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Photovoltaic-powered regulated cathodic-protection system

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Abstract

The objective of a cathodic protection system is to protect metallic structures against corrosion. To achieve this, a sacrificial anode is connected to the protected structure (which acts as a cathode) through a d.c. power supply. To stop the corrosion, the protected structure requires a constant current. The current is determined by the metal and area of the structure, as well as the surrounding medium. The major difficulty in achieving a constant current is the variation in the resistivity of the surrounding medium that is caused by changes in the climatic conditions. Conventional cathodic-protection systems resolve this problem by manual adjustment of the d.c. voltage periodically to obtain a constant current. Such adjustment depends on the experience of the technician and the accuracy of the measuring equipment. Moreover if the interval between successive adjustments is relatively long, the corrosion could become excessive. To overcome such difficulties, an automatically regulated system has been developed. The proposed system senses variations is the resistivity of the surrounding medium and adjusts the d.c. voltage accordingly so that the current is kept constant at the required level. The design of a solar photovoltaic system to supply the required d.c. power is discussed in this communication.

Introduction

Corrosion is the destructive attack of a metal by a chemical or electrochemical reaction with its environment. Corrosion studies have three important objectives [1]. The first is economic, that is, the reduction of material losses that result from corrosion. The second is improvement in the safety of the operating equipment that otherwise, through corrosion, may fail with catastrophic consequences; examples are pressure vessels, boilers and bridges. The third objective is the conservation of limited metallic resources.

Cathodic protection is a technique that is employed to minimize corrosion by supplying an external current to the corroding metal surface. Current leaves the auxiliary anode (called a 'sacrificial' anode), enters both the cathodic and anodic areas of the corrosion cells, and returns to the d.c. source [2]. There are two basic approaches to cathodic protection. The first technique does not require a power supply to impress current from the sacrificial anode to the cathodically protected area. To achieve this, the potential of the anode metal must be much higher than that of the cathode metal (according to the galvanic series). These anodes are mostly high purity alloys of

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magnesium, zinc and aluminium [3]. Such a technique is suitable if the current demand is limited so that the galvanic potential difference is sufficient to supply the required current.

The second and more widely used technique is the 'impressed current' system. In this, a d.c. power supply is necessary to impress the required current. The d.c. power is obtained from either a rectifier (if a.c. power is available) or a diesel generator. Recently, solar and wind systems have been used to supply, d.c. power to cathodic-protection systems that are situated in remote areas where a.c. power is not available. In this work, the design of a solar photovoltaic system is considered.

The amount of d.c. current required to stop (or minimize) corrosion is determined by the following factors [1]:

- the protected metallic area
- the electrolyte between the sacrificial anode and the protected cathode
- the metals of both the anode and the cathode
- the coating type of the protected structure; proper coating reduces the required d.c. current significantly since it acts as an insulation between the protected structure and the surrounding medium

The d.c. voltage is designed to supply the required current. The major difficulty is that the electrolyte (e.g., soil) resistivity varies with climatic conditions. Since electrolyte resistance is a part of the system circuit, then for a constant d.c. voltage, the d.c. current will vary as climatic conditions change. The conventional solution of such a problem is discussed in the next section.

Conventional cathodic-protection system

Figure 1 shows a conventional system for protecting a buried pipeline. The d.c. power is obtained from a rectifier. The regular inspection of a protected structure includes examining the coating and measuring the potential difference between the structure and the electrolyte. Unproperly painted areas of the structure are subject to rapid corrosion because of the direct contact between the metal and the electrolyte. A widely used technique to measure the potential difference employs a copper–copper sulfate electrode (shown in Fig. 2) as a reference half-cell [4]. It consists of a copper rod immersed in saturated copper sulfate solution; both are housed in a plastic cylinder with a porous wooden plug at the bottom. The copper rod extends out the top to enable connection to a high-accuracy voltmeter.

Experience shows that when the potential difference ranges from -0.85 to -2.0 V relative to the copper–copper sulfate electrode, the corrosion is essentially

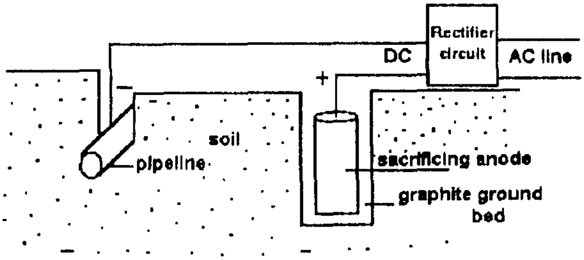

Fig. 1. Schematic diagram of cathodically protected pipeline.

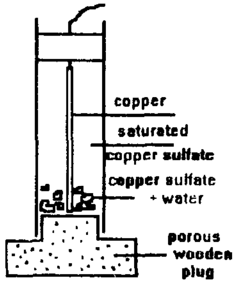

Fig. 2. Copper–copper sulfate reference half-cell.

stopped on steel structures in soils and waters. By contrast, if the voltage exceeds −0.85 V, corrosion takes place. On the other hand, if the voltage is below −2 V (i.e., the overprotein case), the coating may be damaged, especially in the case of thin coatings. To set the voltage within the allowed safe limits (−0.85 to −2 V), the d.c. voltage of the power supply must be adjusted periodically. To perform this task, a technician, with a hand-carried half-cell and a sensitive voltmeter, has to measure the potential at each test point along the line. The technician estimates the required d.c. voltage to maintain the potential difference across the pipeline within the allowed limits. The technician waits for some time after the adjustment and then re-measures the voltages across the pipeline. This process is repeated if any of the test points gives a voltage outside the allowed limits. Thus, the procedure is a trial-and-error process. Clearly, the following drawbacks are associated with the technique:

(i) it is time consuming and tedious;

(ii) it is a non-accurate process since it depends mainly on the experience of the technician, and

(iii) it allows metallic structure corrosion during the periods when the d.c. voltage of the supply is not correct; if such a period is extensive, serious corrosion may take place and may lead to appreciable damage to the metallic structure. An automatically regulated system is discussed hereafter to avoid these difficulties.

Regulated cathodic-protection system

A block diagram of the proposed regulated cathodic-protection system is shown in Fig. 3. The system is composed of the following components.

(i) A photovoltaic (PV) array to generate d.c. power from solar radiation.

(ii) A battery to store the d.c. power generated by the PV array, such a design allows the supply of current during nights and cloudy days.

(iii) A load voltage regulator (LVR). This circuit is fed from the storage battery and supplies the load with the required voltage under the varying climatic conditions. The LVR is a controlled d.c. chopper circuit [5, 6], that is controlled by a signal received from the feedback circuit.

(iv) A battery voltage regulator (BVR) circuit [7] that is used to protect the battery against overcharging and deep discharging to prolong the battery lifetime.

(v) A selector circuit that is designed to select the input of maximum amplitude amongst all input voltages. The input voltages are those measured at the test points along the pipeline. The allowed voltage range at all test points should remain between

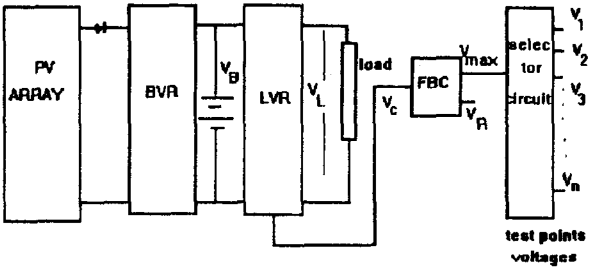

Fig. 3. Black diagram of the regulated cathodic-protection system.

-0.85 and -2 V, as discussed above. If this condition is not satisfied, the d.c. voltage must be adjusted. This is done automatically by the LVR circuit.

(vi) A feedback circuit (FBC), that is used to generate a correcting voltage, V_c, proportional to the difference between the maximum voltage at the test points, V_{max}, and the reference voltage $V_R(=-0.85\ \text{V})$. The value of V_c is fed to the LVR circuit to correct V_L in such a way that the d.c. load current remains at the required value. Consequently, V_{max} returns to within the allowed range and corrosion is essentially stopped.

Principles of operation of the regulated cathodic-potection system

The voltages at the test points are measured (as shown in Fig. 3) and fed to the input of the selector circuit whose output (denoted by V_{max}) is the maximum voltage of its inputs. The value of V_{max} is compared with a reference voltage V_R which equals the maximum allowed voltage (-0.85 V). The feedback circuit generates a correcting voltage V_c that is proportional to the difference between V_{max} and V_R. The voltage V_c is applied to the LVR circuit so that the chopper circuit duty cycle is adjusted to the correct value. If V_{max} exceeds -0.85 V (which means that corrosion may take place), the duty cycle of the chopper is increased and as a result V_L increases and thus causes the system current to increase so that corrosion is stopped. If V_{max} lies between the allowed limits (-0.85 and -2 V), the duty cycle remains unchanged. If V_{max} is below -2 V, the duty cycle is reduced so that the cathodic current is reduced. The detailed design of such a circuit will be reported in a later communication.

Design of photovoltaic system

The d.c. power may be supplied by a solar photovoltaic (PV) system. The system objective is to supply a constant load current. The system operating voltage is variable according to the electrolyte conditions, as discussed above. Hence, the system power is not constant. The power demand is less during rainy days where soil resistivity decreases and, consequently, the required system voltage and power are also smaller. Thus, a natural matching between load demand and available solar radiation is obtained since solar radiation is smaller during cloudy and rainy days.

A conservative design of the solar PV system considers a constant power load demand equal to its maximum value. Maximum load demand takes place during dry days where soil resistivity is maximum; this condition necessitates a higher operating voltage and, consequently, higher power.

For a constant load power, the optimum tilt angle of the solar PV array is equal to the latitude angle plus 15° for tropical areas [8]. Thus, if Cairo city at 30° N is considered, then the optimum tilt angle is about 45°. The solar radiation on a horizontal surface in Cairo is given in ref. 9. The design of the PV system depends on determining two main factors, namely, the array factor F_a and the storage factor F_s. F_a is defined as:

$$F_a = \frac{\text{PV array peak power (W)}}{\text{load power (W)}} \tag{1}$$

while F_s is defined as:

$$F_s = \frac{\text{battery storage capacity (kWh)}}{\text{daily load energy demand (kWh/day)}} \tag{2}$$

Since the load must be supplied by energy 24 h a day throughout the year and during the cloudy days when the solar radiation is low, both F_a and F_s are oversized. A detailed simulation computer program for a PV solar system showed that for a constant load (load power is constant day and night throughout the year), the values of F_a and F_s are 9 and 4.24, respectively [10]. This design considers the climatic conditions of Cairo city (30° N) with two successive cloudy days during each month of winter season and 30 dispersed cloudy days throught the year.

Consider the following example. If it is required to design a PV facility to power a cathodic-protection system to protect a 6-inch steel pipeline of 2 km length, then it is first necessary to compute the required d.c. current. The current is about 1 mA/ft^2 [1]. Thus, the surface area of the pipeline in square feet has to be multiplied by 1 mA. This shows that the required current is 10.3 A. The d.c. voltage depends on the soil resistivity, i.e., a larger soil resistivity requires a larger voltage, and vice versa. Suppose that 24 V d.c. is satisfactory, then the load power will be $24 \times 10.3 = 247.2$ W. Accordingly, the array size will be $247.2 \times F_a = 247.2 \times 9 = 2225$ W peak. The daily load energy is $247.2 \times 24 = 5932.8$ Wh. The battery storage size will be $5932.8 \times F_s = 25155$ Wh.

Conclusions

A regulated cathodic-protection system avoids the difficulties associated with conventional counterparts. The proposed system has the following advantages:

(i) it saves labour costs;

(ii) saves energy because the voltage is automatically adjusted so that the d.c. voltage is never more than the required value and there is no dissipation in a potentiomer;

(iii) corrosion is essentially stopped since the metallic structure will always receive the exact required d.c. current, and

(iv) coating destruction is almost entirely stopped since overprotection is eliminated.

Hence, the proposed technology provides economic advantages over conventional systems. Furthermore, only a minor cost is added to the conventional system; this is associated with the electronic circuits that are required for the system control.

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