Use of photovoltaic converters in electrochemical protection systems for underground pipelines

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Abstract. Currently, electrochemical protection of pipelines is provided by cathodic protection stations, which receive electric energy from power lines laid along the pipeline route. The construction and installation of facilities that ensure the transmission of electricity from centralized sources to locations of cathodic protection stations and the conversion of its parameters to the required level is characterized by significant capital costs. In recent years, there has been a leap forward in the development of alternative energy sources, which allows us to consider them as sources for power supply of cathodic protection stations. This paper describes the possibility of using photovoltaic converters to power cathodic protection stations. In addition, an implementation scheme was proposed and analyzed.

1. Introduction

The main material for the manufacture of trunk pipelines is steel. During operation, it corrodes under the influence of the environment. There are corrosion of the outer and inner walls of pipelines. Corrosion of the outer wall of pipelines induces about 95% of failures, and corrosion of the inner wall of pipelines only 5%. This is because the main pipelines are used for transporting prepared corrosion-inert products.

Regardless of the corrosiveness of the external environment, the corrosion protection of underground and underwater pipelines is carried out using integrated protection, including protective coatings (passive protection) and electrochemical protection (active protection) [1].

Primary corrosion protection of pipelines is provided by insulating coatings. Coatings provide passive protection of pipelines against corrosion and prevent contact between the metal of the pipeline and the corrosive environment (water, oxygen, air, etc.). In the formation of defects in the insulation coating and the metal pipe is laid bare, corrosion protection is carried out by the electrochemical protection (ECP) system.

The essence of ECP system is the artificial polarization of the pipeline (cathode) to shift its potential in the negative direction. As a result, the operation of the corrosion pair is terminated. ECP is provided if the polarization potential satisfies certain criteria. For underground metal structures, the potential difference should be negative than –0.85 V (relative to the copper-sulfate reference electrode). Studies [2] confirm that at this potential difference corrosion rate is significantly reduced (for steels are in most common corrosives – less than 0.1 mm per year). Protective polarization of the cathode can be achieved by applying a protective potential from a direct current source or using materials as an additional anode, whose own potential is more negative than the cathode material.
A DC source is the basic element of the cathodic protection station (CPS). Other elements of the CPS are: anode grounding, copper-sulfate reference electrode, protective grounding, cathodic output pipe (drainage cable), and connecting cables. Deep anode grounding conductors are designed to create a grounding circuit (anode field), which usually consists of several grounding conductors connected in parallel.

The negative pole of the DC source is connected to the pipeline, and the positive to the artificially created grounding anode. The current of the power source from the positive pole enters the ground through the anode ground and then enters the pipe through damaged sections of insulation. Next, the current returns to the minus of the power source through the connecting wire. At the same time, cathodic polarization begins on bare sections of the pipeline.

Copper-sulfate reference electrodes control the potential of the pipeline. To measure the electrochemical potentials, the specified electrode is installed in the ground, then the potential is measured between the electrode and the pipeline. The magnitude of this potential gives an indication of the degree of protection structures against corrosion.

The length of the protected section of the pipe depends on the corrosion properties of the soil, the quality of insulation and the power of the CPS. On the protected section, the protective potential created by the CPS ensures the absence of electrochemical corrosion on the cathode (pipeline). At the same time, the anode (grounding) is intensively destroyed due to the activation of the anode process.

Modern DC sources have good technical and economic indicators. However, the existing methods for their power supply from high-voltage power lines using transformers are cumbersome, has high material consumption and cost. Therefore, the search for alternative solutions is an urgent problem.

2. Existing power supply schemes for CPS

Power supply of cathodic protection stations is most often carried out in the third category of reliability. Technological facilities and electrical receivers of the third category can be supplied with electricity from one power source, provided that the power supply interruptions for repairing the power supply system do not exceed 1 day. As power sources, both 0.4 – 20 kV power lines and autonomous power sources can be used. Moreover, if there are no means of remote monitoring in the area with stray currents and (or) with high corrosiveness of the environment, the second category of power supply reliability can be assigned to the ECP system.

The use of ECPs in areas far from centralized power supply networks is difficult because it is necessary to build power lines and a certain number N of transformer substations TS along the pipeline route.

A typical power supply scheme of the CPS and substation design option is shown in figure 1. The CPS is powered from the secondary winding of the transformer T (220 V) via a circuit breaker QF. The primary winding of the transformer is connected to a long-distance power line with a voltage of 6 (10) kV, through a disconnect or QS and a fuse FU. Transformer substation buses (most often buses for power supply to gas cooling units) feed the long-distance power line [3].

The positive terminal of the CPS is connected to the anode ground, and the negative is connected to the protected pipeline. The value of the output voltage in modern CPS is automatically adjusted. The magnitude of this voltage does not exceed several tens of volts. At the same time, the power consumed by the cathodic protection stations is 0.5 – 5 kW. Today in operation is a wide range of cathodic protection stations, differing in circuit topology and characteristics. So, two types of converters are used at gas transmission facilities. The first type of converters are rectifiers, connected to the AC network through a transformer. The second type are inverter converters operating on the principle of an intermediate link of increased frequency.

The construction of a 6 (10) kV long-distance power line for powering only CPS is extremely costly. At the same time, power electrical equipment has a low utilization rate. Therefore, the use of autonomous energy sources, in particular renewable energy sources, is an urgent problem [4].
3. Proposed power supply scheme for CPS

In regions where wind conditions are optimal for using wind energy (regions with average annual wind speeds of more than 4.5 m/s), the use of wind power units is advisable for power supply to low-power consumers. Currently, interest in wind power plants as sources of power for cathodic CPS is increasing. This fact is evidenced by regulatory and technical documents in the field of technological design and operation of gas pipelines.

Another type of alternative energy that can be effectively used in the construction of power systems for CPS is solar energy [5]. A properly designed photovoltaic system will avoid costly extension of the power grid. It can also become an alternative to expensive generators operating on hydrocarbon fuels, requiring constant refueling and having a high cost of maintenance.

Studies of the use of photovoltaic converters for power supply of ECP plants are actively conducted in countries with high solar energy potential [6, 7]. The issues of constructing and calculating power supply systems of ECP plants using photoelectric converters are described in [8, 9]. In connection with the improvement of technical characteristics and the reduction in the cost of photovoltaic converters, interest in them as sources of energy for powering ECP plants is growing.

The block diagram of the CPS powered by solar panels is shown in Figure 2. Energy to ensure stable operation of the CPS, is supplied to the cathode current regulator either from solar panels or from the battery array. Energy flows are controlled by a charge – discharge controller. Maintaining a given mode of ECP on the pipe is carried out by the cathodic current regulator.

Solar panels as CPS power supplies have characteristic features. They have non-linear I-V curves. Their bending depends on the power of the energy light and the temperature of the panels. Figure 3 shows the I-V curves of the panel at a fixed temperature for five values of the energy illumination S1>S2>S3>S4>S5. It also shows the I-V curves of the loads for two values of the load resistance R2<R1.

The curves in figure 3 show that changes in the load parameters lead to a significant change in the mode of solar panel. Let the load of the solar panel have resistance R1, then the voltage and current of the solar panel had the values U1 and I1. Then there is a reduction of the value of the load resistance R1 to a value R2. As a result, there is a significant decrease in voltage to U2 and a slight increase in current to I2. Based on this, the solar panel can be characterized by a large value of the output resistance, which requires the use of special control devices to coordinate it with other components of power supply system.
Figure 2. Block diagram of the cathodic protection stations powered by solar panels.

Figure 4 shows graphs of the panel’s power \((P=U \cdot I)\) dependence on the voltage \(U\). It can be seen that the graphs have peaks for each illumination value. Moreover, if the illumination is \(S_1\), then mode point 1 is located to the right of the maximum, and if the illumination is \(S_2\), then mode point 2 is located to the left. In both cases, less power is consumed than the solar panel can provide.

Figure 3. I-V curves of solar panel.

Figure 4. P-V curves of solar panel.

The buck converter is used to align the solar panel with the battery (figure 5). The cathode current is controlled by buck-boost converter. The converter circuit is shown in figure 6.

Figure 5. Buck converter scheme.

Figure 6. Buck-boost converter scheme.
The power switch VT of the buck converter is controlled through the driver by a signal from the microcontroller with function of the maximum power point tracking. The carrier frequency \( f_0 \) of the pulse converter depends on the dynamic properties of the power switches. GTO thyristors allow switching frequencies up to 1 kHz, IGBT transistors up to 10 kHz, field effect transistors up to 1000 kHz and higher. It is obvious that the carrier frequency determines the possible speed of regulation of the parameters of the converted energy and the dimensions of the reactive elements.

Voltage \( U_{d1} \) is supplied from the output of the solar panel. Due to pulse width modulation (PWM), the output voltage \( U_{d2} \) is adjusted and the equivalent load resistance for the solar panel changes. The average voltage value at the buck converter output depends on the value of the input voltage and the parameter \( D \). It is equal to the ratio of the voltage pulse duration at the output of the DC/DC converter to the tact duration \( T_0 \):

\[
D = \frac{\tau}{T_0} = \tau \cdot f_0.
\]  

(1)

Thus, the control characteristic of the DC/DC converter can be represented as

\[
U_{d2} = \psi(D) \cdot U_{d1} = D \cdot U_{d1}.
\]  

(2)

Information from the voltage sensor VS and current sensor CS of the solar panel is fed to the microcontroller, which implements the PWM control signal \( D \) down-converter voltage. At each operation cycle, the power received from the solar panel is calculated \( P_k = U_k I_k \). Then, the obtained \( P_k \) value is compared with the \( P_{k-1} \) value at the previous measure. At the same time, the control signal \( D_k \) at this control cycle is compared with the signal \( D_{k-1} \) in the previous step. Depending on the values of the obtained differences, the control signal is corrected up or down with a given discreteness \( \Delta D_k \). As a result, each cycle of the system operation is accompanied by the search for the maximum power point taken from the solar panel.

Monitoring the state of the battery array in the power supply system is carried out along with the search for the maximum power point. When the battery reaches 100%, the controller disconnects it from the solar panel, protecting it from overcharging and premature failure.

Voltage \( U_{d2} \) is applied to the cathode current regulator. A feature of this circuit is the ability to control the output voltage \( U_{d3} \) and to invert its polarity due to PWM. The control characteristic for this converter is:

\[
U_{d3} = \frac{D}{1-D} \cdot U_{d2}.
\]  

(3)

Formula (3) shows that if \( D = 0.5 \), then the output voltage is equal in magnitude to the input voltage, but has the opposite polarity. If \( D < 0.5 \), then the output voltage is lower than the input voltage. Conversely, if \( D > 0.5 \), then the output voltage is higher than the voltage at the input of the converter. Thus, changing the parameter \( D \) of the cathode current regulator can provide the desired potential value on the protected pipeline.

4. Results and Discussion

Table 1 shows comparative cost estimates for creating an ECP system with various sources of power supply. As an example of calculation, the distance between the compressor stations is 100 km. Pipeline corrosion protection is carried out by 20 stations with a power of 300 W each.

Costs were calculated based on the average price level of equipment and work. For example, the cost of one kilometer of a power line was $16,000. The calculation of the photovoltaic power supply system was carried out taking into account the monthly values of solar radiation in the Saratov region.

When calculating the photovoltaic system, the use of monocrystalline silicon solar panels with an efficiency of 16% was assumed. The area of the solar panels was chosen so that they ensure the
functioning of the CPS on days with the least solar radiation. Currently, the cost of monocrystalline silicon solar panels is approximately $ 0.5 / W.

The capacity of the batteries should be such that the cathodic protection station is energized at night and on cloudy days. The use of helium batteries is promising for photovoltaic power supply systems.

Table 1. Approximate calculation of costs for the construction of electrochemical protection systems of various types.

| Name                                | Cost ($ US) | powered by transmission line | powered by PV converters |
|-------------------------------------|-------------|------------------------------|--------------------------|
| Transmission line construction      | 1,600,000   | -                            |                          |
| Site preparation for equipment installation | 35,000     | 35,000                       |                          |
| Transformer substations             | 20,000      | -                            |                          |
| PV panels                           | -           | 32,000                       |                          |
| Accumulator batteries               | -           | 106,000                      |                          |
| DC/DC converters and controllers    | -           | 24,000                       |                          |
| Cathodic protection stations        | 20,000      | 20,000                       |                          |
| Software and other expenses         | 6,000       | 6,000                        |                          |
| Total                               | 1,681,000   | 223,000                      |                          |

A comparison of the data shows that the cost of building an ECP system with power supply using photovoltaic converters is about 7 times less than power supply using power lines.

5. Conclusion
The use of solar energy to power CPS is a promising area. The development of this direction will significantly reduce the capital costs of creating an EPS for underground pipelines.

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