# New Reliable, Efficient, and Cost-Effective Cathodic Protection System

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## *Abstract*

*Electrochemical corrosion represents one of the most significant challenges facing modern industrial and civil infrastructure, causing the gradual degradation of underground and underwater metal and reinforced concrete structures. As a result of electrochemical reactions, structural elements lose their mechanical strength, reliability, and long-term serviceability, leading to substantial economic losses and increased maintenance costs worldwide. The corrosion process develops when metal atoms transfer electrons to depolarizing agents present in the surrounding environment, while the presence of moisture and electrolytes enables ion transport and accelerates corrosion. Therefore, the development of reliable and efficient corrosion protection technologies remains one of the key objectives of modern engineering. Among existing anti-corrosion methods, cathodic protection is considered one of the most effective techniques for protecting metal structures. Traditional cathodic protection systems are primarily based on sacrificial anodes or impressed current systems powered by an external direct current source. Despite their widespread application in underground and underwater metal and reinforced concrete structures, these systems are often associated with high energy consumption, limited-service life of anodic elements, complex maintenance requirements, and the gradual degradation of anodic grounding electrodes caused by electrolysis. The aim of the research was to develop a new, reliable, energy-efficient, and economically sustainable cathodic protection system capable of extending the operational lifetime of both protected structures and anodic grounding electrodes. The proposed system operates on the principle of alternating current and provides intensive cathodic polarization of the protected structure, while the main anodic grounding electrode functions not under continuous oxidation, but in an oxidation–reduction regime. The system includes a transformer, capacitor, oppositely connected parallel diodes, anodic grounding electrodes, and conductive filler materials, enabling automatic stabilization of the protective current without the need for an additional automatic regulator. The proposed protection principle ensures equality between the incoming and outgoing currents of the electrode, thereby eliminating electrolytic degradation of the anodic grounding electrode. This represents one of the major advantages of the system and significantly increases its operational reliability. The developed protection system can be applied to underground and underwater linear metal structures, reinforced concrete constructions, marine infrastructure, reservoirs, foundations, anchors, and other engineering facilities operating in aggressive corrosive environments.*

**Keywords:** *Cathodic Protection; Electrochemical Corrosion; Anode Grounding Electrode; Sacrificial Anode; Transformer; Corrosion Protection*

## 1. Introduction

Electrochemical corrosion is a physicochemical process through which metallic and reinforced concrete structures gradually deteriorate, leading to mechanical weakening, structural damage, and substantial economic losses. The process occurs when metal atoms transfer electrons to a depolarizer, which acts as an electron acceptor in the surrounding environment. The presence of an electrolyte is essential for this reaction because it enables ion transport; therefore, water and moisture are among the principal causes of corrosion [1,2].

Corrosion is generally defined as the slow but irreversible degradation of materials resulting from chemical and electrochemical reactions. Electrochemical corrosion is the most common form and originates from the thermodynamic instability of metals under environmental conditions. It represents a natural tendency of engineered metallic materials to return to a more stable chemical state.

One of the traditional and effective methods of corrosion protection is galvanization, in which a metal surface is coated with zinc [2]. Because zinc is electrochemically more active than steel, it functions as a sacrificial anode and corrodes preferentially, thereby reducing the corrosion rate of the protected metal and extending its service life.

Modern engineering practice extensively utilizes cathodic protection systems based on the principle that the protected metal remains permanently in a cathodic state. Under these conditions, the metal does not lose electrons and therefore does not undergo anodic oxidation [1,3].

The two principal categories of cathodic protection systems are:

1. Sacrificial (galvanic) anode systems, which employ zinc, magnesium, or aluminum anodes that corrode instead of the protected structure;
2. Impressed current cathodic protection systems (ICCP), which utilize an external power source to maintain the required negative potential on the protected structure.

Electrochemical corrosion is a complex process occurring on the metal surface and within its microstructure. Oxidation and reduction reactions develop at spatially separated locations, forming local anodic and cathodic regions. Because metals are excellent conductors of electrons, they facilitate electron transfer between these regions, thereby accelerating corrosion processes.

Even a thin layer of moisture can provide sufficient ionic conductivity for corrosion reactions. Consequently, corrosion damage can occur not only in highly humid environments but also under relatively dry conditions.

Although protective coatings such as paints, varnishes, and polymer layers are widely used to isolate metallic surfaces from aggressive environments, these coatings often develop micro-defects that allow corrosive agents to reach the metal surface. Therefore, electrochemical protection methods, particularly cathodic protection, are considered more reliable and durable solutions [3,4].

Corrosion control is not only a technical challenge but also a major economic concern. Worldwide corrosion-related damage to infrastructure amounts to billions of dollars annually, emphasizing the importance of developing advanced and reliable protection technologies.

## 2. Cathodic Protection Systems and Their Applications

Since the late nineteenth century, steel-framed structures have been extensively used in multi-story buildings[5]. Over time, their protective properties deteriorate, making them increasingly vulnerable to corrosion. The volume of corrosion products may become 7–11 times greater than the original steel volume, resulting in structural deformation and damage to surrounding finishing materials.

Prior to 1990, rehabilitation methods mainly consisted of mechanical cleaning and protective coatings. Although effective in the short term, these methods were labor-intensive, expensive, and frequently destructive. Since the 1990s, cathodic and sacrificial protection technologies have become increasingly widespread, significantly extending the service life of steel structures[3,4].

In sacrificial protection systems, more active metals are attached to the protected structure and corrode preferentially. However, in steel-framed buildings the high electrical resistance often limits the voltage generated by galvanic anodes, making it insufficient to provide adequate protection current. In such cases, impressed current cathodic protection systems are used because they permit adjustment of the protection current according to environmental conditions.

The selection of anodes is a critical factor in system performance. Mixed metal oxide-coated titanium anodes are commonly used because of their durability and efficiency [4]. However, in reinforced concrete structures where steel reinforcement is deeply embedded, discrete rod anodes often provide more effective current distribution.

Typical applications of cathodic protection include:

- Marine structures such as piers, offshore platforms, ships, and coastal facilities;
- Underground linear infrastructure including oil and gas pipelines;
- Reinforced concrete structures such as retaining walls, highways, bridges, tunnels, and building foundations;
- Reservoirs and wells;
- Steel anchor systems including cable anchors, solid rod anchors, self-drilling anchors, friction anchors, and mechanical expansion anchors.

The long-term stability of anode grounding electrodes is one of the most important factors determining system reliability. Consequently, the development of innovative anode grounding systems remains a significant engineering objective.

### *2.1 Proposed Alternating Current Cathodic Protection System*

Researchers at the Grigol Tsulukidze Mining Institute have developed a novel alternating-current cathodic protection system. In the proposed design, the protected structure continuously operates in an intensive reduction (cathodic) mode. Simultaneously, the primary anode grounding electrodes function in an oxidation-reduction regime rather than under continuous oxidation conditions, while the sacrificial anodes operate in a half-cycle oxidation mode.

This approach prevents the electrolytic degradation of the primary anode grounding electrodes and substantially increases system service life.

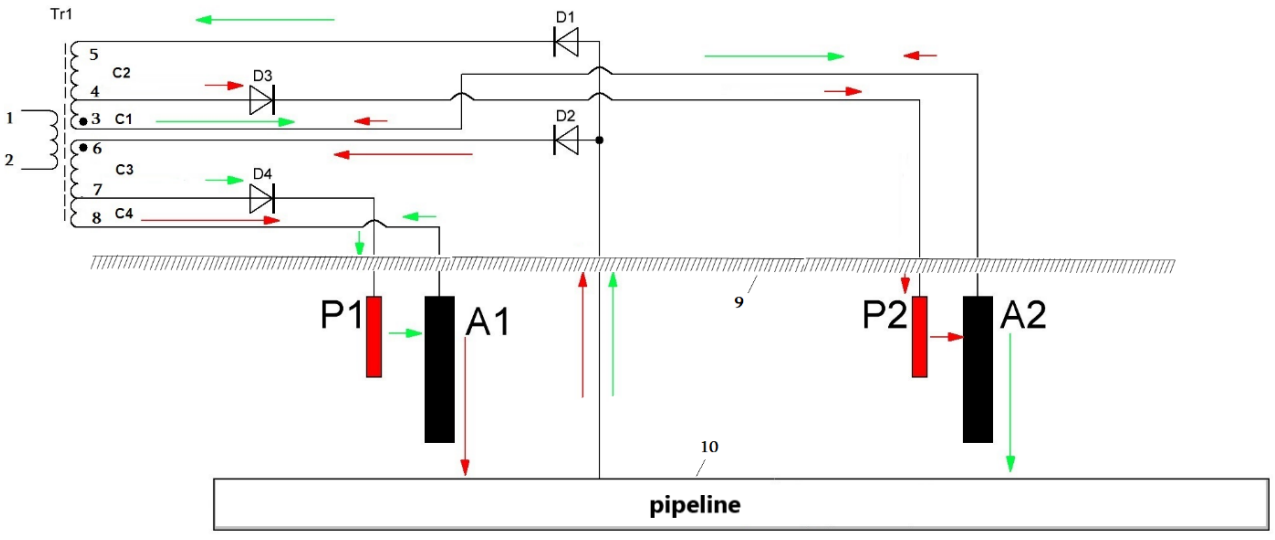


Fig. 1. Schematic diagram of the proposed cathodic protection system.

The device incorporates an AC power source represented by transformer Tr1. The primary winding (terminals 1 and 2) is designed for a nominal voltage of 220/230 V and a maximum temperature rise of +50°C.

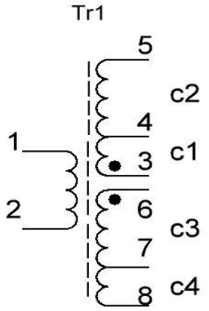

Fig. 2. Transformer design and calculation parameters.

The transformer contains two secondary windings designed for a nominal current of 12 A. The resistance equivalent of the anode-pipeline circuit is approximately ten times greater than that of the anode-sacrificial electrode circuit. The voltage of section C1 is approximately ten times lower than that of section C2, while section C4 is approximately ten times lower than section C3.

The electrical configuration includes two anode grounding electrodes (A1 and A2), two sacrificial electrodes (P1 and P2), four diodes (D1–D4), and the protected underground pipeline. The arrangement enables current flow patterns that maintain cathodic protection of the pipeline while simultaneously reducing destructive anodic processes within the grounding electrodes.

During operation, the voltage between terminals 3 and 5 generates a half-wave protection current through anode grounding electrode A2, the surrounding soil, the protected pipeline, and diode D1. Similarly, the voltage between terminals 6 and 8 generates the second half-wave protection current through anode grounding electrode A1 and diode D2.

The voltages between terminals 3 and 4, and between terminals 7 and 8, are selected so that the currents flowing through sacrificial anodes P2 and P1 respectively are equal in magnitude and opposite in direction to the pipeline protection current during each half-cycle.

Consequently, during one half-cycle the circuits involving A2 and P1 are active, whereas during the second half-cycle the circuits involving A1 and P2 are active.

As a result, the pipeline experiences a unidirectional protection current during each complete cycle. The anode grounding electrodes carry alternating sinusoidal currents, whereas the sacrificial electrodes carry half-wave alternating currents.

Therefore:

- The pipeline operates in an intensive reduction mode;
- Anode grounding electrodes A1 and A2 operate in an oxidation-reduction regime;
- Sacrificial anodes P1 and P2 operate in a half-cycle oxidation regime.

This operating principle significantly minimizes electrolytic destruction of the anode grounding electrodes.

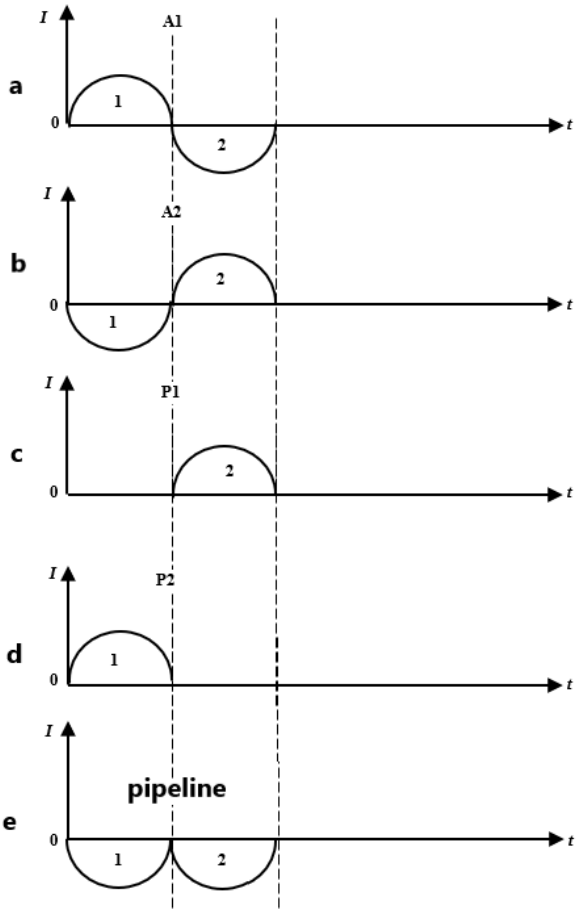

Fig. 3. One-cycle current flow diagrams within the cathodic protection system.

where:

a) Current flow diagram in anode grounding electrode A1;

b) Current flow diagram in anode grounding electrode A2;

c) Current flow diagram in sacrificial anode P1;

d) Current flow diagram in sacrificial anode P2;

e) Protection current flow diagram in the protected pipeline.

The proposed design makes it possible to use inexpensive recycled iron materials instead of costly alloy electrodes for both anode grounding electrodes and sacrificial electrodes. Consequently, the service life of the protection system is increased while overall system costs are reduced.

Compared with conventional cathodic protection devices, the proposed system offers simplicity, high reliability, and lower implementation costs.

## 3. Conclusion

The proposed cathodic protection system represents a reliable, efficient, and economically attractive solution for mitigating electrochemical corrosion in critical infrastructure.

The innovative operating principle substantially reduces the electrolytic degradation of anode grounding electrodes while maintaining effective cathodic protection of the protected structure. The system enables the use of inexpensive iron-based materials instead of costly alloy electrodes, thereby reducing installation and maintenance costs.

The proposed technology offers high reliability, simple construction, and extended operational life compared with conventional cathodic protection systems. Its implementation can significantly increase infrastructure durability, reduce maintenance expenditures, improve environmental and energy safety, and protect valuable engineering assets against corrosion damage.

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