2015) Netherlands	International Society of Microbial Ecology Journal	The paper discussed the role of microorganisms in corrosion control	99	1962-2014
3	Monitoring and evaluation of cathodic protection performance for oil and gas pipelines: a nigeria situation.	Onyechi et al. (2014) Nigeria	Journal of natural gas science and engineering	The study monitors and evaluates the extent of cathodic protection performance on the Trans-Niger Pipelines (TNP) onshore Nigeria.	32	1974-2013
4	Remote monitoring of oil pipelines cathodic protection system via GSM and its application to SCADA system	Irannejad & Iraninejad (2014) Iran	International Journal of Science and Research	The paper explained a device for remote sending the cathodic protection information of oil and gas pipelines and applying it to SCADA system via GSM.	3	2008-2010
5	Non intrusive online corrosion monitoring.	Saluja et al. (2009) India	Proceedings of the national seminar & exhibition on non-destructive evaluation	The paper presents a new non-intrusive technology to monitor corrosion using ultrasonic and software.	6	2001-2009
6	Intelligent remote monitoring system for cathodic protection of transmission pipelines	Peratta et al. (2009) USA	NACE Corrosion Conference, Atlanta, Georgia	The paper presents an intelligent remote monitoring system for the assessment of coated transmission pipelines of few hundred kilometers long.	22	1988-2009
7	Artificial neural network models for predicting condition of offshore oil and gas pipelines	El-Abbasy et al. (2014) Canada	Automation in Construction	The paper proposed models predicting the condition of offshore oil and gas pipelines, the models are developed using artificial neural network technique.	26	1987-2014
8	Real-time corrosion control system for cathodic protection of	Kim et al. (2015) Korea	Corrosion science and technology	The paper focuses on the development and build-up of real-time monitoring and	14	1996-2011

	buried pipes for nuclear power plant.			control system of buried pipes.		
9	Cathodic Protection Remote Monitoring Based on Wireless Sensor Network.	Al-Faiz & Mezher (2012) Iraq	Scientific Research	In the paper, the use of cathodic protection system and how they can be developed to simulate corrosion control solution was illustrated.	12	2000-2012
10	Understanding Virtual Reality Technology : Advances and Applications	Onyesolu M.O. (2015) Nigeria	Advances in computer science and engineering	The paper discussed the numerous applications of VR such as simulation, design evaluation, ergonomics study etc.	52	1992-2009
11	Virtual reality applications in manufacturing industries : Past research , present findings , and future directions	Choi et al. (2015) Korea	Concurrent Engineering, Research and Applications	Trends in past and present research were examined and future virtual reality research directions and application plans for manufacturing enterprises are discussed.	171	1991-2014
12	Corrosion Prevention and Control Training in an Immersive Virtual Learning Environment.	Rustin D Webster (2014) USA	NACE International Corrosion Conference Series.	To develop and provide portable VR system containing purposely designed and developed immersive virtual learning environment.	50	1956-2012
13	Corrosion problems during oil and gas production and its mitigation	Popoola et al. (2013) Nigeria	International Journal of Industrial Chemistry	The paper gives a comprehensive review of corrosion problems during oil and gas production and its mitigation.	78	1949-2012
14	Revealing the relationship between grain size and corrosion rate of metals	Ralson et al. (2010) Australia	Scrita Materialia	The paper correlates with total grain boundary length and reveals an important fundamental relationship that can be exploited for material durability and design	22	1980-2009
15	Wireless Sensor Networks for Leakage Detection in Underground Pipelines : A Survey Paper.	(Al-kadi et al., 2013) Saudi Arabia	Procedia computer science	The paper discussed the four different solutions for leaks in pipelines using wireless sensor networks	20	1990-2012
16	Integrated Fiber Optic Sensing System for Pipeline Corrosion Monitoring	Huang et al. (2015) USA	Pipelines 2015	In the paper, an integrated fiber optic sensing system is developed to assess the corrosion of on-shore buried metallic transmission pipelines in a real time manner	27	2000-2014

17	MISE-PIPE : Magnetic induction-based wireless sensor networks for underground pipeline monitoring	Sun et al. (2011)	Ad Hoc networks	The paper presents magnetic induction (MI)-based wireless sensor network for underground pipeline monitoring, to produce lost cost and real-time leakage detection.	44	1990-2010
18	Visualising Environmental Corrosion in Outdoor Augmented reality	Walsh & Thomas (2011) Australia	Proceedings of the 12th australian user interface conference	The paper provides a description of outdoor visualization of environmental corrosion data.	23	1997-2009
19	Pipeline Internal Corrosion Monitoring System with Pitting Corrosrion Monitoring ability	Zhiping et al. (2012) China	Electronic measurement technology 2	The paper developed a pipeline corrosion monitoring system based on the potential matrix method.	32	2001-2011
20	Long period fiber grating sensors coated with nano iron/silica particles for corrosion monitoring	Huang (2013) China	Smart materials and structures	In the study, a long fiber grating sensor coated with a thin film of nano iron and silica particles is designed and tested for corrosion and environmental monitoring.	43	1996-2017

Table 3: Analysis of 2015 – 2020 papers

S/N	Article	Author, Country and year	Journal	Objective of the paper	Number of papers studied	Duration
1	A Reliable Internet of Things based Architecture for Oil and Gas Industry.	Khan, Aalsalem, Khan & Hossain (2017).	2017 19th international conference on advanced communication technology (ICACT)	A NOVEL IoT based architecture is proposed for oil and gas industries to make data collection reliable and quick.	**42**	**2002-2016**
2	Design and analysis of the cathodic protection system of oil and gas pipelines, using distributed equivalent circuit model.	Oghli et al. (2020) Iran	Journal of natural gas science and engineering	The paper proposed a new distributed model to design a cathodic protection system for oil and gas transmission pipelines, which is extendable and can be useable in other structures.	26	1955-2018
3	Remote monitorng and intelligent controls of a cathodic protection system of gas trasmission pipelines	Das (2017) Bangladesh	Department of petroleum and mineral resources engineering (PMRE), BUET.	To design, develop, instal and test a remote monitoring and intelligent control system for cathodic protection.	24	1974-2017

4	Monitoring and Control on Impressed Current Cathodic Protection for Oil Pipelines	Jasim A. Harbi et al. (2017) Iraq	Al-Nahrain Journal for Engineering Sciences (NJES)	The paper presents the design and implemention of a Supervisory Control and Data Acquisition system (SCADA) for monitoring and controlling the corrosion of a carbon steel pipe buried in soil	12	2003-2014
5	A networked control system for gas pipeline cathodic protection	Abate et al. (2019) Italy	IEEE Transactions on Instrumentation and Measurement	The implementation of a low cost-system able to monitor and control the pipeline potential in a suitable measurement point.	30	1967-2018
6	High accuracy ultrasonic corrosion monitoring.	Zou & Cegla (2017) UK	Electrochemistry Communications	The presents an ultrasonic approach for monitoring corrosion and electrodeposition	11	1961-2016
7	Techniques for corrosion monitoring	Yang (2020) USA	Woodhead publishing.	The paper focuses on the dissemination of the corrosion monitoring information for the asset operators to combat corrosion	25	1994-2019
8	Linear Wireless Sensor Networks (LWSNs) for Cathodic Protection Monitoring of Pipelines	Kara et al. (2019) Turkey	International Conference on Mechatronics, Robotics and Systems Engineering (MoRSE)	The paper presents design considerations and implementation (LWSNs) to be used in cathodic protection monitoring of oil and natural gas pipelines.	11	2009-2019
9	Towards immersive designing of production processes using virtual reality techniques	Buzjak & Kunica (2018) Croatia	Interdisciplinary Description of Complex Systems	The paper provides a novel approach to the implementation of virtual reality within planning and design of manual processes and systems.	20	1983-2017
10	Real Time Environment Simulation through Virtual Reality	Maheswari et al. (2018) India	International Journal of Engineering and Technology	To develop a simulation which changes its environment based on the outside environment.	12	2010-2018
11	Monitoring cathodic protection of buried pipeline by means of a potential probe with an embedded zinc reference electrode	Brenna et al. (2016) Italy	Journal of Material and Design.	In the paper, a new probe with a zinc reference electrode embedded in a proper backfill is proposed.	18	2002-2016
12	The cost of corrosion in China	Hou et al. (2017) China	Nature Partner Journal of Materials	The study sought to determine the national cost	25	1950-2016

			Degradation	of corrosion and costs associated with representative industries in china.		
13	Wireless Sensor Networks in Oil Pipeline Systems Using Electromagnetic Waves	(Alper et al., n.d.)	2015 9th International conference on electrical and electronics engineering.	The paper addresses the challenges of hostile underground environments for the realization of wireless sensor networks in oil pipeline systems.	18	1989-2015
14	Towards realisation of wireless sensor network-based water pipeline monitoring systems : a comprehensive review of techniques and platforms	Obeid et al. (2016) Saudi Arabia	IET science, measurement & technology	The study presents a comprehensive survey on software and hardware solutions proposed in the literature for water pipeline infrastructure monitoring.	46	1960-2015
15	Factors influencing corrosion of metal pipes in soils	Wasim et al. (2018) Australia	Enviromental chemistry letters	The paper reviews factors causing corrosion of buried pipes in soils.	112	1925-2018
16	Factors influencing corrosion of metal pipes in soils	Wasim et al. (2018) Australia	Enviromental chemistry letters	The paper reviews factors causing corrosion of buried pipes in soils.	112	1925-2018
17	Pipeline Monitoring System by Using Wireless Sensor Network	Golshan et al. (2016) Malaysia	Journal of mechanical and civil engineering	The paper addresses the detection of and localization problems for the acoustic sensor networks using signal processing techniques.	23	1972-2014
18	Pipeline corrosion control in oil and gas industry : A case study of nnpc / ppmc system 2a pipeline	Unueroh et el. (2016) Nigeria	Nigerian Journal of Technology	The paper presents different types of corrosion on system 2A pipeline, caused by poor maintenance, severe mutilation due to vandalization and coating failures.	10	1987-2011
19	Review of Corrosion Role in Gas Pipeline and Some Methods for Preventing It.	Karami (2019) Iran	Journal of pressure vessel technology	In the paper, corrosion and its types were investigated. Cathodic method of corrosion control is explained.	13	2002-2011
20	A Review Paper on Internet of Things(IoT) and its Applications	Sarika et el. (2019) India	International Research Journal of Engineering and Technology (IRJET)	The paper focuses on the meaning, components and application of Internet of Things (IoT)	14	2010-2017

Table 4: Analysis of 2021 – 2022 papers

S/N	Article	Author, Country and year	Journal	Objective of the paper	Number of papers studied	Duration
1	Predictive maintenance Framework for Cathodic Protection Systems using Data Analytics	Rossouw & Doorsamy (2021) South Africa	Energies	The paper presents a predictive maintenance framework based on the core function of the ICCP system.	44	1991-2021
2	Complete Integrated Automation of the Electrochemical Corrosion Protection System of Pipelines Based on IoT and Big Data Analytics	Oleksandr Prokhorov et al. (2022) Ukraine	MDPI Journal	The paper presents collection, analysis and control of Cathodic Protection System Remotely based on IoT.	15	2009-2022
3	Corrosion Fundamentals and Characterization Techniques	Cragnolino G.A. (2021) USA	Techniques for corrosion monitoring	The presents an overview of the different types of corrosion and the common techniques used to study and characterize corroded metal surfaces and corrosion products.	18	2003-2020
4	Predictive maintenance Framework for Cathodic Protection Systems using Data Analytics	Rossouw & Doorsamy (2021) South Africa	Energies	The paper presents a predictive maintenance framework based on the core function of the ICCP system.	44	1991-2021
5	Remote Monitoring and Comuter Applicatons.	Smalling et al. (2021) USA	Techniques for Corrosion Monitoring	The paper discusses the current state of remote monitoring, as it concerns corrosion control systems.	34	1997-2020
6	Corrosion monitoring under cathodic protection conditions ising multielectrode array sensors.	Sun et al. (2021) USA	Techniques for corrosion monitoring	The paper presents a new corrosion sensor, the coupled multielectrode array sensor (CMAS), for CP monitoring.	54	1998-2020
7	Application of SCADA System by Using (Fuzzy Logic Controller) on the Cathodic Protection System for Oil Pipelines	Harbi J.A. (2021) Iraq	Journal of Petroleum Research & Studies (JPRS)	The study is to design and execute supervisory control and data acquisition system (SCADA) to monitor and control the corrosion of a pipeline buried under ground.	15	1998-2014
8	Is COVID-19 pushing us to the Fifth Industrial Revolution (Society 5.0)	Sarfraz, Zouina & Sarfraz, Azza & Iftikar, Hamza & Akhund, Ramsha. (2021) Pakistan	Pakistan Journal of Medical Sciences	The study focuses on the fact that Covid-19 promotes Industry 4.0 leading us to Industry 5.0	19	1994-2020

3. Results and Discussions

3.1 Introduction of Corrosion

Corrosion is not an entirely new topic. It has existed since the beginning of time and has been experienced in all spheres of life. Corrosion is a destructive electrochemical process that depends on time and the local environment of metals. It is a naturally occurring phenomenon with detrimental cost implications to industries (Hou et al., 2017). It originates when the oxidation and reduction reactions occur, creating a metal loss in metals' internal or external surfaces. In the oxidation (anodic) reaction, electrons are removed from the metals, while in the reduction (cathodic) reaction, the electrons are consumed, maintaining charge neutrality.

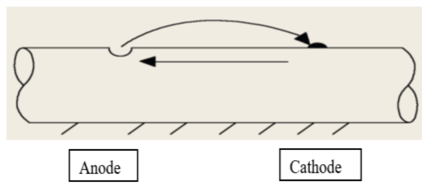

Figure 1: Cathodic cell on Pipe (Durham & Durham, 2005)

3.2 Causes of Corrosion

Current flows from one point to another once there is a voltage difference between the two points (anode and cathode). This voltage difference may be generated by naturally occurring reactions or by stray current reactions. Naturally occurring corrosion takes place because of local action cells on the surface of the structure. Stray current reactions occur when some source of current, external to the structure itself, causes corrosion on the structure. The presence of dissimilar metals, alloys, mechanical stresses, temperature differences in metals or electrolytes, dissimilar soils, and micro-biological influence all result in the corrosion of metals.

3.3 Classification of Corrosion

Based on the characteristics of the environment**,** Ragnolino (2021) classified corrosion is into two groups, namely:

1. **Chemical corrosion:** this occurs when a metal is exposed to a reactive gas or non-conducting liquid.
2. **Electrochemical corrosion:** in this type of corrosion, hydrous oxide films are formed when the metal is in contact with a conducting medium or mostly liquid containing a reactive substance. In this scenario, local anodic and cathodic sites are created.

3.3 Electrochemical Reactions

An electrochemical reaction involves the transfer of electrons between two dissimilar metals present in an electrolytic medium (Pierre, 2008). Therefore the corrosion processes of metals are electrochemical in nature. The process is divided into the oxidation (anodic) reaction and the reduction (cathodic) reaction (Virtanen, 2009). Oxidation is the reaction between substances and oxygen molecules. In the oxidation reaction, the corroded metal forms an oxide through the loss of electrons. Oxidation and reduction take place side by side.

Reduction is the term applied to gaining one or more electrons to an atom or molecule, which then forms a negatively charged ion or neutral element. A reduction reaction occurs any time that an atom or molecule gains electrons. The atom or molecule increases in negative charge (Das, 2017). These corrosion reactions can either be uniform or localized. It is uniform when it occurs all over the metal surface or localized when it is separated at specific cathodic and anodic sites. Localized corrosion mostly takes place when heterogeneity exists.

3.4 Corrosion Cell

Corrosion occurs due to the formation of electrochemical cells. For corrosion to occur, these four elements must be present. Electrochemical corrosion can be prevented by eliminating any of these four components of a corrosion cell. The necessary factors for corrosion are:

1. **Anode:** this is the less noble site on the metal where oxidation occurs. Reduction involves the gain of electrons. **The following half-cell** reaction can express oxidation reactions at the anode.

$$\mathbf{M} \longrightarrow \boldsymbol{M^{n+} + ne^-}$$

2. **Cathode:** this is the nobler site on the metal where reduction occurs. Oxidation involves the loss of electrons. The reduction half-reaction at the cathode depends on environmental conditions.
   H^+ + e- → H
3. **Electrolyte:** is the electrically conductive medium where the anode and cathode are located. For example, soil, water or moisture.

4. **Electrical connection between the anode and the cathode:** this could be in the form of a wire, metal or wall. The cathode and anode must be electrically connected for corrosion to occur.

5. **Potential difference:** a voltage difference must exist between the cathode and anode.

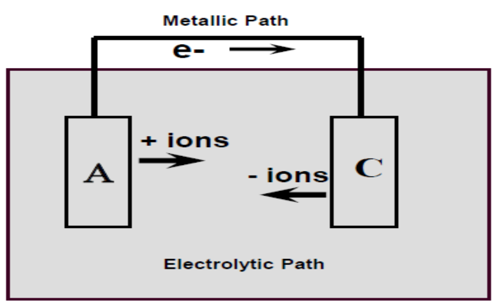

Figure 2: Electrochemical Corrosion Cell (Das, 2017)

The potential difference causes currents to flow. Electrochemical cells are driven by the potential difference between the anode and the cathode.

3.5 Corrosion in Pipelines

According to Karami (2019), pipelines buried underground are the most important means by which oil and gas industries transport or store the large part of oil, gas or other chemicals. These industries rely on the strength of steel and other metals to build pipelines, storage tanks, and other infrastructure that stand up to the rigours of industry activity. Crude oil and gas pipelines are situated onshore, offshore or in swampy areas possessing adverse environmental and natural effects that cause metals to rust when exposed to contact with water or soil. Pipelines are in contact with the aggressive soil, varying climatic conditions, microorganisms and stray currents that initiate corrosion processes (Popov & Kumaraguru, n.d.).

Over time, these pipes corrode due to exposure to environmental conditions and may even cause underground leakages. Corrosion of pipelines occurs in both their external and internal parts. Corrosion occurring in the subsurface transmission pipeline for oil and gas has both direct and indirect technical, economic and environmental consequences (Oghli et al., 2020). Metal corrosion may result in pipelines failures which are not good for the oil and gas industries because of the huge cost involvement and environmental damage it poses (Bahadori, 2014). Poor maintenance practices, leading to reduced operational capabilities of oil and gas pipelines, are associated with bad management (Lilly et al., 2007). Hence, monitoring of pipelines is crucial in industrial usages and designs.

3.6 Protection of Oil and Gas Pipelines against Corrosion

Pipelines daily transport and distribute vast amounts of oil and gas across the world. They are considered the safest method of transporting oil and gas because of their limited number of failures. Pipelines are very costly and positioned along with large distances. Their protection is crucial because of the need for uninterrupted continuous use for material transport.

Corrosion in pipelines can be minimized or prevented using appropriate environmentally friendly and sustainable corrosion control strategies. Corrosion prevention methods such as cleaning, coatings, and electrochemical interference are based on the inhibition of microbial growth and metabolism (Kip & Veen, 2015). The two most important ways of protecting pipelines are the use of coatings and cathodic protection. Pipeline integrity is maintained by simultaneous application of the protective coating and Cathodic Protection (Onyechi Pius et al., 2014). Inhibitors have also been used to reduce corrosion activities on pipelines.

3.6.1 Use of inhibitors:

Inhibition is a preventive measure against corrosive attacks on metals. Inhibitors are chemical compounds that, when added in small concentrations to the environment, can decrease corrosion of the exposed metal (Trabanelli, 1987). Inhibitors reduce the rates at which the oxidation or reduction partial reactions occur. They protect the surface of metals either by merging with them or by reacting with the impurities in the environment that may cause pollution. They are added in small quantities to the corrosive media to decrease or prevent the reaction of the metal with the media (Raja & Sethuraman, 2008).

3.6.2 Protective Coating of buried or submerged pipelines

Pipeline coatings are one part of the two-art defence against subsurface corrosion of metallic pipes. Coatings are used on the exterior parts of pipes, while linens are used on the interior parts. Coatings inhibit corrosion by barring the electrolyte and protecting the metal. Usually, dielectric materials that prevent the movement of electrons and ions are used. To enhance the material and equipment life, protective coatings are used to form a protective layer or barrier on the material to avoid direct contact with the process media.

No coating system is defect-free. Coatings and cathodic protection work together. Coatings play an essential role in CP. Cathodic protection can be applied without coatings, whereas coatings should not be used without cathodic protection. Findings from Onyechi Pius et al. (2014) show that the CP performance on pipelines is dependent on the physical state (coating disbandment) of the pipes and their years under operation. Coatings can fail for numerous reasons, so the cathodic systems are designed to compensate for coating defects and deterioration. A pipeline with an external protective coating and supplemented by a CP system is regarded as fully guarded against external corrosion, provided the installed CP system delivers a protective potential of at least 850mV for a saturated copper/copper sulphate electrode contacting the electrolyte (Lilly et al., 2007).

3.7 Cathodic Protection (CP) of Oil and Gas Pipelines.

Cathodic protection (CP) systems are fundamental to pipeline integrity management. They are widely used on transmission and (high or intermediate pressure) distribution pipelines in gas, petrochemical and water sectors (Irannejad & Iraninejad, 2014). The cathode protection (CP) method is widely used in the oil and gas industry to prevent or reduce rust and corrosion of structures and metal pipelines or their associated cost (Oghli et al., 2020). It is the electrical solution to the corrosion problem (Durham & Durham, 2005). It electronically alters the surface condition of the metals to move the anodic reaction elsewhere.

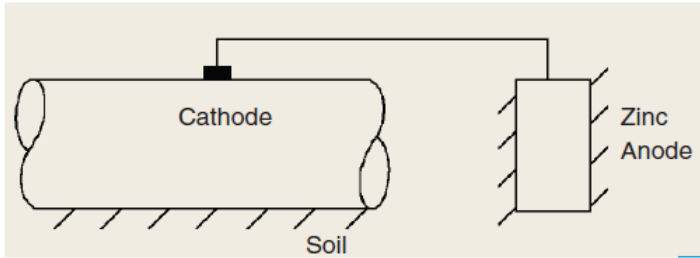

Figure 3: Cathodically Protected Pipe (Durham & Durham, 2005)

The science of CP is based on electrochemistry. Corrosion of metal equipment in contact with the earth is a natural phenomenon. To control this corrosion, CP systems sacrifice one material to protect another. This is primarily done by impressing a specific current density onto the protected equipment. For this system to work, there must be a complete electric path from a negative source, to the protected structure, through the electrolyte, via the ground bed, to the positive side of the source. The current flow resulting from CP is designed and intended to protect the metal pipe (Durham & Durham, 2005).

To control corrosion, the pipeline surface is made the cathode in an electrochemical cell utilizing an impressed direct current or attachment of sacrificial anodes such as Mg, Al, or Zn. Suppose two dissimilar metals are touching and an external conducting path exists in the presence of moisture or other materials acting as an electrolyte between the metals. In that case, electrochemical cells are created, and one of the metals can be corrosion (Bahadori, 2014). Depending on the metals, one will act as a cathode and the other an anode of the cell, and there will be resulting corrosion of the anode.

CP works by converting all anodes that are likely to corrode the cathodes. Most conventional models recommended by the designers are based on the equivalent circuit of the overall CP system. These are lumped models and may be helpful for compact systems like integrated industrial plants, where oil and gas pipelines are installed in kilometres. Lumped models lead to inaccurate results. To guarantee a more effective CP system, (Oghli et al., 2020) designed a functional design for the under-protected structures by using actual measured soil resistance throughout the structure instead of a fixed mean value.

Past researches indicate that cathodic protection is the most promising method of protecting pipelines (Abate et al., 2019). Unueroh et al. (2016) affirm that the use of the cathodic protection technique as a method of controlling corrosion in oil and gas pipelines is effective and efficient compared to other methods. Thus, constant monitoring is needed to achieve optimum efficiency. The use of corrosion sensors for monitoring the effectiveness of CP is a relatively new development. (Sun et al., 2021) introduced the coupled multielectrode array sensor that measures the corrosion rate when CP is not sufficient and the degree of CP when the CP is sufficient.

Low soil resistivity enhances cathodic protection by lowering the anode-to-earth resistance, thus allowing higher current output for a given voltage (Das, 2017). To preserve the effectiveness of the CP system, monitoring the potential distribution along the net is essential. (Abate et al., 2019) proposed a novel networked control system based on fuzzy logic and an existing wM-Bus at 169-MHz infrastructures for gas metering. The system is a low-cost system that monitors and controls the pipeline potential at a suitable measurement point.

In the long term, adopting a cathodic protection system is cost-effective to install a properly designed CP system on a pipeline network than have to locate and repair pipeline leaks. Installation of CP systems has considerably extended the operational lives of pipeline networks while operating the pipelines within their safe design envelopes (Lilly et al., 2007). The main advantage of cathodic protection systems over other forms of corrosion treatment is that it is applied simply by maintaining a DC circuit, and its effectiveness can be monitored continuously.

3.8 Remote Monitoring of Cathodic Protection

The Traditional monitoring of CP systems in pipelines requires periodic inspection and thorough analysis of the data from specialized operators. Field inspection is costly, time-consuming, and prone to human errors if not done by qualified personnel. This makes remote monitoring required to continuously check the condition of these structures and communicate the information to where it could be stored and analyzed (Smalling et al., 2021).

In recent times, technologies have been developed, and modern methods have been applied to replace the traditional methods of being on the site. Remote corrosion monitoring systems attached to the pipelines enable companies to collect accurate corrosion measurement data from the fields and also detect or predict possible problems.

Remote monitoring is the new development that automates the data collection process and provides operators with a proactive surveillance system. A remote corrosion monitoring system consists of various sensors, a power supply, a data acquisition system and a cellular network for data transfer. Solar panels can be used in the absence of electrical power grids to supply power. Sometimes, electrochemical multi-probe instruments with data collection capabilities are used to measure and record critical parameters contributing to corrosion.

Saluja, Costain, & Leden, (2009) presented the non-intrusive online method of monitoring corrosion using the permanently installed ultrasonic sensor and a software to automatically collect and store data remotely.

The method of remote monitoring is mainly used for the impressed current cathodic protection systems. In the remote monitoring of cathodic protection, the output voltage and current from the transformer, the supply of AC to the transformer, the CP levels ON and OFF the pipelines are monitored to ensure the correct level of cathodic protection. Data gotten is transmitted automatically and wirelessly from the fields through a software package where it is displayed, saved and available for expert analysis.

Peratta, Baynham, Adey, & Pimenta, (2009) presented an intelligent remote monitoring system that collects, transmits and interprets measurements of potential coming from different sensors distributed in the field along the pipeline in order to have a continuous monitoring and assessment of the system. This system made use of standard communications technologies such as cellular phones, antennas and GPS devices to assess readings on remote sensors, and therefore allowing for remote pipeline monitoring.

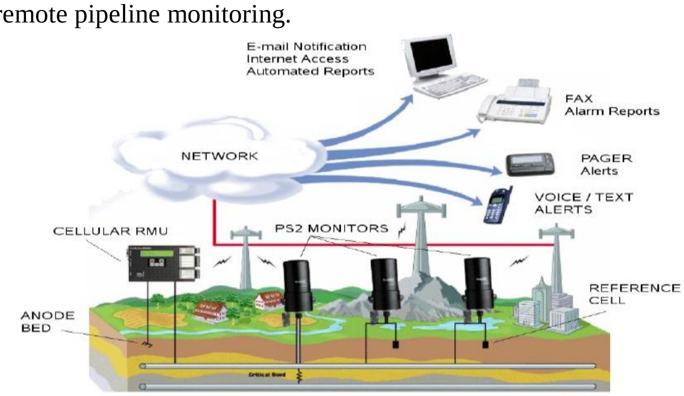

Figure 4: Schematic for the functioning of the GPS system (Peratta et al., 2009)

In addition, digitalization of corrosion monitoring over cloud platforms are now possible. The Internet of Things (IoT) have also provided pervasive sensing solutions that help optimise the use of wireless sensors.

3.9 Real-Time Remote Monitoring of Cathodic Protection

Pipelines are subject to deterioration and degradation. Studies identify corrosion as the most crucial damaging mechanism of pipelines. Internal and external corrosions affect the security and integrity of pipelines over time; thus, pipelines always need continuous inspection (Karami, 2019). Protection methods have been applied from the very beginning stages of the production of pipelines. It is essential that monitoring of pipelines be effectively carried out to optimize their operation and use in varying locations and to reduce the likelihood of failure (El-abbasy et al., 2014).

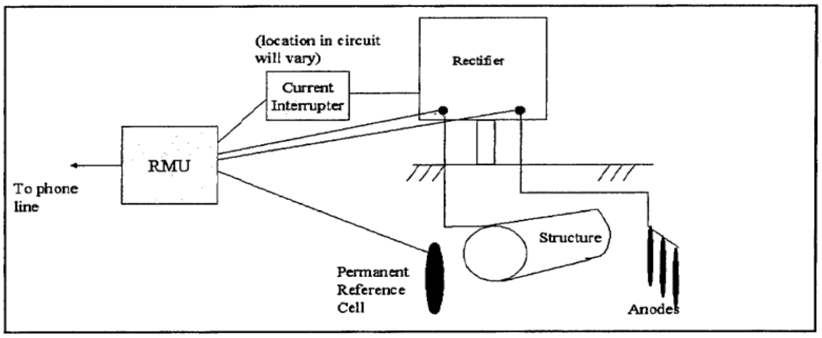

Figure 5: General Cathodic Protection Remote Monitoring Unit Schematic (Das, 2017)

Kim et al. (2015) developed a real-time monitoring and control system of buried pipes tape-coated carbon steel pipe for a primary component cooling water system, asphalt-coated cast iron pipe for fire protection system, and pre-stressed concrete cylinder pipe for seawater cooling system. A control system for cathodic protection was installed on each test pipe which has been monitored and controlled. COMSOL Multiphysics (Altsoft co.) was used to calculate the protection range and optimization; computer simulation was performed

A SCADA system is a type of industrial control system used to collect and control data from a remote location. Harbi (2021) designed a Supervisory Control and Data Acquisition system (SCADA) to monitor and control the corrosion of a pipeline buried underground. SCADA systems can control the corrosion in pipes, equipment, and structures by collecting data from cathodic protection system sensors in real-time and displaying the obtained data to the observers. Also, a microcontroller equipped with many sensors and a communication system is used to control and monitor the process of an impressed current cathodic protection (ICCP) process for Pipeline.

Cathodic protection (CP) systems are fundamental to pipeline integrity management and are widely used on transmission and (high or intermediate pressure) distribution pipelines in gas, petrochemical and water sectors. Routine measurements of CP levels are required to comply with regulatory safety standards. Manual measurements are costly and can only indicate problems on the pipelines after they have occurred. Remote monitoring of CP is a new development that automates the data collection process and provides operators with a proactive surveillance system. Irannejad & Iraninejad (2014) explained a device for remote sending the cathodic protection information of oil and gas pipelines and applying it to the SCADA system via GMS.

(El-abbasy et al., 2014) developed a model that can redirect the condition of oil and gas pipelines using the artificial neural network (ANN) technique based on historical inspection data.
This model helps pipeline operators assess and predict the condition of existing oil and gas pipelines and hence prioritizes the planning of their inspection and rehabilitation.

Most detection systems deployed for monitoring in oil and gas industries are based on Wireless sensor networks (WSN) systems or SCADA systems with limitations. WSN based systems are incompatible and not homogenous systems. They lack coordinated communication and transparency among regions and processes, while SCADA systems are expensive, inflexible, not scalable, and provide data with a long delay.

Khan et al. (2017) proposed a novel Internet of Things based architecture that involves smart objects for oil and gas industries. With minimum human intervention, the system will be able to make simple, secure, robust, reliable and quick data collection from connected objects, perform predictive maintenance of oil and gas industrial assets by analyzing various parameters (sensed data) and detecting failure modes either before they are going to take place or when the equipment will likely to fail or need service.

Kara et al., (2019) presents design considerations and implementation of linear wireless sensor networks (LWSNs) to be used in cathodic protection (CP) monitoring of oil and
natural gas pipelines are positioned in high rise mountains and deep valleys or other extreme locations where communication infrastructure is unavailable, or there is limited or interrupted access to the infrastructure. Al-Faiz & Mezher, (2012) developed and simulated a Cathodic Protection (CP) system for corrosion control using the wireless sensor Network technology (WSN) that collect potential data and to realize remote data transmission. The Labview 2010 program was used due to its high potentials, alongside a Tool Kit that supports the wireless sensor network.

3.10 Digital Technologies for Corrosion Monitoring

There is continuous increase in the online monitoring of corrosion for industrial applications. Industry 4.0, embedded systems, semantic machine to machine communication, Internet of Things (IoT) and cyber-physical systems (CPS) technologies, Sensor advancement have also impacted corrosion monitoring techniques. Various industry 4.0 technologies such as data analytics for cathodic protection (Rossouw & Doorsamy, 2021) that result in smart methods have also started being for the protection of pipelines.

Industry 4.0 is made possible by advancements in hardware and software technologies, such as miniaturization, sensors, storage capacities and computing power, that are now cheap enough for deployment at scale in production. Amongst the main envisaged benefits of industry 4.0, the data gotten from sensors can be used to monitor every pipeline for prompt maintenance.

3.10.1 Evolution of Industrial Ages

Technical advances have changed the way humans produce things. This first revolution occurred in the 18th century. The end of the 18th century saw the introduction of manufacturing processes and the emergence of mechanization. Mass extraction of coal along with the invention of the steam engine created a new type of energy that quickened all processes. Water and steam powered engines were produced to enable workers with mass production of goods. This resulted in increased production efficiency and scale.

The second industrial revolution began in the 19th century through the discovery of electricity gas and oil. Mass production of goods by electrically powered machines in assembly lines became standard practice. As a result of the development of the combustion engines, the steel industry began to develop and grow alongside the exponential demands for steel. Various production management techniques such as division of labor and just-in-time manufacturing systems were introduced to improve quality and output.

The third industrial revolution which appeared in the last few decades of the 20th century was brought about by advancements in electronics industry. The rise of electronics - transistor and microprocessor, integrated circuits, automated machines and memory-programmable controls resulted in reduced effort and increased speed. The integration of electronic hardware into manufacturing systems also created the need for software systems that enable these devices.

The fourth industrial revolution, also known as Industry 4.0 is currently being implemented. The boom in the internet and telecommunication industry changed the way systems can be connected and information exchanged. This resulted in changes in the manufacturing industry as boundaries between the physical and virtual worlds were merged.

The fifth industrial revolution, also known as Industry 5.0 which is the future talks about personalisation. Post the automation and removal of human intervention in manufacturing processes, human touch would be back in manufacturing. It would be a sync and utilisation of the technological advancement and cognitive and thinking skills of humans to provide a personalised experience (Ashima G, 2021).

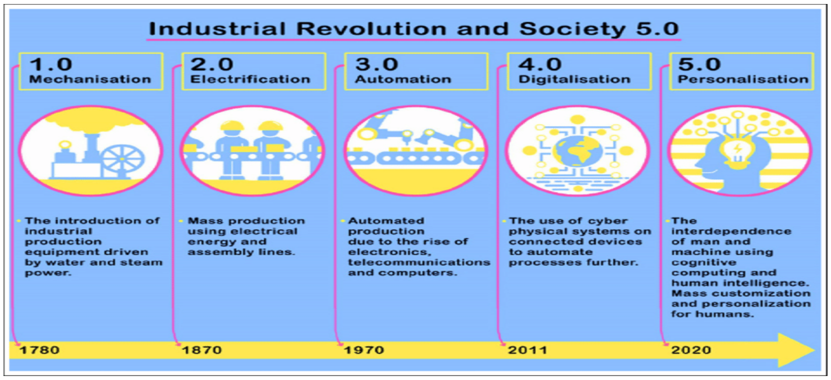

Figure 6: The timeline of industrial revolutions (Sarfraz et al., 2021)

3.10.2 Industry 4.0

Several emerging technologies converging to provide digital solutions has resulted in Industry 4.0. Industry 4.0 promises huge potential through new business models, increased resource productivity and cross-value chain efficiencies, enabling smart factories that are capable of profitably producing custom specific items in an agile way (Okeagu & Mgbemena 2022).

Industry 4.0 is made possible by advancements in hardware and software technologies, such as miniaturization, sensors, storage capacities and computing power, that are now cheap enough for deployment at scale in production (Hammer, 2016). In industry 4.0, embedded systems, semantic machine to machine communication, Internet of Things (IoT) and cyber-physical systems (CPS) technologies are integrating the virtual space with the physical world. The first three industrial revolutions were associated with mechanization, electrification and the rise of information technology, however, the fourth industrial revolution is driven by the introduction of the Internet of Things and Services in the manufacturing environment.

Industry 4.0 implies the digitization of manufacturing via connected networks, interacting and working together, promoting information sharing and analysis along the full global value chains. By effectively implementing Industry 4.0, companies aim to significantly improve their competitive position, increasing value creation and minimizing risks, with the adoption of more efficient and faster production systems and innovative technologies.

Amongst the main envisaged benefits of industry 4.0 are integrated product development with shorter operations cycle times, quick delivery times, faster time to market new products and services, improved quality, and product/service customization that satisfy individual consumer demands, leading to higher product individualization, higher flexibility with faster and more versatile production processes able to produce smaller lot quantities with high quality, increased resource efficiency and lower costs. The data gotten from sensors can be used to monitor every process and unit produced, so as to reduce error rates since and detect special causes of variation rather than using control or inspecting of products and processes.

Industry 4.0 technologies are divided into front-end and base technologies. Front end technologies consider how these technologies influence every stage of manufacturing to give Smart manufacturing processes, Smart products, Smart supply chain, and Smart working processes. Base-technologies consisting technologies having their different capabilities yet required to complete an integrated manufacturing system. They include Internet of things (IoT), Cloud computing, big data and Analytics.

3.10.3 Internet of Things (IoT)

Internet of Things can simply be defined as an interaction between the physical and digital worlds (Vermesan et al). Current research on Internet of Things (IoT) mainly focuses on how to enable general objects to see, hear, and smell the physical world for themselves, and make them connected to share the observations. In that sense, monitoring and decision making can be moved from the human side to the machine side (Sarika et al, 2019).

The components of the architecture of the Internet of Things are the Edge Things, Field Protocols, IoT Smart Gateway and Cloud Protocol.

- Edge Things: This is where the data is collected and processed. These could be actuators, sensors, devices and significant thing called gateway which does the main work of establishing communication between things and cloud services and also manage the action between the things (Sarika et al).
- Field Protocols: These also known as IoT Network Protocols are communication type used for communication between one or more devices at the edge with each other and also with the smart gateway. Some of the popular ones are LoRaWAN, Bluetooth, Zigbee, Wi-Fi, Near Field Communication (NFC).
- IoT Smart Gateway: This is an intelligent hub that connects all IoT devices, sensors, virtual platform. It routes and manages data between the IoT devices and the cloud.
- Cloud Protocols: These also known as IoT Data Communication Protocols are protocols which ensure that information between sensors, devices, gateways, servers, and user applications are well read and understood by another. Some of the popular protocols are Message Queue Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), Advanced Message Queuing Protocol (AMQP), and Hypetext Transfer Protocol (HTTP).

3.10.4 Virtual Reality

Virtual reality (VR), a major technology of industry 4.0, can be viewed as a computer-generated interface that imitates reality, allowing a user to interact in an imaginative world using specific interaction devices such as head mounted displays, haptic gloves, motion trackers and sensors Buzjak & Kunica, (2018). VR enables the visual simulation of an artificial environment within which a user can interact with objects and be fully or partially immersed. Virtual Reality (VR) has existed in various forms since the late 1960s and as a field of research, it has continued to advance over the years (Onyesolu, 2015).

VR technology enables problems to be predicted, solved, and controlled by connecting real (physical) sites with virtual ones in real time. Application of VR technologies improve rapidly, have become common and has gained its cost competitiveness (Choi et al., 2015).

The immersive experience of Virtual Reality has been applied in various real time simulated events. Maheswari, Gnanamalar, Gomathy, & Sharmila, (2018) designed an embedded device which could collect sensor values of environment defining variables like pressure, temperature, altitude and amount of light from sensors and use it accordingly to change the virtual environment of the simulation in real time. The sensors transmit the reading of environment defining factors to a cloud services provided by Thingspeak platform. These reading are archived and can be accessed by the android application to change its environment.

Virtual reality developed using the virtual reality modelling language (VRML) was also applied in (Kyung et al., 2005) to give 3D visualisation in the non-destructive evaluation of reinforced steel bars.

(Rustin D Webster, 2014) designed and developed a low cost, scalable and portable VR system for immersive virtual corrosion training environment. Augmented reality has also been utilised to visualize corrosion data (Walsh & Thomas, 2011).

4. Conclusion

Due to the long-term exposure of pipelines to environmental conditions, they corrode which may even lead to underground leakages. The corrosion occurs in both their internal and external part. This metal corrosion often leads to pipeline failure, especially when there are poor maintenance practices and inefficient monitoring techniques. These lapses incur huge cost involvement and environmental damages. The paper showed the two most important ways of protecting pipelines, which are through the use of coatings and cathodic protection. The study also depicts that cathodic protection is the most promising method of protecting pipelines. The functional requirement of the cathodic system was presented and clearly explained. The installation of cathodic systems will considerably extend the operational lives of pipeline networks while operating the pipelines within their safe design envelopes. It is applied simply by maintaining a DC circuit, and its effectiveness monitored continuously.

Remote monitoring involves intelligent systems that collects, transmits and interprets measurements of potential coming from different sensors distributed in the field along the pipeline in order to have a continuous monitoring and assessment of the system. The system makes use cellular phones, antennas and GPS devices to access readings on remote sensors.

The following have been identified as the major benefits of remote monitoring: It solves problem associated with the manual measurement method, it is suitable for inaccessible locations, it guarantees automatic, repeatable and reliable results, it reduces operational monitoring cost and provide a web-based view of the corrosion data collected in real-time. These can only be achieved through the use of Industry 4.0 technologies.

Different Industry 4.0 technologies were also presented for online and real-time cathodic corrosion monitoring systems. The enablers include: cloud computing, big data, data analytics, virtual reality, internet of things (IoT) and cyber-physical systems.

In the situation of another lockdown or community clash leading to the inaccessibility of pipelines, efficient real-time collaboration between remotely located teams is needed in the oil and gas industry. This is to ensure the smooth running of all inspection activities. Experts can monitor the activities going on at the site despite the distance. This work will also serve as a stepping stone to other researchers for further improvement on the application of low-cost virtual reality systems by Nigeria's oil and gas industries.

5. References

Abate, F., Caro, D. Di, Leo, G. Di, & Pietrosanto, A. (2019). A Networked Control System for Gas Pipeline Cathodic Protection. *IEEE Transactions on Instrumentation and Measurement*, *PP*, 1–10. https://doi.org/10.1109/TIM.2019.2906968

Al-Faiz, M. Z., & Mezher, L. S. (2012). Cathodic Protection Remote Monitoring Based on Wireless Sensor Network. *Scientific Research*, *4*, 226–233.

Al-kadi, T., Al-tuwaijri, Z., & Al-omran, A. (2013). Wireless Sensor Networks for Leakage Detection in Underground Pipelines : A Survey Paper. *Procedia - Procedia Computer Science*, *21*, 491–498. https://doi.org/10.1016/j.procs.2013.09.067

Alper, M., Sokullu, R., & Balc, A. (2015). Wireless Sensor Networks in Oil Pipeline Systems Using Electromagnetic Waves. 143–147.

Bahadori, A. (2014). *Cathodic Corrosion Protection Systems A Guide for Oil and Gas Industries*.

Brenna, A., Lazzari, L., Pedeferri, M., & Ormellese, M. (2016). Monitoring cathodic protection of buried pipeline by means of a potential probe with an embedded zinc reference electrode. *Journal of Material and Design*. https://doi.org/10.1016/j.matdes.2016.11.089

Buzjak, D., & Kunica, Z. (2018). TOWARDS IMMERSIVE DESIGNING OF PRODUCTION PROCESSES USING. *Interdisciplinary Description of Complex Systems*, *16*(1), 110–123. https://doi.org/10.7906/indecs.16.1.8

Choi, S., Jung, K., & Noh, S. Do. (2015). Virtual reality applications in manufacturing industries : Past research , present findings , and future. *Concurrent Engineering, Research and Applications*, 1–24. https://doi.org/10.1177/1063293X14568814

Das, B. C. (2017). *REMOTE MONITORING AND INTELLIGENT CONTROLS OF CATHODIC PROTECTION SYSTEM OF GAS TRANSMISSION PIPELINES*.

Durham, R. A., & Durham, M. O. (2005). Consequences and standards from using Cathodic Protection systems to prevent corrosion. *IEEE Industry Applications Society 50th Annual Petroleum and Chemical Industry Conference Paper*, 41–47.

El-abbasy, M. S., Senouci, A., Zayed, T., Mirahadi, F., & Parvizsedghy, L. (2014). Artificial neural network models for predicting condition of offshore oil and gas pipelines. *Automation in Construction*, *45*, 50–65. https://doi.org/10.1016/j.autcon.2014.05.003

Golshan, M., Ghavamian, A., Mohammed, A., & Abdulshaheed, A. (2016). *Related papers Pipeline Monitoring System by Using Wireless Sensor Network*. https://doi.org/10.9790/1684-1303054353

Harbi, J. A. (2021). Journal of Petroleum Research & Studies (JPRS) Application of SCADA System by Using (Fuzzy Logic Controller) on the Cathodic Protection System for Oil Pipelines . التيار القسري المسلط على أ نابيب النفط .تاذ ةصلاخلا*Journal of Petroleum Reserch & Studies (JPRS)*, *3*(30), 53–68.

Hou, B., Li, X., Ma, X., Du, C., Zhang, D., Zheng, M., … Ma, F. (2017). The cost of corrosion in China. *Nature Partner Journal of Materials Degradation*, (June). https://doi.org/10.1038/s41529-017-0005-2

Huang, Y., Liang, X., Galedar, S. A., & Azarmi, F. (2015). *Integrated Fiber Optic Sensing System for Pipeline Corrosion Monitoring*. 1667–1676.

Huang, Y., Gao, Z., Chen, G., & Xiao, H. (2013). Long period fiber grating sensors coated with nano iron/silica particles for corrosion monitoring. *Smart Materials and Structures*, *22*(7).

Irannejad, M., & Iraninejad, M. (2014). Remote Monitoring of Oil Pipelines Cathodic Protection System via GSM and Its Application to SCADA System. *International Journal of Science and Research*, *3*(5), 2012–2015.

Jaske, C. E., Beavers, J. A., & Thompson, N. G. (1995). Improving Plant Reliability through Corrosion Monitoring. *Fourth International Conference on Process Plant Reliability*.

Jin, Y., & Eydgahi, A. (2008). *Monitoring of Distributed Pipeline Systems by Wireless Sensor Networks*.

Kane, R. D., & Eden, A. (2003). Online, Real Time Corrosion monitoring for improving Pipeline Integrity. *Technology and Experience*.

Kara, A., Imran, M. A. Al, & Karadag, K. (2019). Linear Wireless Sensor Networks for Cathodic Protection Monitoring of Pipelines. *International Conference on Mechatronics, Robotics and Systems Engineering (MoRSE)*, (December), 4–6.

Karami, M. (2019). Review of Corrosion Role in Gas Pipeline and Some Methods for Preventing It. *Journal of Pressure Vessel Technology*, *134*. https://doi.org/10.1115/1.400612.

Khan, W. Z., Aalsalem, M. Y., Khan, M. K., & Hossain, S. (2017). *A Reliable Internet of Things based Architecture for Oil and Gas Industry*. 705–710.

Kim, K. T., Kim, H. W., Kim, Y. S., Chang, H. Y., Lim, B. T., & Park, H. B. (2015). REAL-TIME CORROSION CONTROL SYSTEM FOR CATHODIC PROTECTION OF BURIED PIPES FOR NUCLEAR POWER PLANT. *CORROSION SCIENCE AND TECHNOLOGY*, *14*(1).

Kip, N., & Veen, J. A. Van. (2015). The dual role of microbes in corrosion. *International Society of Microbial Ecology Journal*, 542–551. https://doi.org/10.1038/ismej.2014.169

Kyung, J.-W., Yokota, M., Leelalerkiet, V., & Ohtsu, M. (2005). Virtual reality Presentation for Nondestructive Evaluation of Rebar Corrosion in Concrete based on Inverse BEM. *Journal of Korean Society for Nondestructive Testing*, *25*(3), 157–162.

Lilly, M. T., Ihekwoaba, S. C., Ogaji, S. O. T., & Probert, S. D. (2007). Prolonging the lives of buried crude-oil and natural-gas pipelines by cathodic protection. M.T. Lilly. *Applied Energy*, *84*(9).

Liu, X., Xiong, J., Lv, Y., & Zuo, Y. (2009). Study on corrosion electrochemical behavior of several different coating systems by EIS. *Progress in Organic Coatings*, *64*(4), 497–503. https://doi.org/10.1016/j.porgcoat.2008.08.012

Maheswari, R., Gnanamalar, S. S. R., Gomathy, V., & Sharmila, B. (2018). Real Time Environment Simulation through Virtual Reality. *International Journal of Engineering and Technology*, (July). https://doi.org/10.14419/ijet.v7i2.24.12121

Mgbemena, C. E., Tiwari, A., Xu, Y., Prabhu, V., & Hutabarat, W. (2020). Ergonomic evaluation on the manufacturing shop floor: A review of hardware and software technologies. CIRP Journal of Manufacturing Science and Technology, 30, 68-78.

Obeid, A. M., Karray, F., Jmal, M. W., Abid, M., Qasim, S. M., & Bensaleh, M. S. (2016). Towards realisation of wireless sensor network-based water pipeline monitoring systems : a comprehensive review of techniques and platforms. 1–7. https://doi.org/10.1049/iet-smt.2015.0255

Oghli, H. M., Akhbari, M., Kalaki, A., & Eskandarzade, M. (2020). Design and Analysis of the Cathodic Protection System of Oil and Gas Pipelines, Using Distributed Equivalent Circuit Model. *Journal of Natural Gas Science and Engineering*, 103701. https://doi.org/10.1016/j.jngse.2020.103701

Okeagu, F. N., & Mgbemena, C. E. (2022). A Systematic Review of Digital Twin Systems for Improved Predictive Maintenance of Equipment in Smart Factories. International Journal of Industrial and Production Engineering, 1(1), 1–20. Retrieved From https://journals.unizik.edu.ng/index.php/ijipe/article/view/1041

Onyechi Pius, C., Nnaemeka, S. P., Cornelius, O., & Chinenye, A. (2014). MONITORING AND EVALUATION OF CATHODIC PROTECTION PERFORMANCE FOR OIL AND GAS PIPELINES: A NIGERIA SITUATION. *International Journal of Advanced Scientific and Technical Research*, *1*(4), 47–65.

Onyesolu, M. O. (2015). *Understanding Virtual Reality Technology : Advances and Applications*. (March 2011). https://doi.org/10.5772/15529

Peratta, A., Baynham, J., Adey, R., & Pimenta, G. F. (2009). Intelligent remote monitoring system for cathodic protection of transmission pipelines. *Paper Presented at the Corrosion Conference*, (March 2015).

Popoola, L. T., Grema, A. S., Latinwo, G. K., Gutti, B., & Balogun, A. S. (2013). Corrosion problems during oil and gas production and its mitigation. *International Journal of Industrial Chemistry*, *4*(35), 1–15.

Cragnolino, G. A. (2021). Corrosion Fundamentals and Characterization Techniques. *TECHNIQUS FOR CORROSION MONITORING (Second Edition)*, 7–42.c

Raja, P. B., & Sethuraman, M. G. (2008). Natural products as corrosion inhibitor for metals in corrosive media — A review. *Materials Letters*, *62*, 113–116. https://doi.org/10.1016/j.matlet.2007.04.079.

Rossouw, E., & Doorsamy, W. (2021). Predictive maintenance Framework for Cathodic Protection Systems using Data Analytics. *Energies*, *14*.

Rustin D Webster. (2014). Corrosion Prevention and Control Training in an Immersive Virtual Learning Environment. *NACE International Corrosion Conference Series*.

Saluja, A., Costain, J., & Leden, E. Van der. (2009). Non Intrusive Online Corrosion Monitoring. *Proceedings of the National Seminar & Exhibition on Non-Destructive Evaluation*.

Shipilov, S. A., & May, I. Le. (2006). Structural integrity of aging buried pipelines having cathodic protection. *Engineering Failure Analysis*, *13*, 1159–1176. https://doi.org/10.1016/j.engfailanal.2005.07.008

Smalling, R., Kruft, E., Webb, D., & Lyon-House, L. (2021). Remote Monitoring and Comuter Applicatons. In *Techniques for Corrosion Monitoring (Second Edition)* (pp. 475–495). Woodhead ublishing Series in Metls and Surface Engineering.

Sun, X., Sun, D., & Yang, L. (2021). CORROSION MONITORING UNDER CATHODIC PROTECTION CONDITIONS ISING MULTIELECTRODE ARRAY SENSORS. In *TECHNIQUS FOR CORROSION MONITORING* (pp. 539–570).

Sun, Z., Wang, P., Vuran, M. C., Al-rodhaan, M. A., Al-dhelaan, A. M., & Akyildiz, I. F. (2011). Ad Hoc Networks MISE-PIPE : Magnetic induction-based wireless sensor networks for underground pipeline monitoring. *Ad Hoc Networks*, *9*(3), 218–227. https://doi.org/10.1016/j.adhoc.2010.10.006

Unueroh, U., Omonria, G., Efosa, O., & Awotunde, M. (2016). PIPELINE CORROSION CONTROL IN OIL AND GAS INDUSTRY : A CASE STUDY OF NNPC / PPMC SYSTEM 2A PIPELINE. *Nigerian Journal of*

Technology, *35*(2), 317–320.
Walsh, J. A., & Thomas, B. H. (2011). Visualising Environmental Corrosion in Outdoor Augmented reality. *Proceedings of the 12th Australian User Interface Conference*, 39–46.
Wasim, M., Shoaib, S., & Asiri, A. M. (2018). Factors influencing corrosion of metal pipes in soils. *Environmental Chemistry Letters*, *16*, 861–879.
Yang, L. (2020). Techniques for Corrosion Monitoring. *Woodhead Publishing*.
Zhiping, Z., Junbi, L., & Zhengjun, W. (2012). Pipeline Internal Corrosion Monitoring System with Pitting Corrosrion Monitoring ability. *Electronic Measurement Technology 2*.
Zou, F., & Cegla, F. (2017). High Accuracy Ultrasonic Corrosion Monitoring. *Electrochemistry Communications*, *82*, 134–138.
Sarfraz, Zouina & Sarfraz, Azza & Iftikar, Hamza & Akhund, Ramsha. (2021). Is COVID-19 pushing us to the Fifth Industrial Revolution (Society 5.0)?. *Pakistan Journal of Medical Sciences. 37. 10.12669/*pjms.37.2.3387.
Mrs. Sarika A. Korade, Dr. Vinit Kotak, Mrs. Asha Durafe. (2019). A Review Paper on Internet of Things(IoT) and its Applications. *International Research Journal of Engineering and Technology (IRJET). Volume: 06*