The Latest Developments in Concrete Corrosion Protection for Infrastructure Assets

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ABSTRACT

Impressed current and galvanic cathodic protection systems have been widely used in Australia for the corrosion protection of bridges and wharves over the past thirty years.

However, in many applications the corrosion protection system selected for a structure is not the optimum technical solution available for long-term corrosion protection. Less effective corrosion protection solutions have been selected by asset owners, not because of cost considerations, but rather due to the notion of adopting one-off treatment for corrosion protection which does not require ongoing maintenance and monitoring.

In recent years, there have been considerable developments in impressed current, galvanic anode technology, and power supply equipment. These recent advancements now allow for the selection of reliable long-term corrosion protection solutions for individual structures, lowering the inclination for asset owners to use less effective, one-off treatments.

This paper provides guidelines on the selection process for determining the optimum corrosion protection solution for reinforced concrete structures. This paper also highlights the advantages and disadvantages of the available cathodic protection technologies, and presents the latest technological developments in galvanic anode, hybrid, and impressed current cathodic protection systems.

Keywords: corrosion, anode, galvanic, monitoring, maintenance

1. INTRODUCTION

Impressed Current Cathodic Protection (ICCP) for reinforced concrete structures is a proven technology which can provide long-term corrosion protection for structures located in marine environments. This technology has been installed on numerous structures in Australia over the past 30 years and it is the technology of choice for asset owners for the protection of structures subject to chloride-induced corrosion (1).

Sacrificial Anode Cathodic Protection (SACP) and Hybrid Anode Cathodic Protection (HACP) are currently areas of substantial growth. These types of systems are becoming increasingly attractive because of their simplicity and low monitoring and maintenance requirements.

The selection process for the optimum corrosion protection system for structures suffering from chloride induced corrosion is normally based on various considerations such as the cause and extent of concrete deterioration, the level of corrosion activity, the continuity status of the embedded rebar within the structure, the size and location of the structure, the remaining service life of the structure, and the cost and maintenance requirements associated with the selected repair methodology.

This paper presents the basic theory of ICCP, SACP and HACP systems, the latest developments associated with these technologies, and the guidelines for selecting the optimum system for corrosion protection.

2. CATHODIC PROTECTION TECHNOLOGY

When steel corrodes in concrete, the electrochemical process is comparable to that of a battery. In a battery, electrons which are generated because two dissimilar metals are exposed to an acidic solution (paste or gel in conventional batteries) which corrodes one metal and creates a harmless reaction in the other. This corrosion reaction at the ‘anode’ generates electrons that are consumed by the ‘cathode’.

When steel reinforcement begins to corrode in concrete, a small area becomes the positive pole (anode) and another much larger area becomes the negative pole (cathode). The corrosion current flows out of the steel at the anode (the corroding part), passes through the concrete and to another part of the steel where there is no corrosion occurring (the cathode). This current flow is called the corrosion circuit and the steel dissolved at the anode forms iron oxide.

In a practical battery, the electrical connection between positive and negative poles can be disconnected. The circuit is then broken and the dissolution of metal stops.

In concrete, the corrosion circuit is buried in the structure and the electrical current running through the concrete cannot easily be disconnected. Cathodic protection technology is based on stopping the current from running through the concrete by providing a new current from an external source via an external anode in contact with the concrete. The flow of electrons between the new anode and the reinforcing steel changes the previously positive poles (anodes) into current receivers. Thus, all of the reinforcement becomes the negative pole or cathode, and hence the name ‘cathodic protection’.

For reinforced concrete structures, there are three types of cathodic protection systems; Impressed Current Cathodic Protection (ICCP), Sacrificial Anode Cathodic Protection (SACP) and Hybrid Anode Cathodic Protection (HACP).

2.1 Impressed Current Cathodic Protection (ICCP)

Impressed current cathodic protection (ICCP) is a well-established technology for the corrosion protection of reinforced concrete structures. All aspects related to the design, installation, monitoring and protection criteria for ICCP systems are documented in global standards such as the NACE Standard SP 2290-2007 (2), International Standard ISO 12696:2012 (3) and the Australian Standard AS 2832.5 – 2008 (4).

Impressed current cathodic protection involves the installation of an external anode within the concrete to provide protection to the embedded steel. The application of cathodic protection current promotes the development of steel passivity as a result of the production of hydroxyl ions at the steel-concrete interface which stabilise the protective passive film on the steel bars (5). The protective oxide layer inhibits the formation of anodic and cathodic sites on the embedded steel and this stops the corrosion reaction. There are two common types of anodes which are used in most concrete ICCP systems in Australia. Both anodes use Mixed Metal Oxide (MMO) activated Titanium mesh, however with a variance in shape and the method of installation.

2.2 Sacrificial Anode Cathodic Protection (SACP)

This technology has become increasingly attractive in recent years because of its simplicity and low monitoring and maintenance requirements. The anode which is normally made from zinc, is connected to the reinforcing steel and the potential difference between the zinc and the steel causes a protection current to flow from the zinc to the steel.

Galvanic anodes in concrete are usually supplied with a proprietary backfill which provides space for the products of anodic dissolution. As the failure to provide a conductive bridge between an oxidised anode and concrete will effectively stop the protection current, most of the recent innovations and the failures of galvanic anode systems have been associated with the backfill material.

For many years, galvanic anode systems have been installed in conjunction with concrete patch repairs to reduce the occurrence of the incipient anode effect and to prolong the life of the patch repair. Normally in such applications, no permanent monitoring system is incorporated and there is no reliable data about the level of the effectiveness from the installation of these anodes. The installation of galvanic anodes had been traditionally viewed as an additional corrosion prevention low-cost measure.

Currently, and mainly for small bridges, SACP systems have been installed as global cathodic protection systems. Whilst there is no facility for current adjustment for these systems, in many cases, monitoring of the SACP system using embedded reference electrodes in concrete is carried out. The reference electrodes are normally installed in representative areas of the structure. The performance data is assessed based on the applicable Australian Standard AS 2832-2008 (R2018).

2.3 Hybrid Anode Cathodic Protection (HACP)

HACP systems differ from the purely galvanic systems. HACP technology consists of applying a temporary impressed current followed by permanent galvanic protection. The principle of this system is that during the initial impressed current phase, active pits are realkalised and this arrests active corrosion and returns the reinforcing steel to a passive state. Following the application of impressed current for a pre-determined period of time, the passivity of the steel is then maintained by the galvanic anodes embedded in the concrete.

HACP system design is based on assumptions related to the estimated cathodic protection current required for the initial phase to passivate the reinforcement, and then the maintenance current required for the galvanic protection phase to maintain passivity of the reinforcement.

The original hybrid anode system was developed in 2006 (6) and consists of galvanic anodes made of zinc and installed in backfill material in drilled holes in the concrete. The anodes are connected by individual cables to junction boxes and to temporary power supply units. The cathodic protection current is delivered to the structure through these anodes for a pre-determined duration of time during the first stage of the process to passivate the steel. The duration of the impressed current phase is related to the resistivity of the concrete and the ability of the system to deliver the required current at the maximum permitted circuit voltage to reach the specified current requirements for this phase. Following completion of the initial impressed current phase, the temporary power supply units are removed, and the anode cables are connected to the steel for phase 2 of the galvanic protection treatment. Normally, such a system would incorporate embedded reference electrodes for all circuits and permanent monitoring to assess whether additional current injection is required during the life of the system.

The installation requirements of HACP systems are similar to the installation of impressed current systems in terms of cabling, junction boxes and reference electrodes. The hybrid anodes are installed in drilled holes in the concrete. In comparison to a ribbon anode ICCP system, the hybrid anode installation is more labour intensive and is more destructive due to the number of holes required for anode installation. The key difference between HACP systems and ICCP systems is that for HACP system there is no permanent power supply unit to deliver ongoing cathodic protection current and there is no requirement for the ongoing maintenance of power supply unit.

3. NEW DEVELOPMENTS IN CORROSION PROTECTION SYSTEMS

3.1 New innovative Hybrid Anode Cathodic Protection (HACP)

New HACP technology has recently been developed for commercial use. The original two stage concept is applicable for this innovation; however, the major difference is that the two-stage protection is achieved within a single anode unit encased in an activated cementitious mortar. The key aspect of the innovation allows switching from Stage 1 to Stage 2 automatically without human intervention. This eliminates the major complexities associated with the execution of the impressed current phase of the old hybrid anode system.

The installation of the new HACP system is comparatively simple and is more akin to the installation of SACP systems rather than ICCP systems. The duration needed for system installation (compared to old hybrid anode system) is substantially shorter. For this system, the anodes can be installed in slot cuts within the concrete cover making the installation work less destructive and less costly. The anode installation within the cover will also substantially enhance anode performance because the level of chloride concentration is higher in the concrete cover and consequently the resistivity of the concrete is lower which enhances the current delivery from anode to rebar. The cable from each anode, or from multiple anodes, is connected to the embedded rebar within the concrete. There is no need to install permanent reference electrodes for each circuit. Reference electrodes can be installed in representative areas of the structure to assess system performance and verify the level of corrosion protection in accordance to the applicable Australian Standard AS 2832.5-2008 (R2018).

The major advantage of the new HACP technology is the system's capacity to provide much higher levels of corrosion protection than SACP systems, while the installation is identical to SACP system installation. Initial data from a recently commissioned major new HACP installation to a large bridge in NSW indicates that full corrosion protection in accordance to AS 2832.5-2008 (R2018) was achieved. Long-term performance data would be required to verify the ongoing performance of the system. However, taking into consideration the low installation cost, the short duration required for installation and the initial performance results, under the correct conditions, the new HACP technology can be considered alongside SACP and ICCP systems as a viable option for corrosion protection of reinforced concrete structures.

3.2. New concepts for ICCP Control Systems

Various types of ICCP control systems have been installed in Australia over the past three decades. These control systems range from basic manually operated phase control technology systems, to highly advanced systems with full remote monitoring and control capabilities including remote facilities for depolarisation testing and various levels of alarm functionality.

While manually operated heavy-duty cathodic protection systems have provided continuous and reliable delivery of cathodic protection current to many structures in Australia over the past years, these systems use superseded technology which is no longer commercially available, and most of the system components are no longer supported/serviced by their manufacturers.

In recent years, cathodic protection systems with remote monitoring and control capabilities have been specified by consultants and assets owners for improved monitoring of impressed current cathodic protection systems. The complexity to operate these systems and the high level of maintenance associated with maintaining complex electronic components has resulted in higher maintenance costs for assets owners and frequent interruption of the continuity of cathodic protection current delivery to the structures. The major issue with these systems is that they are fully controlled by software. Any software or communication failure will lead to the failure of the entire system and the interruption of the cathodic protection current delivery.

Technical Report 73 for cathodic protection of steel in concrete (6) was the first document that clearly outlined the concept of a DC power supply unit which combines full on-site manual system with an independent remote monitoring and control functionality. Technical Report 73 stated that in the event of failure of the automatic and remote control, the DC outputs shall revert to user set manual control.

The key advantage of the DC power supply unit as outlined in Technical Report 73 is that the continuity of CP current delivery is always maintained by the onsite manual system regardless of any software or hardware failure related to the remote monitoring and control function.

Recent developments in high precision digital control buck converters, combined with the recent major development of reliable quality components such as industrial computers, modems, routers and switches, etc. has allowed for the manufacturing of advanced new control systems with open-source hardware and open-source software technology for ICCP applications. The key advantage of this innovation is that the failure of a modem or a PC within the control system would not affect CP current delivery and the corrosion protection of the structure. In addition, there is no proprietary complex software to operate the system. All hardware parts are industrial type heavy duty components which are available commercially for spare part replacement or ongoing system maintenance.

The new concept control systems have the following characteristics:

- Standalone manual operation.
- Local displays for current and voltage for each circuit for on-site monitoring.
- Local manual interruption capability for instant OFF current interruption.
- Separate independent functions for web-based functional checks.
- Separate independent functions for remote system adjustment.

3.3 Solar Technology for ICCP Systems

The concept of using solar power for impressed current cathodic protection systems is not new. However, recent developments in high precision digital control buck converter technology, lithium iron battery technology, improved efficiency and the reduced cost of PV systems has led to the development of reliable Solar ICCP systems which are capable of delivering the required cathodic protection current suitable for remote small and medium sized ICCP installations.

The adoption of Solar ICCP technology eliminates the need for permanent 230 VAC power supply and relies on solar power to deliver CP current to the concrete structure.

Further advances in the area of routers and communications components offer the option to incorporate remote monitoring for Solar ICCP systems to ensure that they are functional at all times and are delivering the required corrosion protection current with minimal maintenance.

3.4 Cathodic Protection Management System (CPMS)

The main challenge associated with ICCP systems is related to ongoing maintenance, which can often extend over a system’s design life of 30 years or more, and the ability for successive maintenance managers and their consultants to access all of the relevant data to operate their systems over that period. This data includes the original specifications, original drawings, consultant’s reports, maintenance records and performance records…etc. In addition to this, having a simplistic, reliable and cost-effective system for managing multiple assets is one of the challenges for asset managers for the long-term management of their structures and ICCP systems.

Cathodic Protection Management System (CPMS) is an advanced management tool for the efficient monitoring and maintenance of cathodic protection (CP) systems (7). The web-based management system provides a simple and reliable platform for managing the maintenance and monitoring requirements of multiple ICCP systems. Further, CPMS incorporates a portal for each system which allows, subject to the hardware configuration on site, functional check of the system operation and full system monitoring and adjustment.

The key features of CPMS include:

- Simple and secure access for users through a password protected website.
- Online yearly maintenance programs for all structures showing up-to-date work progress and recommendations for future maintenance work for planning and budgeting purposes.
- All historical CP system data is consolidated onto one platform. This allows full transparency related to the status of the systems, information sharing and easy transition of responsibilities between successive asset managers.
- Functional check capability and remote monitoring and control.

4. THE SELECTION CRITERIA FOR CORROSION PROTECTION SYSTEMS FOR CONCRETE STRUCTURES

The selection process for the corrosion protection solution for an individual structure is a relatively complex process. It requires a detailed assessment of the condition of the structure and knowledge related to the advantages and disadvantages and applicability of the available systems. In some cases where there is additional complexity, performing a trial installation to verify the optimum system may be required.

Some of the key issues which may impact on the selection of repair methodology include:

- Impressed current cathodic protection systems are more likely to meet the requirements of the applicable standards and deliver adequate corrosion protection for structures with high corrosion activity and for structures with relatively high concrete resistivity.
- A commonly overlooked issue during the selection process of the optimum corrosion protection system is the effect of the ‘residual protection’ of impressed current cathodic protection systems. Recently published research work (8) related to the long-term benefit of ICCP systems states that “based on the laboratory test results and analysis of data from 6 operating CP systems, it can be generally concluded that for a large percentage of the embedded rebar in a reinforced concrete structure subject to impressed current CP system, the direct result of cathodic protection is not only stopping the reinforcement corrosion but improving the corrosion resistance of the embedded rebar. The primary contributing factors for improving the corrosion resistance of embedded rebar are the reduction of chloride concentration at the steel level and the passivation of the embedded rebar as a direct result of the cathodic protection current”.
- The level of rebar continuity within the elements to be protected by any electrochemical protection system should be considered during the corrosion protection system selection. For structures where there is a lack of continuity of reinforcement, the use of SACP systems would offer a better solution as it is unlikely to have stray current corrosion as a result of rebar discontinuity.
- Consideration should be given to the availability of mains power supply in the vicinity of the structure. Where no mains power can be provided, Solar ICCP system, SACP or HACP should be considered.
- Consideration should be given to the life of the proposed protection system and the available budget for system design, installation and long-term maintenance and monitoring. It is essential to note that ICCP systems can be more cost effective than the original “old” hybrid anode system. Galvanic systems may offer a cost advantage

for small structures (as there is no cost associated with power supply units or ongoing maintenance and monitoring costs), however for large systems, the cost savings may be negligible in comparison to the technical advantage of ICCP against SACP.

- The selection process of the optimum system should take into consideration the structural impact of system installation. Drilling large numbers of holes in the concrete to accommodate anodes may not be the most desired solution especially when alternative and less destructive options are available.

For each structure, a detailed assessment of the structure must be performed. The typical testing procedure is included in AS 2832.5 - 2008 (4). The optimum repair solution may not incorporate any electrochemical treatment or may include a combination of galvanic based systems in conjunction with an ICCP system. There is no one solution which can be applied for each application and it essential that the solution involves structural considerations and an understanding of the long-term maintenance requirements.

5. CONCLUSION

Electrochemical protection systems for steel in concrete can be effectively utilised to provide corrosion protection to structures suffering from chloride-induced corrosion. However, it is the role of engineers and consultants operating in the field of infrastructure rehabilitation to provide the correct advice to assets owners with respect to selecting the optimum system for the long-term protection of their assets.

Various aspects of electrochemical protection systems for steel in concrete structures are detailed in international and Australian standards and this information is available to assist owners, consulting engineers and contractors to correctly design, install, test, commission, monitor and maintain these systems.

The recent advances in hybrid anode technology, ICCP control systems, solar power technology and cathodic protection maintenance and monitoring can assist assets owners to select the optimum system which meets the corrosion protection requirements as per the applicable standards and can provide long-term corrosion protection to their assets.

Regardless of the selected electrochemical protection system (ICCP, SACP or HACP), it is always necessary and essential to design and install the system to meet the requirements of the latest revision of applicable Australian Standard for cathodic protection.

6. REFERENCES

1. A. Cheaitani and S. Cheytani, Future Directions for Designing Low Maintenance Impressed Current Concrete Cathodic Protection Systems, EuroCorr 2018
2. NACE International, Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures. SP0290-2007 (formerly RP0290)] (2007)
3. The European International Standard, Cathodic Protection of Steel in Concrete. ISO 12696:2016] (2016)
4. Standards Australia, AS 2832.5 – 2008, Cathodic Protection of Metals, Part 5: Steel in Concrete Structures (2008)
5. P. Chess, Cathodic Protection for Reinforced Concrete Structures (2019), Taylor & Francis, CRC press, P. 95 ISBN 978-1-138-47727-8
6. Technical Report 73, Cathodic Protection of Steel in Concrete, August 2011, The Concrete Society.
7. K. Morton and A. Cheaitani. Coasts & Ports 2017 Conference, A New Approach for the Management of Cathodic Protection Systems, Cairns, 21-23 June 2017
8. S. Cheytani, Data analysis of the long-term residual effect of cathodic protection on reinforced concrete structures, MPhil Thesis UNSW, Australia (2020)

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