**Principles of Cathodic Protection Using Solar Panels for Marine Structures Located Away from Stationary Electric Power Sources**

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**Abstract.** The operability of the device for cathodic protection of metals in natural seawater using the solar panel as the only direct current source was experimentally studied. It was shown that the cathode device, powered only by a solar battery, allows cathodic protection of marine structures with a degree of protection of up to 86% without the use of additional energy sources. Protection is achieved by the formation of calcareous coatings in the daytime, which provide protection in the nighttime, when the cathode current is absent.

**Introduction**

Cathodic protection is the most effective protection of offshore structures [1, 2]. These structures are often located far from stationary sources of electric current, so it is advisable to use autonomous sources. One of such reliable sources of direct current is solar panels, whose service life exceeds 25 years. They have one significant drawback-they do not generate electricity at night and for the continuity of cathodic protection, these devices must include batteries that have a significantly shorter life compared to solar panels and require maintenance. It has been well known that the cathodic protection of offshore structures is accompanied by the formation of calcareous deposits on the metal surface [2, 3-10], which have a protective ability [11–17], which allows the cathodic protection current to be switched off for a certain period, for example, for repair or for replacing anodes. This fact has been noticed for a long time and laid the foundation for the principles of conducting direct experiments on cathodic protection from devices powered only by solar panels.

The aim of this work is a direct experimental evaluation of the operation of the device for the cathodic protection of low-alloy steels in natural seawater under various current conditions with power supplied by only the solar panel.

**Experimental**

A device for cathodic protection powered by a solar panel was made at the Department of Chemistry and Ecology of Maritime State University named after admiral G.I. Nevelskoy (MSUN). The schematic diagram of the device is shown in Figure 1.

The contact ends of the anode and cathode coupons were insulated by silicone sealant “Siflex-219” to protect them from the effects of seawater. The power supply to the circuit “cathode anode” from the voltage converter PN (DC/DC: \( U_{in} = 2.5–20 \text{ V}, U_{out} = 2.5 \text{ V} \)) was carried out via normally open (NO) contacts P1.1 of the current relay P1 (\( U_{on} = 8.0 \text{ V}, U_{off} = 2.0 \text{ V} \)). With a sufficient voltage at the output of the solar panel, the SP contacts closed, and the circuit received power (Figure 1).

To control the values of the current supplied to the coupons, resistors R1–R4 were used, which at a given value of the supply voltage supported various values of the current density on the protected coupons. The resistors were selected in such a way that their resistance values were a multiple of 2: \( R1 = 5.4 \text{ k}\Omega; R2 = 2.7 \text{ k}\Omega; R3 = 1.35 \text{ k}\Omega; R4 = 0.675 \text{ k}\Omega \). With a supply voltage of
$U_{\text{supp}} = 2.5 \text{ V}$ and equal cathode areas $S_k = 80 \text{ cm}^2$, respectively, 2 will be a multiple of the current density on the cathode coupons: 58; 116; 231; 463 mA m$^{-2}$.

Figure 1. Schematic diagram of cathodic protection powered by a solar panel. SP - solar panel; PN - voltage converter; P1 - relay coil, P1.1 - normally open contacts; R1–R4 - calibrated resistors; Up - terminals for measuring potentials; P - cathodically protected coupons; C - control coupons without protection; SCE - silver chloride reference electrode; A - insoluble anode.

The device was tested from a pier in the natural seawater of the MSUN yacht club (Fedorov Bay, Vladivostok).

As a direct current source, the standard single-crystal solar panel (SOLARLAND) with 12 V power of 30 W was used.

Coupons from low-alloy steel St3-2hp according to Russian standard GOST 19903-2015 were used as protected and control coupons. The insoluble anode of 400×25×1.5 mm was platinum titanium. The coupons and the anode were mounted on a frame measuring 520×400 mm using a polyethylene cord. The frame with the test coupons was immersed to a depth of 2 m. Before mounting to the frame, the coupons were treated with hydrochloric acid (1:3), washed with distilled water, dried at 90°C for 0.5 hours and weighed on an AW-220 analytical balance (Shimadzu).

After the experiment, the corrosion products were removed from the coupons in accordance with Russian standard GOST 9.907-83, washed, dried at 90°C and weighed on an analytical balance to determine the weight loss of the coupons $\Delta m_{\text{cor}}$. By which the losses of their corrosion rate $V_{\text{cr}}$ were estimated. The degree of protection of the coupons was determined by the formula

$$\eta = \frac{V_{ac} - V_{cr}}{V_{ac}} \times 100\%,$$

where $V_{ac}$ - average corrosion rate of four control coupons, $V_{cr}$ - corrosion rate of protected coupons.

**Results and Its Discussion**

The testing facility worked for 817 days (2.24 years). The results of the measurements and the calculated values of corrosion losses and corrosion rates are presented in Table.

From the Table, it can be seen that the average corrosion rate of control coupons without protection was 0.069 mm y$^{-1}$, and the corrosion rates of protected coupons, depending on the protection current, were in the range 0.009–0.074 mm y$^{-1}$. The results on corrosion of coupons without protection were in agreement with the previous corrosion tests of shipbuilding low alloy steels in similar waters of the Amursky Bay [18]. The coupons protected by currents of 231 mA m$^{-2}$
and 463 mA m\(^2\) had the lowest corrosion rates of 0.013 mm y\(^{-1}\) and 0.009 mm y\(^{-1}\), respectively, which indicates their protective effect up to 86%.

Table. Test results of protected and control coupons in a pilot installation for cathodic protection using a solar panel.

| No. | Coupons | Corrosion loss \(\Delta m_{\text{cor}}\) [g] | Current density \(i\) [mA m\(^{-2}\)] | Corrosion rate \(V_{\text{cr}}\) [mm y\(^{-1}\)] | Protective effect [%] |
|-----|---------|------------------------------------------|-------------------------------|---------------------------------|-------------------|
| 1   | Protected | 10.3533 | 58 | 0.074 | -7 |
| 2   |          | 4.2042 | 116 | 0.030 | 56 |
| 3   |          | 1.7975 | 231 | 0.013 | 81 |
| 4   |          | 1.2996 | 463 | 0.009 | 86 |
| 01  | Control  | 11.9743 | - | 0.086 | - |
| 02  |          | 8.7994 | - | 0.063 | - |
| 03  |          | 8.9768 | - | 0.064 | - |
| 04  |          | 8.5542 | - | 0.063 | - |

Based on the results obtained, it can be concluded that in order to ensure maximum cathodic protection of low-alloy steels in sea water when using solar panels as the only constant current source, cathodic current densities in the range from 0.25 to 0.45 A m\(^{-2}\) are needed when calcareous deposit with equal amounts of CaCO\(_3\) and Mg (OH)\(_2\) [8].

The results obtained during the operation of a cathodic device powered only by a solar panel allow to conclude that it is possible to carry out cathodic protection of metals in sea water without the use of batteries and other direct current sources by forming protective coatings of calcareous deposits in the daytime. Such protection will be highly economical for offshore structures located away from traditional sources of electricity and human resources.

**Conclusion**

The verification of the operation of the cathodic protection device of offshore structures using only the solar panel for 2.24 years showed that a protective effect of up to 86% could be achieved with a cathodic current density in the range from 0.25 to 0.45 mA m\(^{-2}\). It can be concluded that the possibility of cathodic protection of metals in seawater without the use of other direct current sources.

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