Applications of solar photovoltaics in powering cathodic protection systems - A review

Ali O. M. Maka[1*],Tariq Nawaz Chaudhary[2],Gasim Alaswad[3],Othoman Elsayah[4]

[1]The Libyan Centre for Research and Development of Saharian communities; Murzuq, Libya.
[2] Faculty of Arts Science and Technology, University of Northampton, UK.
3University of Gharyan, Civil engineering department, Libya.
[4]Faculty of technical science Sebha, Libya.
*Corresponding author email: maca_2412@yahoo.co.uk **ORCID**: https://orcid.org/0000-0002-9005-1500

Abstract

Corrosion is a phenomenon that occurs on pipes, reinforced concrete structures, and storage tanks and causes a major impact on the facility structures and can have a major impact on a facility's structural integrity. This can result in a serious failure in the system and lead to substantial economic losses. One of the solutions widely used to eliminate the corrosion effects is by applying cathodic protection, which depends on direct current as the supply potential. The technique of cathodic protection is used to control corrosion in the utilisation of reinforced concrete structures, pipelines, storage tanks, etc. A photovoltaic cathodic protection system is normally used as an energy source to supply the system. This research reviews the technique utilised for applying solar photovoltaics in powering systems of cathodic protection. Subsequently, it highlights the methods of cathodic protection systems, sacrificial anode cathodic protection and the impressed current cathodic protection. Finally, it's indicated that applying solar photovoltaics in powering cathodic protection systems has great efficacy in controlling the corrosion in the facility's equipment in a smarter, controlled way. Furthermore, this study provides significant insight into the designing and operating the domain of solar photovoltaic systems that power cathode protection systems.

Keywords: Solar photovoltaic; Corrosion; Cathodic protection; Smarter control; Impressed current cathodic protection; Sacrificial anode cathodic protection.

Nomenclature

A	The surface area of the metal exposed	CP&C	corrosion prevention and control
A_{mod}	Area of solar PV modules	MPPT	Maximum power point tracking
B	Safety factor	O&M	Operation and maintenance
CCP	Current cathodic protection	PV	Photovoltaic

CP	Cathodic protection	PVCP	Photovoltaic cathodic protection
DC	Direct current	PE	Photoelectrodes
E_L	Energy losses in transmission	PEC	Photoelectrochemical
E_{min}	The minimum amount of daily solar radiation.	SACP	Sacrificial anode cathodic protection
E_{pw}	Energy used for the solar PV system.	SDG	Sustainable development goals
E_{el}	Energy needs of the solar PV system controller.	T_d	Operating time while using CP and powered by the PV
E_{pv}	amount of energy produced by PV	t	time
ICCP	Impressed current cathodic protection	W	Weight loss of the metal.
GCCA	Global climate change agreement	**Greek letters**	
MMO	Mixed metal oxide	ρ	Density of metals
K	Constant	η_{pv}	The efficiency of solar PV
R	Rate of corrosion	η_{ak}	Storage efficiency
T_{ak}	Operating time while using the batteries	η_k	Efficiency of controller

1. Introduction

Recently, there have been large demands for sustainable energy, and this has been coupled with a significant rise in energy prices globally (Gielen et al. 2019). Subsequently, the need for this alternative energy encourages us to develop cleaner energy resources to de-carbonise our planet in the near future (Cozzi et al. 2020), specified by (Raimi et al. 2022). Also, in referring to the UN's sustainable development goals (SDGs) are specified in SDG 7 as "Affordable and clean energy" (SDG 2021). Furthermore, the global climate change agreement (GCCA), which includes energy efficiency goals in manufacturing sectors, should be used to reduce carbon emissions and minimise energy costs (IRENA 2018), recently reported by (Izam et al. 2022).

Renewable energy systems are promising energy sources that are clean, environmentally friendly, and contribute to meeting energy needs (Owusu et al. 2016) and specified by (Panwar et al. 2011) and widely described by (Qazi et al. 2019). Moreover, as solar PV technology has significantly developed in recent years, the global deployment of solar PV technology has reached approximately 709,674 MW to fulfil these energy needs (IRENA 2021), as reported by (Maka and Alabid 2022). Based on that, it's important to consider cathodic protection CP systems as one of the most useful applications powered by solar energy with low energy costs. Furthermore, it provides energy savings on facilities, and reduces operational and maintenance expenses.

Corrosion is a random probabilistic phenomenon which is desirable to be studied and understood via interdisciplinary engineering that includes chemistry, metallurgy/materials science, surface science, thermodynamics and kinetics, electrochemistry, mechanics and hydrodynamics (Popoola et al. 2013). Accordingly, many efforts have been made to deal with corrosion from different scientific perspectives.

The key purpose of cathodic protection CP is to decrease the corrosion flow on the surface of a metallic structure due to potential variations between regional anodic and cathodic places. Hence, a current is imposed between the framework and the outer electrode to achieve that. Consequently, the cathodic areas are polarised in the electronegative direction by the outer current from the electrode. Since there is no longer a variance potential between the cathodic and anodic areas on the structure's surface, then corrosion will cease (Kelly et al. 2017).

Controlling corrosion-related defects is a significant problem for a ground-based construction structural integrity. In certain circumstances, such as cathodic protection for storage tanks, cathodic protection (CP) is regulated by legislation or policy (Marcassoli et al. 2017). As a result, the anodic process of metal dissolution on the framework under protection is controlled by cathodic protection. It is a corrosion-prevention technology for metallic structures in an aqueous environment that is largely used on steel drains in the oil & gas industry, mainly to prevent corrosion in underground pipelines and tanks (Janowski et al. 2016). In addition, due to corrosion, a steel's mechanical properties are lost in bond strength (Nadzri et al. 2021). Therefore, the process of cathodic protection is used to avoid the corrosion of metals by making them the cathodes of electrochemical cells (Poursaee 2016). It is paramount to control such phenomena by using a cathodic protection CP technique, which is widely applied throughout the globe in many industries.

These days, the corrosion of steel reinforcement in concrete is one of the biggest challenges facing engineers attempting to maintain the ageing of infrastructure (Broomfield 2023). However, that can deteriorate the integrity of the infrastructure; hence, corrosion rehabilitation systems and solutions have become highly marketable today (Ismail et al. 2007). Corrosion in aqueous solutions is caused via an electrochemical reaction in which both cathodic and anodic electrochemical processes take place at the same time (Bradford et al. 1993). While these anodic and cathodic processes occur at the same rate, no overall net charges are accumulated on the metal due to corrosion (Ech-chebab et al. 2021).

Many energy source methods are fabricated from semiconductor materials and used in the CP system; one example is the so-called photoelectrochemical (PEC) method. It is a modern cathodic protection technology using non-polluting metal and is an environmentally friendly cathodic protection system (Mishra et al. 2000). This system enables an n-type semiconductor photoanode to give the photogenerated electrons cathodic protection. Nevertheless, even though PEC cathodic prevention technology has good prospects for engineering applications, it is still under development (BuAo et al. 2017). Moreover, another energy source technique, so-called photoelectrodes (PE) for photo-induced cathodic protection; this is made from photosensitive materials functioning as anodes, and produces photo-induced electron-hole pairs under the illumination of light. However, the performance of photo-induced cathodic protection relies on the hole scavenger utilised in the cell of the photoelectrode, and this technique is still under research and development (Yang et al. 2017).

The cathodic protection is given by either the impressed current cathodic protection technique (ICCP) or the sacrificial anode cathodic protection technique (SACP) (Khan et al. 2018) recently reported by (Khan et al. 2021), more specified in (BAWA et al. 2020). It is worth mentioning that the galvanic protection systems utilise the galvanic anodes, also sometimes called the sacrificial anodes model (Anis et al. 1994) reported by (Laoun et al. 2009).

Numerous research studies related to the costs of the corrosion effect have been conducted during the last five decades. Subsequently, utilising various methods, the entire consensus came up with corrosion costs ranging from 3% to 4% of each country's gross domestic product (GDP) in the manufacturing countries (Byrne et al. 2016) and reported by (Koch 2017). Comprehensive research undertaken in the United States between 1998 and 2001(Fessler 2008) revealed that annual expenses attributable to the devastating impact of metal corrosion in 1998 amounted to approximately two hundred and seventy-six billion US dollars, representing roughly 3.1% of gross national revenue (Koch et al. 2002) According to research, corrosion expenses account for 4.2 to 4.5% of total national income in Japan and the European Union countries (Van de Krol et al. 2012).

Despite all the available research in the literature, there is still a knowledge gap on integrating solar photovoltaic PV devices powered by cathodic protection CP systems that operate sustainably. Additionally, it ought to meet the operating requirements in an engineering way, with environmental safeguards, with less overall cost. Therefore, this study investigates the potential and operating characteristics of solar photovoltaic modules equipped with a cathodic protection system in a smart way. It reviews the solar photovoltaic powered CP system; it also narrates the technique used to mitigate the corrosion that occurs in building structures and petrochemical facilities, etc. Furthermore, an integrated approach to CP systems is proposed to optimise the system in order to maintain its integrity. The significance of this work is highlighted in the wide range of research/development on utilising solar energy in the application of cathodic protection CP systems. Also, it is deemed as a vital addition to research for the engineers interested in the domain and scholars and customers alike. Consequently, the structure of this work is organised as follows: Section one represents a summary of the introduction. Section two expands on the corrosion phenomenon; Section three details the fundamentals of cathodic protection; Section four includes details of cathodic protection and types of cathodic protection, including both impressed current cathodic protection and sacrificial anode cathodic protection. Section five represents the design and performance analysis of the solar PVCP. Finally, a summary of the conclusions is in section six.

2. Corrosion

Corrosion is a natural phenomenon that occurs when metals and non-metals, such as pipelines, tanks, concrete, etc., are subjected to a corrosive environment (Pedeferri et al. 2018). As a result, the metal deteriorates due to the process, which can quickly be serious enough to warrant repair or replacement (Talbot et al. 2018). The corrosion has two mechanisms via which metals in electrolytes corrode. Firstly, electrolytic corrosion results from the direct current of external sources entering and leaving a specific metallic assembly through the technique of the electrolyte. Secondly, it is an electrochemical procedure in which metal corrodes, particularly once it is in electrical contact with others, in the existence of an electrolyte (James et al. 2010; PE 2006). The level of corrosion can be determined by the mass of metals corroded on a unit surface area of the surface in a uniform attack (Ahdash 2010). Also, the penetration depth can be obtained by various approaches, including uniform attack and pitting (Bradford et al. 1993) and described by (Von Baeckmann et al. 1997). The result of corrosion is the deterioration of the metal; consequently, the corrosion rate (R) can be determined (Okpokwasili et al. 2014) and reported by (Schweitzer 2010).

$$R = \frac{k.W}{\rho.A.t} \quad (1)$$

where (W) is the weight loss of the metal, (t) is time, (k) is a constant, (ρ) is the density of the metal in g/cm^3 and (A) is the surface area of the metal exposed. Corrosion of steel in concrete structures is still a major concern in construction projects (Poursaee 2016) since it can jeopardise structural behaviour and durability (Nadzri et al. 2021); thus supported in (Zhang et al. 2022). In the concrete structure, corrosion occurs when steel deteriorates after exposure to a corrosive environment (Funahashi 2007), presented by (Poursaee 2016) and supported by (Ech-chebab et al. 2022). The presence of oxidising species is usually determined to be the main reason for metal corrosion. Hence, the redox potential of the corrosive medium should be greater than the metal's self-corrosion potential (Bu and Ao 2017). An active-passive alloy with a wide passivity range and a low passive corrosion rate is appropriate for anodic protection (Mishra et al. 2000). However, installing and maintaining electrical equipment is classified as complicated and expensive; consequently, anodic protection is rarely applied (Jones 1996).

The majority of subsurface metal corrosion is caused by electrochemical reactions. As such, the factors affecting subsurface corrosion can be listed as soil pH values, soil resistivity, aeration moistures, and other elements (Bashi et al. 2003). The corrosion has many influences on the material, which are summarised as follows: (i) the costs of corrosion repair are high, (ii) metal thickness will be decreased, (iii) while for transportation, there will be impurities within the pipeline, (iv) significant loss of surface properties, (v) mechanical impairment (Roberge 2008).

Selection of materials is an important aspect of the system design. Based on that, factors to consider during the design process are which corrosion-resistant materials (Craig et al. 2006); and associated materials, that the best respond to corrosion prevention, and to control corrosion prevention and control (CP&C) technologies (PE 2006). It is worth mentioning here that there are three forms of corrosion: (i) uniform corrosion, which attacks metal areas at the same rate; (ii) localised corrosion, which corrodes some areas of metal at different rates; (iii) pitting; where an extremely localised attack results in small pits which can penetrate to perforation (Adly et al. 2017) and more specified by (Shreir 2010). Fig. 1 illustrates an example of real corrosion: (a) external corrosion on the pipelines, (b) corrosion of reinforced concrete structures, and (c) pitting corrosion in the pipe segment.

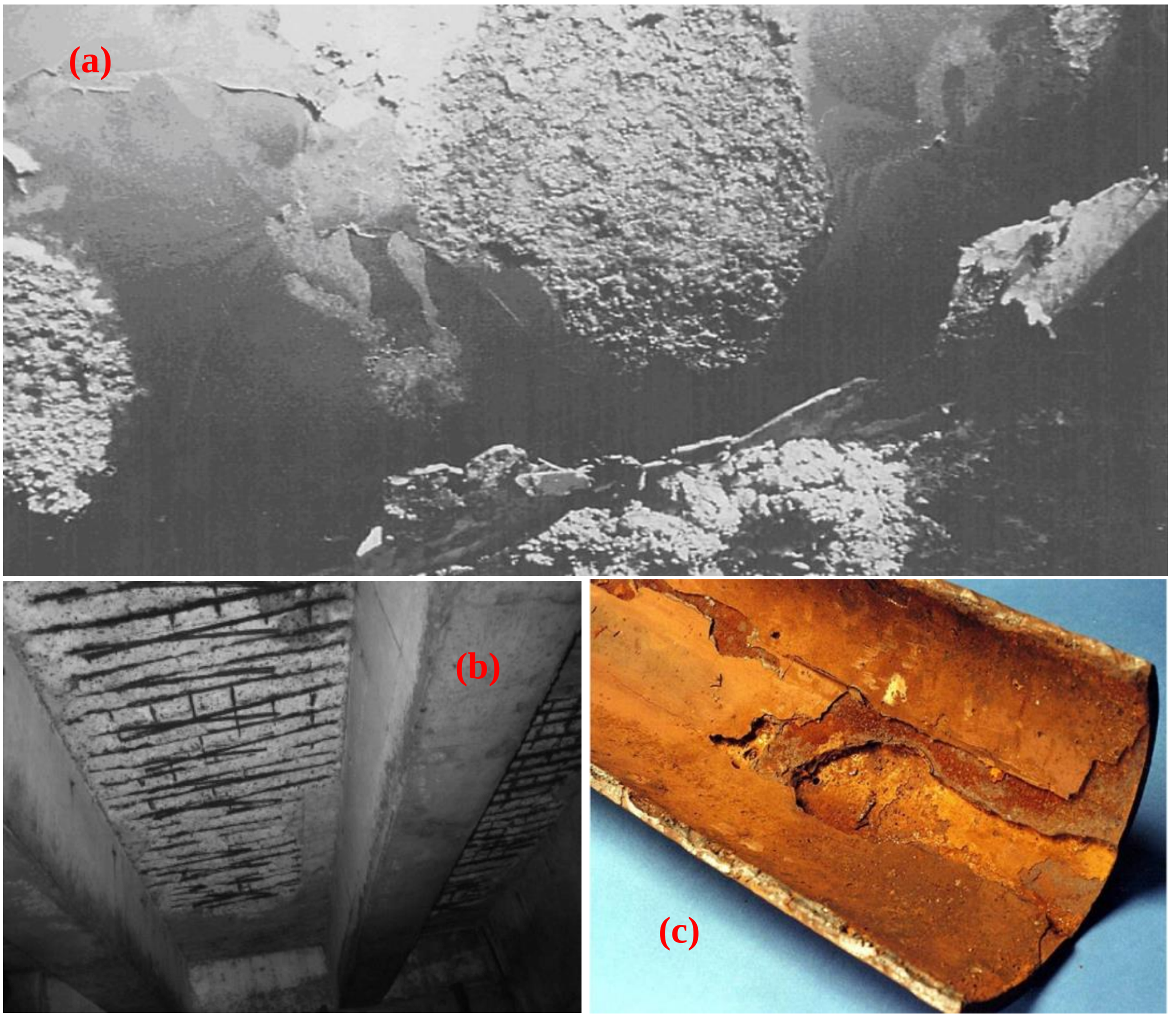

Fig.1. corrosion effects and related risk on some practical applications (a) external corrosion on the pipelines (Peabody 2001), (b) corrosion of reinforced concrete structures (Popoola et al. 2013), and (c) pitting corrosion in the segment of internal pipe (Darmawan 2010).

3. Fundamental of Cathodic Protection

This invention was attributed to the first reported utilisation of cathodic protection in the late 1820s by 'Sir Humphrey Davy'(Ashworth 2010). The Royal Navy requested his advice to evaluate the corrosion of copper sheets used as cladding on naval vessels (James et al. 2010) and reported by (Noyce et al. 2017). Generally, the fundamental of cathodic protection approaches is to supply electrons to a safeguarded metal that loses electrons because of corrosion by giving it a stream of electrons (Harvey 2019).

The corrosion phenomenon ought to be described in order to comprehend the cathodic protection system process. However, corrosion is an electrochemical operation that damages a metal by interacting with the environment surrounding it. The cathodic protection acts via controlling the anodic process of metal disintegration on the structure under protection.

However, in an aqueous environment, it is used such as technology for protecting metallic structures from corrosion and is largely used for steel drains in the oil/gas sector, mostly to safeguard pipelines and underground tanks (Janowski et al. 2016). Cathodic protection decreases the degree of corrosion via the cathodic polarisation of a corrosive metal surface. The cathode and anode processes of iron corrosion are demonstrated in a "dilute aerated neutral electrolyte solution" (Mishra et al. 2000). The reaction of anodic for steel and iron is expressed as,

$$Fe \rightarrow Fe^{2+} + 2\bar{e} \qquad (2)$$

The cathodic reaction that occurs in an acidic solution is expressed as,

$$2H^{+} + 2\bar{e} \rightarrow H_2 \qquad (3)$$

with an abundance of electrons, the cathodic polarisation decreases the rate of half-cell reaction, as expressed by Eq. (2), while correspondingly increasing the rate of oxygen decrease OH^- production (Benedetti et al. 2009) and specified by (Gummow et al. 2002) as expressed via Eq. (3). In solutions of alkaline, with a paucity of hydrogen ions, the water reaction will happen to yield hydrogen and alkaline.

$$2H_2O + 2\bar{e} \rightarrow H_2 + 2OH^{-} \qquad (4)$$

Electrons flow from the metal (anode) to the cathode, where the cathodic reaction consumes them. Oxygen reacts with the metal's surface to produce alkali in the water.

$$O_2 + 2H_2O + 4\bar{e} \longrightarrow 4OH^{-} \qquad (5)$$

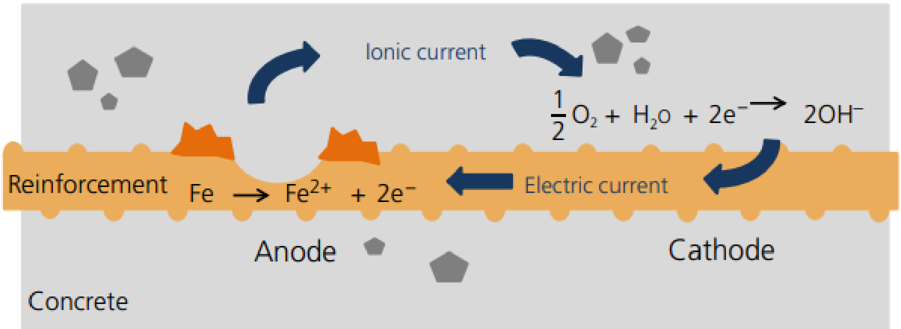

Fig. 2. Corrosion of reinforcement in concrete illustrates reduction reactions and oxidation (Byrne et al. 2016).

Fig. 2 shows the cathodic of an external anode. The anode is coupled to the reinforcement, and the current moves via concrete from the outer anode to the reinforcement, resulting in a positive cathodic reaction at the steel surface and forming hydroxyl ions. The pH rises, and the charge encourages chloride ions to migrate away from the reinforcement (Polder 1998). Although it requires a higher current density, the chloride extraction is comparable to cathodic protection and is a one-time application. The re-alkalisation is a substitute for chloride extraction for carbonated concrete (Byrne et al. 2016).

Due to the deposition of hydrogen or another ion that is loading current, the cathodic zone is protected from corrosion (Bashi et al. 2003). Hydrogen evolution degrades and results in various types of hydrogen damage. As a result, it is explicit that the impressed current should have been kept as close to 1% as possible. The whole potential change from anode to cathode in an impressed current cathodic protection system includes the over-voltage of the cathode, and the ohmic potential change and over-voltage of anodic. Over-voltages are quantified in milli-volts, although the potential of ohmic variations is measured in volts (Ashworth 2010). Consequently, one of the most difficult aspects of designing a cathodic protection scheme is accurately measuring small over-voltages at the cathode-structure surface without interfering with huge ohmic potential variations (Al-Refai 2019).

Cathodic protection should be able to adjust current in order to meet corrosive situations. Furthermore, the current distribution ought to be consistent throughout the whole pipe length (Mishra et al. 2000). However, it is not uniform, as demonstrated by the cells; therefore, it is difficult to have appropriate cathodic protection for the whole protection area when the pipeline is long and subjected to a variety of corrosive environments (Mishra et al. 2000) and reported by (Al-Refai 2019).

Fig. 3 shows the diagram of the principle of cathodic protection; here, it demonstrates the increased CP's needs as the structure's potential is lowered to reduce the rate of anodic dissolution. The cathodic reaction-diffusion is limited at greater density, and the anodic metal dissolution process activates the control. The potential of the metal declines whenever the applied cathodic current density is increased, and the anodic dissolution rate decreases correspondingly. When considering the logarithmic current scale, the needs tend to rise exponentially as the metal's potential decreases (Roberge 1999).

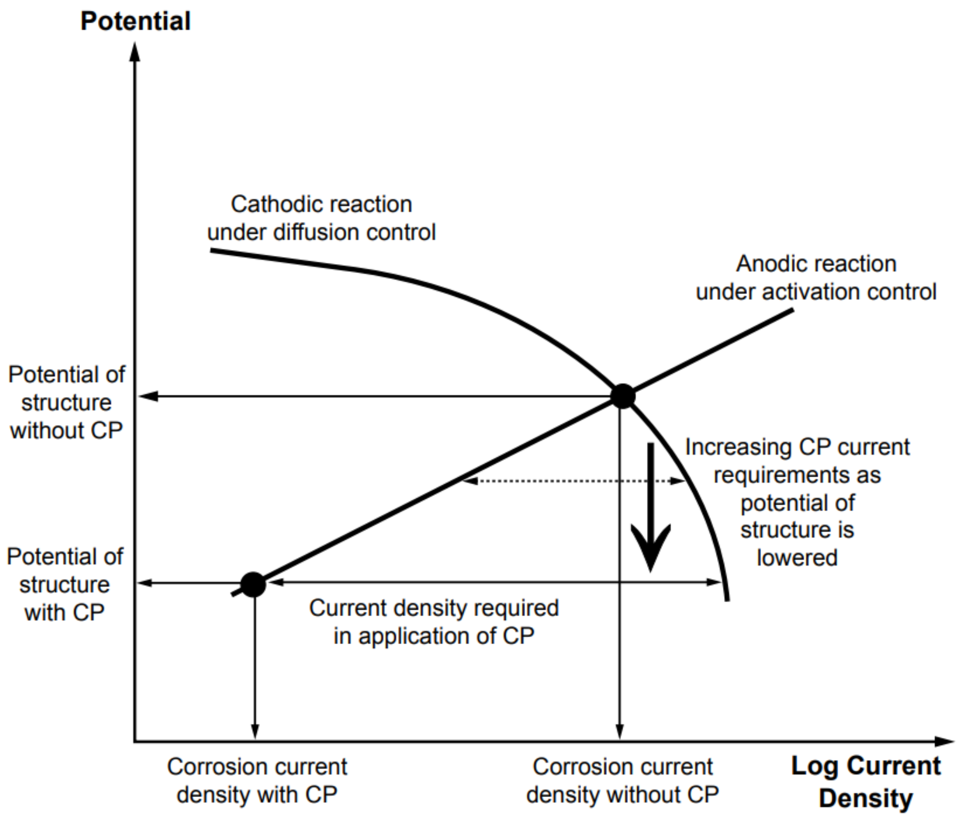

Fig. 3. schematic diagram of the principle of cathodic protection (Roberge 1999).

4. Cathodic Protection

Cathodic protection (CP) is the most extensively utilised method for protecting a metal from corrosion (Abdulbaqi 2018). The CP is commonly used to protect oil and gas pipelines, submarines, underground tanks, ship propeller blades, and other metals buried beneath or in the water (Ashworth 2010). In addition, its life cycle can be extended by adding CP to metal; therefore, it is important to study types of CP technology that are widely used.

4.1. Type of CP System

Cathodic protection is one of the most broadly utilised technologies for preventing metal corrosion. The metal's lifetime can be extended by adapting cathodic protection (Mansouri et al. 2021). There are two types of cathodic protection: sacrificial cathodic protection (SACP), and impressed current cathodic protection (ICCP).

4.1.1. Sacrificial Anode Cathodic Protection (SACP)

The foundation of the SACP method is that the potential difference varies between the steel, which needs to be safeguarded, and another metal in a similar environment causing the driving voltage (Tezdogan et al. 2014). Sacrificial anodes are made from a metal alloy with a higher electrochemical potential. The sacrificial anodes are typically comprised of magnesium, zinc alloys, or aluminium alloys (Abdalsamed et al. 2020). There will be no injecting current in the sacrificial anode, and the electrochemical process will safeguard the metal. It provides driving voltage by using the natural potential difference between the framework and a second metal in a similar environment (Bashi et al. 2003) and more specified by (Hassmoro 2014).

The key advantages of SACP sacrificial anode cathodic protection are that it is easy to design and install, it does not require an external power source, and neither does it require a control system. However, its disadvantages are the current cannot be controlled, and the degree of protection cannot be determined. Also, the anodes need to be replaced if current requirements change, and so require regular visual and determination surveys to monitor the condition of deterioration (Nadzri et al. 2021). Fig. 4 (b) illustrates the schematic of the sacrificial anode technique for cathodic protection. The model of cathodic protection is easier to design and less costly (Abdulbaqi 2018). The current flows through the ground from the anode to the pipeline, this being an electrolytic medium that does not require an external electrical power supply. It is typically unlisted to prevent objects of restricted length (Dyson et al. 2015).

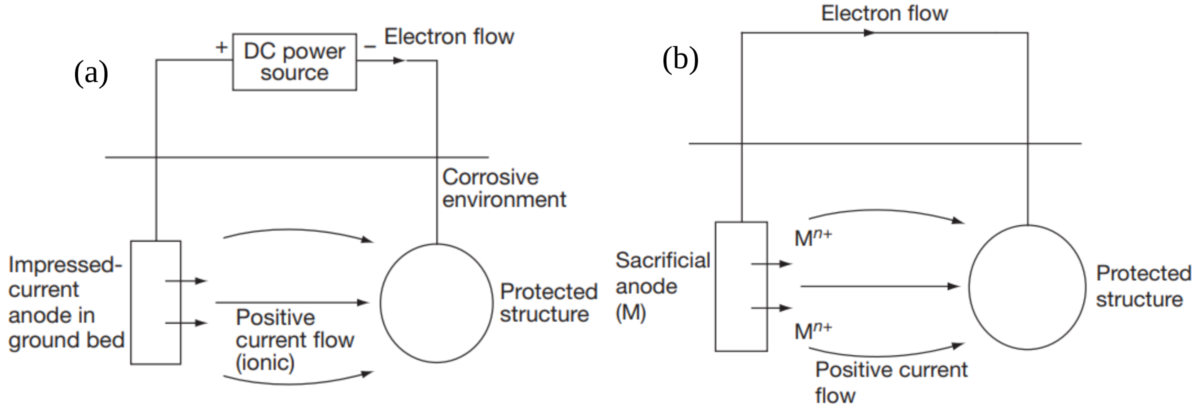

Fig.4. (a) a diagram of cathodic protection CP using the impressed-current technique, and (b) a diagram of cathodic protection CP using the sacrificial anodes technique (Ashworth 2010).

4.1.2. Impressed Current Cathodic Protection (ICCP)

The sacrificial anode cathodic protection system, in particular, is a very attractive technique because of its characteristic simplicity and ease of maintenance (Funahashi et al. 1999; Sagüés et al. 1996). The impressed current anode bed, aqueous solution environment, and the metal to be safeguarded are all part of the impressed current process. Subsequently, the current flows to the carbon steel pipe via an anode bed (Hassmoro 2014). Therefore, according to the research, electrons flow in the opposite direction to the current (Vukcevic 2015). Fig. 4 (a) illustrates a schematic of cathodic protection utilising the impressed-current technique.

Fig.5 (a) illustrates the corrosion area turning into the anode in an electrochemical cell. The non-corroding, cathodic zones in the reinforcement perform a harmless decrease reaction. However, corrosion can be accelerated in structures exposed to chloride conditions, including roads that utilise de-icing salts and coastal structures. The chloride ions permeate concrete and lead to destroying the reinforcement’s passive layer of protection. Corrosion occurs when oxygen and water are present (Byrne et al. 2016). The cathodic protection is very effective when corrosion is caused by chloride contamination (Polder et al. 2009).

Although it can tackle significant corrosion obstacles in huge structures with longer life spans, impressed current cathodic protection is more routinely employed for reinforced concrete than SACP (Wilson et al. 2013) and specified by (Al Masoodi et al. 2021). The ICCP devices can manage corrosion at any chloride level and can account for changing protection necessities owing to their capacity to change the current provided (Kean et al. 1981). The ICCP system has similar basic components as the SACP system. The external anode (non-consumable), on the other hand is coupled to the positive terminal of a supply for low-voltage DC. Fig.5 (b) shows a diagram of ICCP for reinforced concrete. The negative terminal is linked to the reinforcement that allows electrons to pass to the steel/concrete interface, boosting the cathodic process (which produces hydroxide ions from oxygen and water) (Byrne et al. 2016). Hydroxide ions move through the concrete to the anode, where they are oxidised to electrons and oxygen. The circuit is then closed as electrons move to the current supply (Veritas 2010).

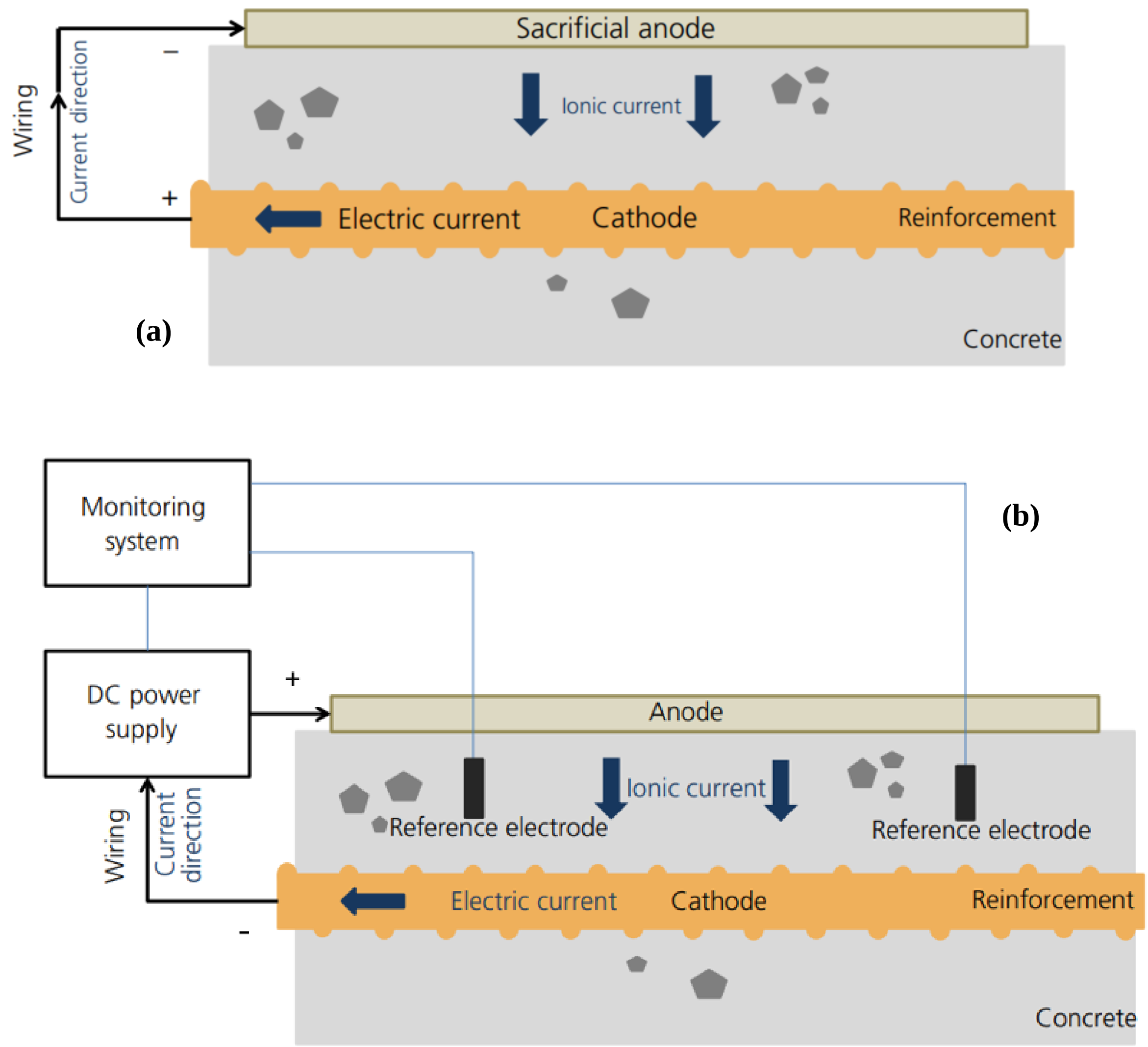

Fig.5. (a) SACP for reinforced concrete, and (b) ICCP for reinforced concrete (Byrne et al. 2016).

Renewable energy sources such as wind turbines and solar modules may be utilised in the CP system. The anodes are connected to a DC power supply in a current cathodic protection CCP system. Because the driving voltage is given by the DC supply in ICCP systems, the anode does not required to be more active than the structure to be safeguarded (Ashworth 2010). The DC output current is usually in the range of 5-100 A and 15-100 V, although 200 V/200 A units are also known. Titanium is a typical anode coated with mixed metal oxide (MMO) or platinum, silicon cast iron, graphite, and other materials (Janowski et al. 2016).

The ICCP system's output ought to be optimised to give sufficient current to safeguard the protected structure. The electrical resistivity of the surrounding area is one of the essential factors in the design of cathodic protection systems. In the storage tank's environments, the resistances range from 1 Ω cm, and for brackish river water to more than 500,000 Ω cm in non-porous granite (Janowski et al. 2016). A potential negative variation of 100-300 mV from the free corrosion potential is a positive indication of appropriate protection, according to one of the prevention standards obtained from field experience (Janowski et al. 2016). Additional requirement based on the normal component of current density states that unless under exceptional or abnormal circumstances, a current of 11 to 22 mA/m^2 of bare metal electrolyte surface has been deemed appropriate for bare metal in the Earth (Janowski et al. 2016). The amount of current flowing in the electrochemical corrosion cell is directly proportional to the rate of corrosion (Guyer et al. 2018).

The key advantages of ICCP are that it can be applied to specific elements, and a high-resistance environment is easily applicable (Nadzri et al. 2021). Also, the current output can be adjusted, and it has cost savings due to minimal concrete removal (Vukcevic 2010). While the disadvantages are the higher risk of interaction, that it needs a monitoring system, and a continuous DC power supply is required, this technique has more efficacy for covering huge areas and long distances. The anode is much more effective in protecting big objects (Abdulbaqi 2018). It is also particularly adaptable to changes in soil resistivity since it can provide the desired current (Arya et al. 2021).

5. Design and Performance Analysis of the Solar PVCP

5.1. Performance characteristics and design of solar PVCP

The sun is one of the naturally available energy resources. Solar photovoltaic PV modules are devices used to generate DC power directly from its radiation. Therefore, the system desires the maximum power point tracking (MPPT) controller to yield maximum power from the solar PV modules, which will improve energy usage.

A solar photovoltaic generation system consists of many components, including solar cell photovoltaic modules, a controller, a regulatory system, and a storage system (Artyukhov et al. 2020). Solar photovoltaic modules are used with structural components to generate DC power directly from solar radiation (Ebrahimi et al. 2018). A charge controller is used to protect against the overcharging of batteries; the photovoltaic energy generated is stored in a battery bank (Hoang 2019). Finally, the storage battery-powered electronic control device functions as a voltage regulator for the load; that component can include maximum power point tracking (MPPT). Fig. 6 illustrates the scheme of the component elements of the solar PVCP system.

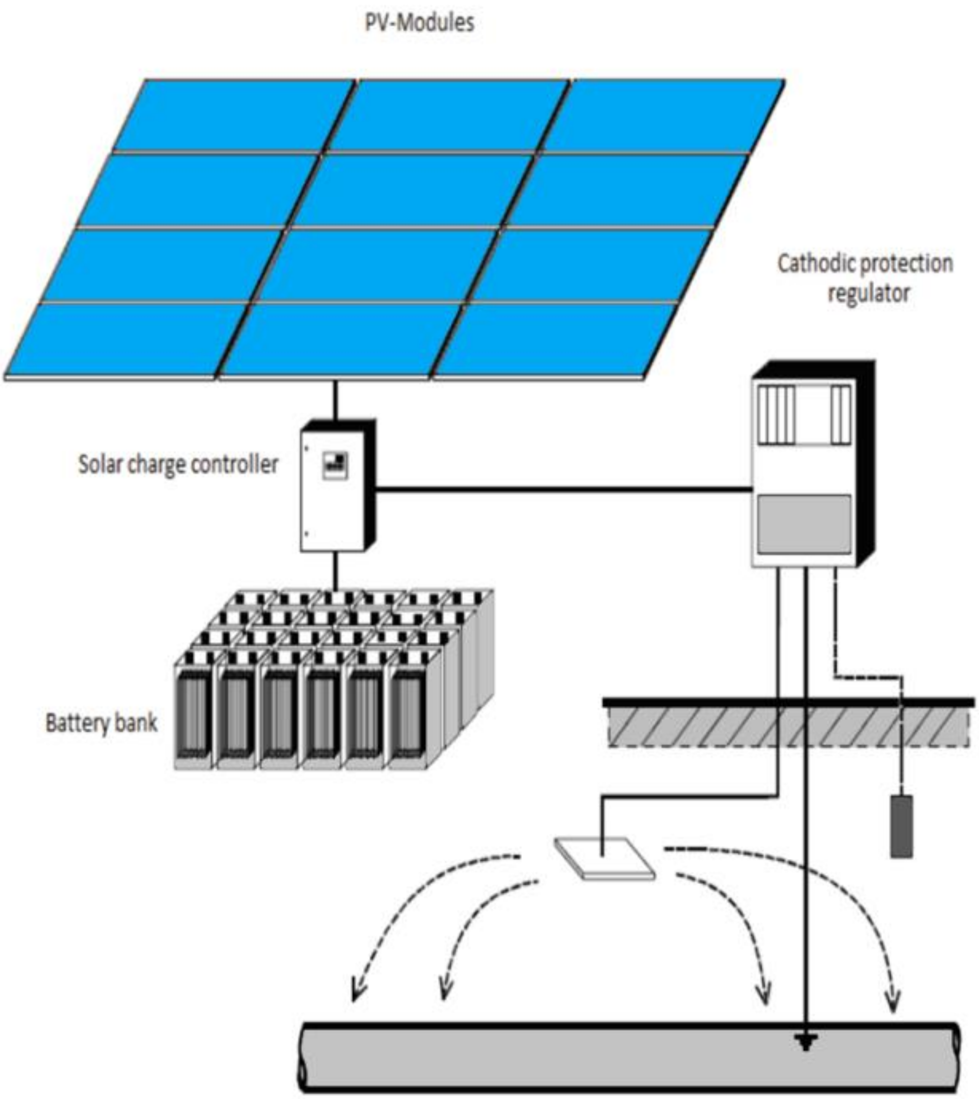

Fig. 6. Scheme of the traditional component elements of solar PVCP system (Malek 2018).

Total energy output in solar PV module-based systems is determined by the amount of solar irradiance available, resulting in an inconsistent power source. Thus, an energy storage system is necessary for systems that require a consistent power source whenever the PV system's power generation is insufficient (Christiana et al. 2022). In addition, a back-up power system will be needed by a solar panel system, particularly for off-the-grid CP systems, in order to ride throughout periods when the solar panels are not producing sufficient electricity (Kelly et al. 2017).

Although, by measuring the potential of polarised pipe versus the buried reference electrode copper-copper sulphated (Cu/CuSO4), the adapter circuit controllers automatically adjust the (DC) output voltage of the adapter circuit; thus, despite soil resistivity variances, the current remained nearly constant at the desired level (Kharzi et al. 2009).

The lifespan of an anode is inversely related to the ripple content: the impressed current system needs a stable DC power supply with good management and as little ripple as possible. Furthermore, even though pipes are usually placed in isolated or remote regions, the power should be provided via autonomous systems. Therefore, one option is to employ diesel generators that demand frequent maintenance; this operation is prohibitively expensive (Anis et al. 1994). For an application in solar photovoltaics, in which the DC voltage is continuously controlled to maintain a constant current, the climate and soil difference and maximum and minimum pipe to soil potential values (Anis et al. 1994) and specified by (Anis 1995) are affected by the following factors: determine the amount of DC required to stop (or reduce) corrosion: (Anis et al. 1994).

- The area of metallic protection.
- The electrolyte between protected cathodic and the sacrificial anode.
- Type and age of the cathode and anode metals.
- The protected structures coating type.

Although it acts as an insulator between the covered structure and the surrounding medium, the appropriate coating significantly reduces the desired DC current. Hence, the DC voltage is set to provide the necessary current. The key difficulty is that the resistivity of the electrolyte, for example, soil, changes with weather conditions. While electrolyte resistance is included in the protected cathodic system circuit, the DC current must change as the environmental situation varies to be able to produce a constant DC voltage (Anis et al. 1994).

Designing cathodic protection systems to reduce anode bed resistance is another key element in decreasing electricity needs. This is simply accomplished by knowing that anode bed resistance is mostly a function of the whole length of the anode system (BRMERL 2013). Therefore, the anode bed resistance may be significantly reduced by designing the anode system to increase the anode length. This means spending a bit extra on drilling expenditure to increase the active anode length in deep anode ground bed systems (Popov et al. 2005).

Consequently, this will raise the cost of the solar PVCP system, however, the profit in solar power system expenses will usually offset the higher expenditures. Also, consider using "long-length linear anodes in shallow anode bed systems", which have decreased the resistance of the anode bed (Kelly et al. 2017).

The amount of potential solar energy, or irradiance, required determines the size of stand-alone photovoltaic cathode protection systems (Dickinson 2018). Therefore, it is essential to size stand-alone Photovoltaic systems to meet the demand load throughout the year with the least solar irradiance and highest load (Lasnier et al. 2017). Nevertheless, some applications of CP might have variable loads based on seasonal variations in soil resistivity from rainy to dry periods. Due to typically higher solar irradiance during the dry period, where soil resistivity and load necessities could be increased, this may work to the advantage of the PV system design. The amount of energy produced by solar PV can be estimated as follows (Janowski et al. 2016):

$$E_{PV} = A_{mod}\ x\ \eta_{PV(T_{amb})}\ x\ E_{min}\ x\ B \tag{6}$$

where (A_{mod}) is the area of solar PV modules, ($\eta_{pv\ (Tamb)}$) is the conversion efficiency of solar PV as a function of ambient temperature, and (B) is the safety factor of the PV system; it varies from 1.5-2.5. (E_{min}) is the minimum amount of daily solar radiation; (E_{pv}) the amount of energy produced by solar PV. The energy needs of the solar PV system controller and transmission losses daily are expressed in Eq. (7) (Janowski et al. 2016):

$$E_{el} = \eta_k\ [(E_{PV} - E_{PW} - E_L)\ x\ \eta_{ak}\ x\ \frac{T_{ak}}{24} + (E_{PV} - E_{PW} - E_L)\ x\ \frac{T_d}{24}] \tag{7}$$

where (η_k) is the efficiency of the controller, (E_{pw}) energy used for the solar PV system needs, (E_L) is energy losses in transmission wires in the solar PV system, and (η_{ak}) is battery storage efficiency. (T_d) is the operating time while using CP, and powered by the PV system from sunrise to sunset. (T_{ak}) is the operating time while using the batteries, which can be assumed as (24h -T_d).

A high electrical load efficiency is required in the design of stand-alone PV systems in order to keep the PV system’s size and cost low. Photovoltaic cathodic protection systems include finding the best-ground bed design involving anode type, size and location and reducing CP circuit resistance. There will also be an ideal ground bed design for each CP application to reduce the overall system cost. Therefore, there are trade-offs between the ground bed expenditure and the design and the reduction of photovoltaic array needs (Oney 1980).

A case study presented by (Alzetouni 2019) discussed the importance of implementing the impressed current CP technique in the oil and gas industry sector, where the key equipment of wall casing and associated frow lines are used. Fig. 7. shows a typical practical example of a solar PVCP system used to protect pipelines in the oil and gas sector. The system consists of four solar PV modules linked together, which absorb photons from the sun and convert energy; subsequently, that energy powers the CP equipment.

Fig. 7. Practical application of solar PV powered cathodic protection CP, (a) front view with batteries and controller, (b) back view of solar PV (SPCP 2021).

According to its need to operate the PV array at the optimum voltage for maximum power usage, batteries would virtually always be necessary for photovoltaic cathodic protection applications (Manimekalai et al. 2013). Moreover, it is essential to enable energy storage to keep the operating load at a steady power level at night and during periods of low solar irradiance.

The photovoltaic systems designer has a variety of battery storage technologies from which to choose, each with its own set of features, design requirements and price (Markvart et al. 2003).

Therefore, nickel-cadmium, lead-acid, and gelled-or starved-electrolyte lead-acid batteries are all common battery types used. However, the most popular type of battery is “the flooded lead-acid battery”, which is relatively cheap and has well-defined features (Christiana et al. 2022).

Additionally, photovoltaic systems are enhanced by “deep-cycle, motive-power tracer batteries” used in electric automotive as well as other deep discharge and usage situations (Christiana et al. 2022). Hence, such batteries have substantially thicker grids than car starting batteries and can withstand multiple deep discharge cycles (Kiehne 2003). The lead-acid battery grids are usually made from antimony or calcium alloyed with lead. The batteries with antimony are much more resistant to deep discharges, sulfation, and temperature variations. The calcium alloy has been developed to help in water conservation and routine maintenance. The gelled-or “starved electrolyte lead-acid batteries” have many of the same features as flooded lead-acid batteries; however, they require less maintenance (Bailey et al. 2014). Although more costly than lead-acid batteries, nickel-cadmium batteries have the benefits of long life, minimal maintenance, and resistance to low and high voltage situations as well as low temperatures (Kiehne 2003). In addition, in well-designed installations, nickel-cadmium batteries might not always need a charge controller to eliminate photovoltaic array overcharge and load over-discharge (Bailey et al. 2014).

The battery size is based on the autonomy of the number of days required for the system process in non-Sun situations. Solar photovoltaic CP systems typically have storage durations of three to eight days and could take advantage of a longer autonomy duration to extend battery life and reduce the average daily depth-of-discharge. The suggestion of lead-acid batteries in sizing, maintenance and installation procedures has been developed (Kelly et al. 2017).

The majority of polycrystalline and single-crystalline silicon photovoltaic panels have fulfilled the testing standards set (Oney 1980). Thus, modules that meet the following criteria are preferred and appropriate for PV cathodic protection systems (Lasnier et al. 2017). For harsh naval uses, the requirements could be desirable. The photovoltaic modules/array could be necessary to charge the batteries adequately with specified current-voltage characteristics based on the system design (Markvart et al. 2003). Low-voltage photovoltaic devices are available from certain producers, designed for the low-voltage potentials needed in photovoltaic cathodic protection systems. In order to maintain long-term reliability, appropriate procedures must be followed while mounting the photovoltaic modules/ array and its associated components (Kharzi et al. 2009).

Solar photovoltaic CP systems should, if possible, be designed to meet national electric code criteria for photovoltaic systems (Kharzi et al. 2009). Circuit breakers, or fused disconnect switches, are recommended to separate the battery bank from other components of the system (McEvoy et al. 2012). The wiring diameters should be optimised to reduce resistance across the system. Also, to avoid deterioration, the appropriate wiring insulating ought to be chosen for the environment. This is particularly essential in the ground bed design, wherein leakage currents, and a loss of power and system effectiveness. That can occur due to insufficient or defective wire insulation (Manimekalai et al. 2013).

When determining the power needs for the cathodic protection system, the photovoltaic system is sized in the same way as other loads. “The national association of corrosion engineers” has released recommended techniques for determining cathodic protection system power requirements (Oney 1980). To some degree, the oversizing of photovoltaic systems may indeed be required in systems where the preventative coatings on the framework constantly deteriorate, resulting in a growing cathodic protection power requirement over time. Inappropriate designs will be avoided, although the framework will provide appropriate protection when the coating does deteriorate (Kelly et al. 2017).

There are various benefits of using solar photovoltaics to power cathodic protection devices. Firstly, eliminating the requirement for fuel or electricity from the grid can lower the cost of maintaining the system. Secondly, solar energy is a renewable and clean form of power, and it can make the system more environmentally friendly. Lastly, reducing the risk of interruptions to electricity caused by electrical failures or fuel shortages may enhance the system's reliability.

Considerations for solar-powered cathodic protection system design involve minimising anode bed resistance and optimising power demands. Hence, with increasing wattage, the cost of the power source for a cathodic protection (CP) system that powered by solar energy rises exponentially. Consequently, spending more money on the CP system design to lower power requirements can significantly affect the solar power system's installation cost.

It's worth mentioning that one application technique of solar PV is the so-called concentrating photovoltaic (CPV) technology, which primarily generates electricity from sunlight (Maka et al. 2024). Hence, the overall effectiveness of that approach can be integrating solar CPV systems with cathodic protection systems (Maka et al. 2020) as reported by (Maka and O'Donovan 2022).

Table 1 describes the related research studies on the solar photovoltaic-powered cathodic protection CP system and analyses the different attempts by many researchers using various approaches. According to the table, a few studies have focused on investigating solar photovoltaics that powered cathodic protection CP system, and we elicited that the system needs further improvement. Therefore, a plan for adopting an integrated approach to CP systems is needed to optimise and maintain the system's integrity.

Table 1. research studies conducted on the solar photovoltaic-powered cathodic protection CP system.

No.	Tools	Method	Observation /remarks	References	Applications
1.	Design and simulation	Using MATLAB/Simulink.	- Economic analysis is performed to compare between rehabilitation of defective pipelines. - The findings indicate that utilising a Photovoltaic powered ICCP system instead of pipeline repair saves a huge amount of money.	(Samoudi 2015).	Protection of pipelines.
2.	Experimental	Reinforcement corrosion treatment.	- The efficiency of solar energy as a cathodic protection system substitute for direct current. - The corrosion rate of the samples treated declined significantly as the treatment time moved.	(Ismaila et al. 2007).	Reinforced concrete cylinder.
3.	Modelling	Rescreen clean energy management software.	- The technology studied indicated that the designed system met the whole yearly energy condition to transport based on the Rescreen results. - The conclusion demonstrates the potential of significant energy reserves with solar energy connections in CP.	(Kusmaya et al. 2018).	Protection of oil and gas pipelines from corrosion.
4.	Experimental	Evaluating solar PV installed for many years.	- Photovoltaic supply systems for providing electrical energy to remote rural CP units are warranted on economic and technological grounds. - Solar photovoltaic generators have an economic and technical advantage versus diesel generators.	(Ibrahim et al. 2004).	Protection of oil and gas pipelines from corrosion.
5.	Modelling	Anodes connected to a DC power source.	- Estimate the number of solar cells required for the ICCP grid power source system that protects the $1m^2$ of metal subsurface tank surface. - Solar panels will be well-suited for ICCP systems with low protective current density and those located away from the power grid, in which the costs of the power source connection offset the cost of a relatively expensive solar power system.	(Janowski et al. 2016).	Protection of tanks.
6.	Numerical modelling	Design of the impressed	- The protective potential is widespread, and the technology may be customised to different materials used in pipeline construction.	(Laoun et al. 2009).	The steel drains in the oil and gas industry.

		cathodic protection.	- The output current is sufficient to protect the pipelines at an affordable cost.		
7.	Simulation	Using Intelligent Method.	- Solar smart cathodic protection devices have been performed. - The dimensions and weight of the system are reduced by eliminating the transformer and oil tank from the framework, which reduces the cost of construction and installation.	(Javadi et al. 2014a).	Underground pipelines.
8.	Numerical calculation	MATLAB/Simulink and PVsyst software.	- The results indicated that installing a solar-powered cathodic protection system for underground pipes is feasible and cost-effective. - Considering the rapidly lowering prices of solar photovoltaic components and these technologies' rising efficiency and reliability.	(Al-Refai 2019).	Cathodic protection for buried pipelines transporting hydrocarbon and other oil products.
9.	Experimental	Built up a prototype and collected the measuring data.	- The prototypes of photovoltaic panels for cathodic protection have been built, and photovoltaic solar energy yields have been investigated. - The system's input and output and the data collected have a high efficiency of 99.2%.	(Hassmoro 2014).	Pipelines CP.
10.	Modelling	Design system to power ICCP.	- It developed a smart model for monitoring new means of powering an ICCP system.	(Sibiya et al. 2018).	Underground pipelines.
11.	Simulation	Fuzzy logic system controller.	- The strength of the fuzzy logic controller alleviates the induced voltage and can compensate for the cathodic protection disruption.	(Shaalan et al. 2022).	Pipeline CP.
12.	Experimental	Microcontroller of CPU that used pulse width modulation (PWM) technique.	- It proved that incorporating solar and wind energy resources with battery storage can be used to operate cathodic protection units (CPUs).	(Akani et al. 2021).	Prototype test on pipes.

5.2. The controller system of solar PVCP

System control is one of the key components of the solar PVCP system that must be considered whilst in the design process. The key challenges arise from variations in the surrounding medium resistivity due to weather conditions; a controlling circuit for managing cathodic protection powered by solar photovoltaic energy has been designed to address this challenge. This describes a controlled cathodic protection system (Kharzi et al. 2009).

Table 2. summarises an application and controlling system used in the CP system. Accordingly, comparing different aspects includes the work's application, nature, and control system, it is deduced that further work will include investigating a smart controller system of solar PV and battery chargers/discharges to retain the system's effectiveness.

Table 2. details the application and control system used in the CP system.

No.	Control system	Tools	References	Applications
1	The electronic control circuitry of electronic control circuits (ECU).	Designed and tested solar PV.	(Mishra et al. 2000).	Pipeline CP.
2	The regulated CP system.	Numerical modelling	(Adly et al. 2017).	Pipeline CP.
3	Microcontroller 16F877 buck-boost.	Simulation.	(Kharzi et al. 2009).	Gas pipeline application protection
4.	The combined controller of the MPPT.	Simulation.	(Javadi et al. 2014a).	Underground pipelines.
5	Microcontroller 16F877 buck-boost controller.	Simulation.	(Kharzi et al. 2006).	Pipeline CP.
6	The control system of the boost converter and L298N IC.	Experimental.	(Faisala et al. 2018).	-
7	Two microcontroller-controlled DC/DC converters.	Simulation.	(S Kharzi et al. 2009).	Pipelines.
8	Two controllers have been proposed; the first type of controller controls the battery.	Simulation.	(Javadi et al. 2014b).	Pipelines.
9	electronic control regulated cathodic protections.	Design / numerical calculation.	(Anis et al. 1994).	Pipelines.
10	electronic control regulated cathodic protections.	Design/ numerical modelling.	(Anis 1995).	-
11	Intelligent solar cathodic protection of the MPPT and PI controller.	Simulation.	(Javidan 2016).	Pipeline.

The control board also includes instruments for monitoring system parameters and control features for performing manual changes and managing operations. The data gathering modules that have been located at the bottom of the unit gather data on output current, output voltage, and reference electrode current (Bailey et al. 2014). In case of a lightning strike, the arrestors, often known as surge protectors, offer a short circuit path to the ground, preventing high current spikes that might harm electronics (BRMERL 2013).

However, the most important part of a photovoltaic cathodic protection system is the control systems that govern the power flow from the photovoltaic array to the batteries, as well as from the batteries to the load (Kiehne 2003). The charge controllers for photovoltaic devices and systems which control the current and voltage in cathodic protection systems are available from various vendors. Higher and lower voltage protection is often necessary for batteries, and this is usually handled by using a series, or shunt controller, to disconnect and re-connect the photovoltaic array from the batteries based on battery voltage. A low-voltage load-disconnection relay could effectively safeguard the batteries from overcharging (Kharzi et al. 2009). The standard system consideration includes the voltage, battery characteristics, the relative sizes of the photovoltaic array, battery, and load. The charge controller connects and disconnects the batteries from the photovoltaic array and loads that depend on specific situations such as current, voltage, temperature, etc. (Merrigan et al. 1992).

In order to provide the necessary overpotential and current to the cathodic protection system, some power conditioning is typically needed between the CP's batteries and the cathodic protection system (Sibiya et al. 2021). Most utility-powered conversion systems use a resistive, or rheostat, controller to regulate and modulate the desired "overpotential and impressed current". Although rheostat controllers are effective and simple, their significant power dissipation makes them ineffective. Alternative solid-state current-regulating devices, such as DC-DC converters could give a significantly more efficient output control (Akani et al. 2021). A reference electrode is an auxiliary item that comes with some cathode protection controllers and is used to estimate the level of the structures being safeguarded (Sibiya et al. 2020).

When designing a cathodic protection system, one must consider the necessities of the system. Consider the protected object as an uncoated metal tank located in an area of sandy soil. The next stage is to determine an anode; as usual, the anode will carry a current; however, the current will probably have little impact on anode choices. The resistance between the anode and the cathode is another factor to consider when selecting an anode. Therefore, the resistance is determined by the soil resistivity and the anode's size (Roger et al. 2018). In addition, the number of salts dissolved in the soil and the moisture content significantly influence it. The relationships between corrosion rate and soil resistivity are presented in Table 3 (Bashi et al. 2003).

Table 3. soil resistivity and rate of corrosion (Bashi et al. 2003).

Soil resistivity (Ω-m)	**Type of corrosion rate (mils/year)**
<25	Severely corrosive (> 13).
26-50	Moderately corrosive (9-12).
51-100	Mildly corrosive (4-9).
>100	Low corrosive (< 4).

The current from the anode travels more or less radially outward because the anode is typically cylindrical. A cylindrical geometry with an infinitely long charged cylinder produces an electric field that varies inversely with the distance from the cylinder. This creates a logarithmic voltage change and a good, nonlinear correlation between the anode's length and diameter and the resistance from the anode to the ground. The ground resistance for various soil resistivities is then proportional to the resistance under standard situations (Roger et al. 2018). The resistance between the anode and the cathode is the anode's resistance to the ground (Wansah et al. 2005).

Photovoltaic CP depends on geographic location and the expense of providing grid power to a remote location. However, according to the reports, the presented technique can be used in various remote locations. For example, an application such as underground storage tanks, pipelines, and other steel infrastructure could benefit from a photovoltaic-powered CP system in remote areas. This technology might also assist in achieving the rising cathode protection monitoring requirements for wharves, ports, seawalls and steel in reinforced concrete pier pilings (Bailey et al. 2014).

Fig. 8. (a) presents the integration system of solar PVs /batteries powered cathodic protection. Through incorporated remote monitoring features that allow remote performance monitoring of the battery pack and photovoltaic systems, inspection intervals can be extended. Also, it includes maximum power point tracking to control the performance of PV devices. This system gives an insight into corrosion scheme optimisation to maintain reliable system performance. The control system of the solar photovoltaic devices and the batteries charge/discharge via a smart solar charge controller to retain the system operative during the night and in non-sunlight conditions. The system will smartly change from day to night mode, collecting and sending data to the central monitoring room throughout space satellite systems. In the pipeline route,

many systems will be installed alongside, enabling the engineers to have a proper view of the pipeline conditions.

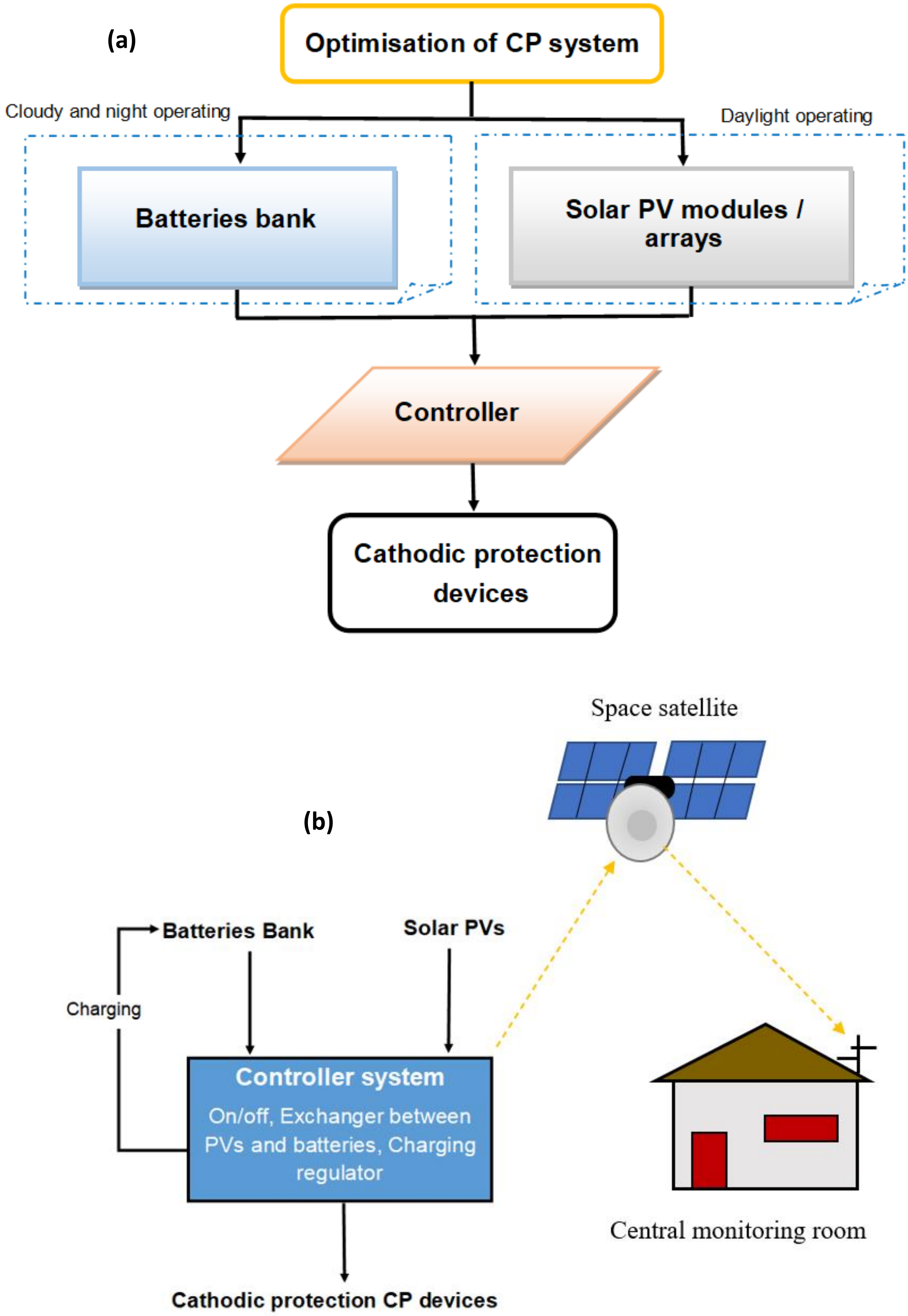

Fig. 8 (a) integration system of solar PVs /batteries powered cathodic protection CP scheme; (b) scheme of a system controller and monitoring of cathodic protection CP.

With the recent development of heavy-duty batteries, such as lithium-ion (Li-ion) batteries, it is recommended these are used to optimise PVCP performance. This battery is the most popular battery used in modern electric vehicles due to its high energy density and weight. The battery in the system is used at night and on overcast days whenever the solar cells generate little or no power. Afterwards, the controller will be used, and the system is finally connected to the pipeline and anode-bed circuit models. Adapting new technology, such as remote sensing and space satellites, will help to monitor performance and detect faults.

Fig.8. (b) describes the scheme for a system controller and the monitoring of cathodic protection. In projects such as pipelines, where the route sometimes reaches thousands of kilometres and will install many mini-stations alongside, a smart control system would be recommended for higher system reliability; the controller and monitoring system function as the on/off, the exchanger between PVs, batteries, and the charging regulator. A reliable autonomous control system requires sensors linked to the central control room, leading to broad system control and monitoring. Furthermore, the devices sent the signal to the central monitoring room via satellite technology. The development of information technology and satellite communication have both been powerful enablers for transforming the use of data. The operator in the monitoring room can see data on each mini-station's solar PVs, batteries and CP devices.

A case study presented by (Abdulwahab et al. 2022) investigated the significance of real-time control systems and remote monitoring of CP systems applied for underground pipelines. Refs. (Adhya et al. 2016) another study by (Kekre et al. 2017) and another reported study by (Sivagami et al. 2021) detailed a method to control remote monitoring for a solar photovoltaics system based on the Internet of Things (IoT). That system can monitor and control the operating parameters of PV devices.

Also, referring to the latest high-speed internet connection provided by Starlink company, the technology is cableless; and it depends on the uses of a cluster of satellites in orbit around the Earth to provide internet connections to customers. These systems can provide internet in the desert, remote areas, or regions without internet infrastructure.

Therefore, this system is able to control and monitor all the system parameters of PV modules and CP performance in the solar CP. A charge controller provides power to the battery, either recharging when the power is supplied to electrical loads or maintaining it. In order to avoid providing voltage or current beyond the battery's charging limits, the charge controller is typically employed to manage the charging current and voltage output from the controller. Therefore, the charging controller's input and output power ranges ought to be consistent with the photovoltaic modules design and the purchased batteries. An electronic control device that is powered by the storage batteries and acts as a load voltage regulator.

Batteries are rated in terms of (Ah) capacity, which corresponds to how much current a battery can produce over a given period of time. For cathodic protection CP applications, deep-cycle batteries with a high number of charge/discharge cycles ought to be used. Before being replaced, a battery system must be capable of providing the required output current. The lifespan and output capacity of lead-acid batteries will vary depending on the quality of the battery purchased and how it is used; however, high temperatures can significantly impact their output capacity and longevity.

The performance of solar modules depends on many environmental operating parameters, for instance, ambient temperature, solar radiation intensity and dust accumulation (McEvoy et al. 2012), as detailed by (Dickinson 2018). These environmental factors are taken into account in the design and installation duty; thus, appropriate locations are selected based on these metrological information (Maka et al. 2021) and details reported by (Maka and O'Donovan 2022); also experimentally performed by (Chaudhary et al. 2023). Moreover, in the desert environment, it requires monitoring/maintenance since dust accumulates over the PV panels and results in substantial losses of performance (Mohamed et al. 2012), recently reported by (A Maka et al. 2021). Therefore, that challenge can be addressed by recommending at least a half-weekly or weekly cleaning framework during blowing sandy winds. Also, the state-of-the-art robotic cleaning system is one of the most efficient technologies widely implemented.

In the solar-powered CP system, the design requires an inspection to ascertain that it is not being too conservative in determining the current installation volume, as the failure may result in over-capacity (Van Blaricum et al. 2001) and specified by (Kelly et al. 2017). In addition, reference (Livera et al. 2022) conducted a failure diagnosis on a large-scale photovoltaic system. The analysis indicates that the methods efficiently detected failures and losses mechanisms and the pipeline's capacity to discern under-performance problems utilising residual, anomaly detection, and cathodic protection approaches.

Therefore, in order to guarantee that the system is not being excessively conservative and adding additional current capacity that is not necessary for the application, the design current ought to be carefully evaluated. For instance, the anode bed resistance is mainly a function of the total anode system length makes it simple to design the cathodic protection system to lower anode bed resistance. Also, anode bed resistance can be significantly decreased by designing the anode system with a longer anode. The power output from solar photovoltaic systems largely depends on the weather conditions. However, this variation can be mitigated by integrating a back-up battery framework, which may store surplus electricity produced during intense sunlight and discharge it during lower sunlight.

Therefore, in applying the structure concretes/pipelines and storage tanks, the CP is one of the bespoke techniques to protect them from corrosion, particularly in the oil and gas industry in the arid desert environment. As a result, the oil is transformed from oil fields in faraway regions to ports in coastal regions so that it is cost-effective and minimises the operation and maintenance (O&M) cost. Another example in Libya is 'the made man reiver' project for transporting the water from the Libyan desert to coastal regions; consequently, huge concrete pipelines are utilised, its dimensions of a diameter of 4m and a length of 7m.

The reliability of the components comprising the photovoltaic system and the reliability of situations suited for producing solar energy influence the photovoltaic modules system's reliability. Based on the recent technological development, it is recommended to adopt remotely controlled monitoring devices. Thus, it is deemed one of the techniques used to enhance the performance of solar PVCP systems. The benefits of the PVCP system are that it can be installed in certain points "mini-station" along pipe routes within longer distances, e.g., in oil and gas fields; sometimes, the location is thousands of kilometres away from the port destination, and which needs to be transported through pipelines. However, smart controlling and monitoring will eliminate human involvement and be substituted for machine-machine communication.

6. Conclusions

This work highlights the need to investigate solar photovoltaic module's potential and operating characteristics equipped with a cathodic protection system. The system is important to safeguard against corrosion impacts in the materials, subsequently cost-effectively. Therefore, corrosion fundamentals should be deeply comprehended to properly choose materials and design, assemble, and use metal structures for the optimal economic life of facilities and safety in oil/gas activities through studies of the root of causing the corrosion phenomenon and considering its remedy before implementing such a valuable project.

This review analysed the results of severe corrosion, which kept the facilities/equipment in a tattered condition. Furthermore, it is worth mentioning that the rehabilitation of such valuable facilities will cost billions of dollars. The important thing to be noticed/highlighted is an adaptation of smart controlling of solar photovoltaic cathodic protection (PVCP), which is a preferred technique for monitoring the system performance characteristics, particularly in remote areas. An integrated system of solar PVs/batteries powered CP is proposed to maintain highly reliable system performance. Likewise, a smart controller system of solar PV, batteries chargers/discharges, keeps the system's efficacy high during night-time and no-sunlight conditions. A reliable autonomous control system leads to broad system monitoring and control.

Lastly, the reviews mentioned above consolidate the approaches of cathodic protection systems, including sacrificial anode cathodic protection (SACP) and the impressed current cathodic protection (ICCP) powered by clean renewable energy resources. In contrast, this approach to the conventional method depends on chemical treatment; it does not require the addition of potentially hazardous chemicals. Although cathodic protection systems avoid breakdowns, repairs, and untimely replacements, their initial cost can be justified in the long run. Therefore, further experimental and validation research and development in different environmental conditions is suggested to develop such an application and improve its design. Subsequently, that may lead to this technology being widely deployed.

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The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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