# Solar Powered Cathodic Protection Using Residual Potential

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*Abstract*—**Solar panels are a viable economical source of power for cathodic protection installations where grid power is not readily available. First those installations where alternative power sources are feasible are discussed. Then solar panel operation is investigated. This includes an overview of the semiconductor construction of the solar cells as well as the effect of incident light levels on the power output. A description of cathodic protection fundamentals outlines a typical configuration including the need for backup power. Because of the hysteresis effect of direct current on the well casing, a method of protecting the well without using batteries for the backup is demonstrated.**

## Introduction

THERE are thousands of miles of buried pipeline within the United States. Since the U.S. Department of Transportation (DOT) has established guidelines for corrosion mitigation on pipelines that carry hazardous materials, there has been significant interest in cathodic protection schemes for these systems.

Furthermore there are literally tens of thousands of oil- and gas-producing wells in the country. While there are no government regulations concerning protection of these wells, there is an economic and environmental interest in reducing the number of failures in these systems. Wells that are part of the storage field are subject to DOT regulation and must be cathodically protected.

While the pipelines are often externally protected from corrosion by coatings and wraps, producing wells are almost always bare. Part of the well pipe may be encased in cement, but much of it is exposed to the earth and corrosive fluid formations. Because of the method of operation, cathodic protection is not used often on oil-producing wells, but is considered highly desirable for gas wells. Many of the reasons for installing cathodic protection on gas wells make solar energy feasible.

In general, oil wells are relatively close together, possibly within 600 ft of each other. Because of this proximity there is interference from adjacent cathodic protection installations. The wells usually require some method of artificial pumping, which means a power source would be readily available if cathodic protection were used.

On the other hand, gas wells are more scattered, usually no closer than one in each square mile section. These wells often operate without artificial pumping and are in remote locations where power is not readily available or where power systems cannot be installed because of land use constraints. This environment encourages the use of alternate energy sources.

Buried hydrocarbon pipelines from the producing wells or between distribution points typically are in very remote areas where land use problems are encountered. The requirement for some method of power supply has created a demand for a wide variety of energy sources.

The most common cathodic protection systems are powered from the generally widespread alternating current (ac) power grid. However, the probability this system will not exist increases with the distance of the installation from populated areas. In the past, diesel or natural gas driven motor generators (MG's) have been used to supply power for rectifiers. Less often, natural gas or LPG fired thermoelectric generators (TEG's) have been used to convert heat directly into direct current (dc) for the cathodic protection system. Alternate systems are used because cost of construction for overhead or underground power lines are prohibitive, or because some land owners (such as the Bureau of Land Management) restrict power poles crossing their land [1].

The alternative for power on remote installations increasingly has become photovoltaic solar power [2]. This is viable because of the size and type of many of the cathodic protection loads. Cathodic protection is the practice of applying small amounts of direct current to a metal structure, resulting in a potential shift on the structure relative to the surrounding soil. The power requirements seldom exceed 1000 W and often are less than 100 W. Since these are relatively low levels of dc power, solar systems increasingly are more competitive than traditional power installations.

## Solar Panel Operation

Although commonly referred to as solar electricity systems, a more appropriate description is a photovoltaic power system. This term is derived from the Greek word "*photo*," meaning light and "volta," named for Alexander Volta, who did some of the early work in electrical development. Light from any source, but most commonly from the Sun, strikes the surface of a solar cell and converts this energy directly into electricity. This is possible because of the semiconductor materials used to form the solid-state device.

Most commercial solar cells at this time are silicon-based structures. The base material is grown silicon that has been doped with boron to cause holes to be the majority current

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TABLE I
SOLAR RADIATION VALUES[a]

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Insolation at Phoenix, AZ: Tilt Angle 15° (South Orientation) | | | | | | | | | | | | | |
| Langley | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Avg |
| Flat | 297 | 408 | 521 | 643 | 724 | 740 | 652 | 612 | 568 | 452 | 339 | 280 | 520 |
| Tilt | 383 | 495 | 581 | 665 | 710 | 709 | 633 | 616 | 611 | 527 | 429 | 371 | 561 |
| Insolation at Fairbanks, AK: Tilt angle 80° (South Orientation) | | | | | | | | | | | | | |
| Langley | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Avg |
| Flat | 19 | 76 | 233 | 385 | 477 | 527 | 444 | 363 | 184 | 86 | 27 | 6 | 236 |
| Tilt | 375 | 330 | 506 | 458 | 419 | 410 | 366 | 369 | 274 | 238 | 215 | 301 | 255 |

[a] Solar radiation is measured in langleys. Areas with high and low quantities of solar radiation are shown. Solar radiation changes with time of year and tilt angle of panel.

carriers ($p$-type material). A material using electrons as the majority current carrier ($n$-type material) is deposited on the $p$-type material to form an $n$–$p$ semiconductor junction. To obtain a low-resistance electrical connection to the semiconductor, a silver grid is deposited onto the material. Unfortunately this screened material covers some of the semiconductor area and reduces its efficiency. A major tradeoff in solar cell design is increasing area and output energy without reducing the series or sheet resistance [3].

Each solar cell has a relatively low power output. A cell typically has an electrical potential of about 0.5 V with peak power produced at 0.45–0.48 V. A 4-in cell will generate 2.0–2.3 A [4]. For larger power requirements, a series–parallel combination of these cells is assembled. A tantalum-oxide, antireflection coating is placed over the cells. This material actually improves the efficiency of the cells rather than restricting the amount of light impacting the semiconductor.

The production of electrical energy starts with the absorption of light photons by the semiconductor material and causing hole–electron pairs to form along the junction. The excess minority carriers diffuse to the proximity of the junctions where an internal electric field separates the holes (to the $p$-side) and electrons (to the $n$-side). These separated charge carriers complete their path through the external load, causing a current flow and electric power output.

The incident photon flux and the energy of the photons affect the current density. This energy varies between seasons because of the orientation of the Earth relative to the Sun. The energy level also varies depending on location, again because of the relative angular position to the sun. The United States Weather Service (USWS) records this type of data. Typical data from areas with maximum and minimum quantities of solar energy are shown in Table I.

The unit of measure used by the USWS is the langley. Equivalent values of 1 langley are calculated below.

$$\begin{aligned} 1 \text{ langley} &= 1 \text{ cal/cm}^3\text{/min} \\ &= 0.23901 \text{ j/m}^2 \\ &= 0.1162 \text{ kW h/m}^2 \\ &= 0.27225 \text{ Btu/ft.} \end{aligned}$$

Fig. 1 is a map of the United States that indicates the multipliers that must be used to correct current output because of differences in irradiation. The panel multiplier can be calculated by dividing 24 h/day by the number of peak sunlight hours in a day.

From Table I it is obvious that the tilt of a flat panel relative to the Sun will also restrict the energy into the panel. It should be noted that the amount of tilt for the panel is determined by the geographical latitude of location. For summer optimization the tilt angle is less than the degrees latitude, while the tilt is greater than the degrees latitude for winter optimization.

## SOLAR PANEL INSTALLATION

The insolation levels of solar incidences are measured on a horizontal plane. The insolation that impacts the solar panel can be improved if the solar panel is tilted toward the Sun. From Fig. 2 it is apparent the maximum solar energy can be derived by adjusting the tilt of the panel for different times of the year. However, as indicated earlier, most solar electrical installations applied on cathodic protection are in remote areas. This remoteness makes it impractical to personally adjust each panel as conditions change significantly.

Power-driven systems have been developed to continually direct the solar panels toward the Sun. Two major problems exist with such systems. First, the energy necessary to move the equipment decreases the benefit derived from optimizing direction. Second, the mechanical drives create a maintenance problem. This overcomes the advantages of a solar energy system, particularly in remote environment.

Cathodic protection designs require the potential on the protected structure to be maintained above a threshold protection level. This creates a relatively constant current requirement. For this reason, most cathodic protection solar systems presently are designed for fixed-panel tilt to optimize the output for winter sun. Since winter sun has less energy than summer sun, a winter optimization tends to average the output of the solar system over the year.

The constant-current requirements of a cathodic protection installation requires an alternative source of electrical energy during periods of low or no solar insolation, such as nighttime. Lead storage batteries have been the traditional medium to balance the output of solar systems. Under this configuration the solar system is designed to provide the constant current requirements plus sufficient energy to charge the batteries for nonproductive times.

There have been some improvements in battery technology in recent years; however, several problems remain. Many

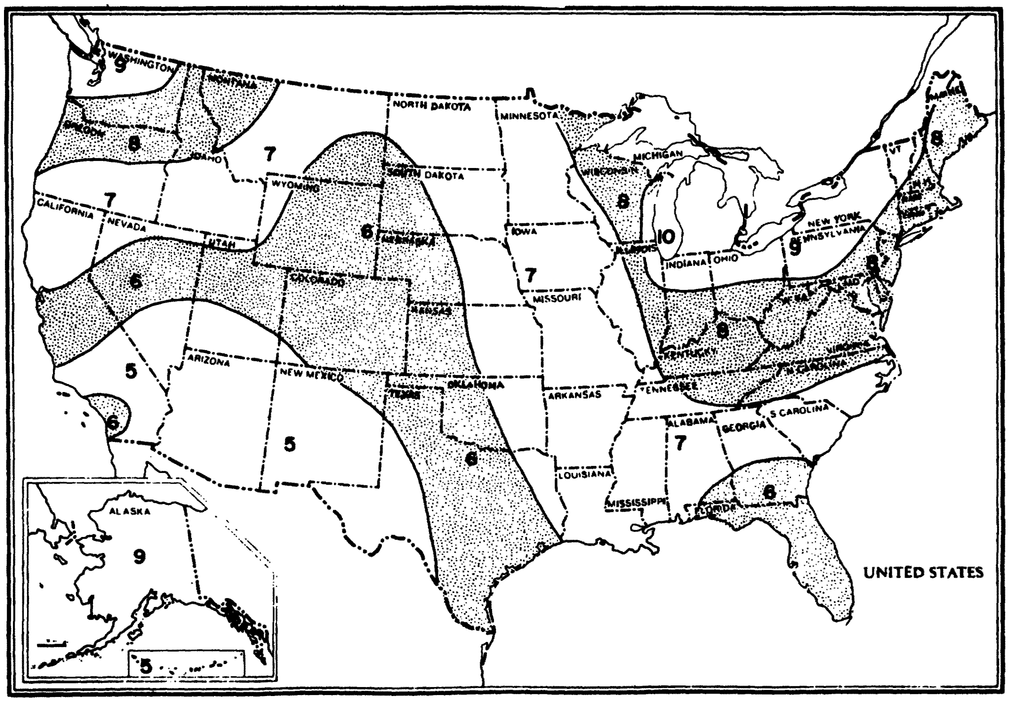


Fig. 1. Solar panel multiplier factors.

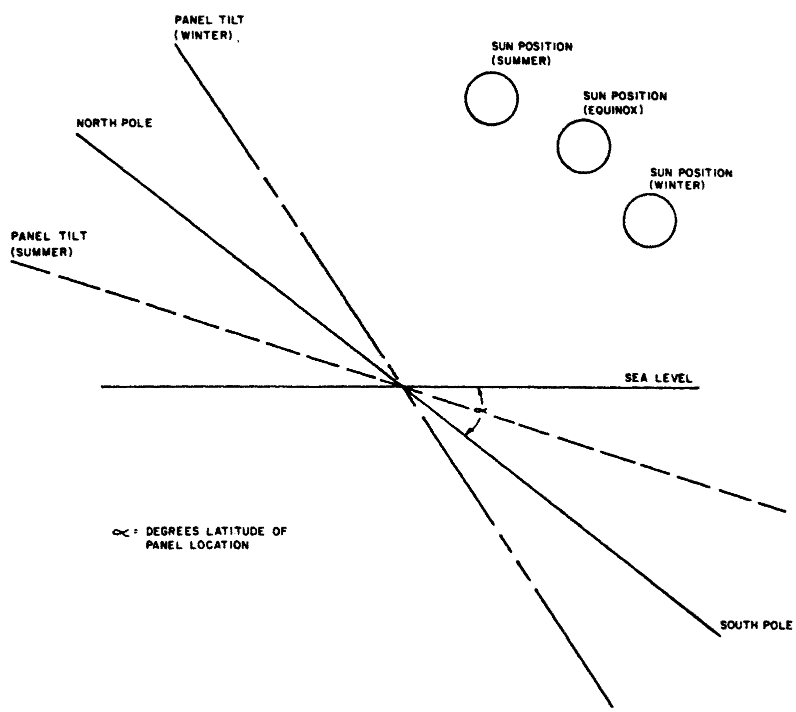


Fig. 2. Solar panel position relative to sun.

remote cathodic protection requirements are in areas that become quite cold and have no protective shelters. Battery packs must be protected from the cold to obtain reasonable current levels and to prevent mechanical problems. Some chemical battery designs emit gases that are corrosive and that may be explosive in a closed area. Proper housing and venting must be used to mitigate these problems. To keep the solar panels from discharging the batteries during low-output times and to prevent overcharging of the batteries requires some method of current control. These devices always have some voltage drop if using solid-state technology, or high current consumption if using mechanical technology. Either condition requires a larger capacity solar system to overcome the losses. Batteries require more energy to be added to the system during charging that can be recovered during discharge operation. This loss of efficiency must also be included in the solar panel design. Simply more maintenance is required on the battery/charger part of the system than on the solar panel portion. This

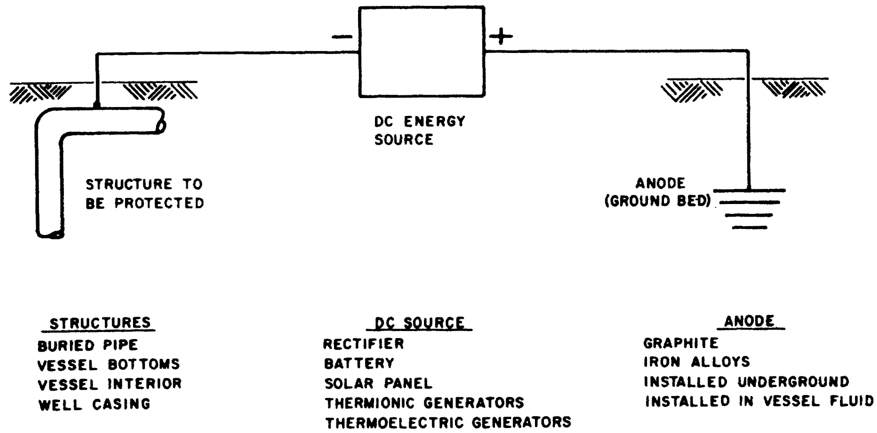


Fig. 3. Cathodic protection systems.

is counterproductive since one of the reasons for using solar panels is the remoteness of the installation.

The performance of many cathodically protected structures offers an alternative to the use of batteries for reserve energy during times that the solar system is not delivering energy.

## Cathodic Protection Fundamentals

A generic impressed current cathodic protection (*C–P*) installation is shown in Fig. 3. Regardless of components used in each of the subsystems, an impressed current *C–P* system applies a negative (conventional current flow) potential to the metal structure to be protected and a positive potential to the anode to be sacrificed. The common medium to which the structure and the anode are both exposed provides a path to complete the circuit. Conventional current will flow from the anode, causing it to sacrifice material. The current will flow through the electrolytic medium to the protected cathode structure, thus preventing loss of metal.

Corrosion will be controlled if the protected structure can be made sufficiently negative relative to the surrounding medium. A copper–copper sulfate half-cell is commonly used for a reference electrode to determine the relative potential of the structure. The electrode is placed in the medium and the potential is measured between the electrode and the structure. It is commonly accepted in the industry that a shift of $-250$ to $-300$ mV from the native state will mitigate corrosion. For bare steel pipe in soil a potential of $-.850$ V is assumed to be the level necessary for protection. This level must be maintained or exceeded (more negatively) at every point on the structure.

For vessels and pipelines the potential can be easily and accurately ascertained quite easily. However, for deep wells it is difficult and sometimes impossible to accurately assess the potential over the entire length of the well casing. For this reason, well casing *C–P* systems should be designed to maintain at least $-1.0$ V on the surface to correct for areas that may not shift as much as the surface potential.

## Hysteresis

One of the interesting effects of cathodic protection on structures is the potential response when the structure is energized and de-energized. When current is first applied, the pipe-to-soil potential increases negatively very rapidly and with time approaches a steady-state condition. Once this steady state is reached the structure is polarized relative to the medium. If the current is then removed, the pipe-to-soil potential rapidly becomes somewhat less negative, then continues more slowly to decrease to the negative state. This response appears to be very similar to the hysteresis effect observed in electromagnetic circuits. Fig. 4 contains an illustration of a normalized hysteresis curve, which has been observed on well casings. This response seems to be more pronounced on well casings than on some other structures, possibly because of installation geometry.

The hysteresis effect may be used to design an alternative cathodic protection system applicable to solar systems. Rather than use a battery with all its associated problems, solar systems have been installed that create sufficient potential on the well casing to maintain a reasonable degree of protection, even during periods of time without sun.

One of the criteria for adequate protection is the well casing can be made sufficiently negative to not discharge overnight, since polarization with rated current and depolarization with no current may take two or three weeks. Without excessive load devices in the controller, some level of energy will be supplied by the solar panel, even on an overcast day.

Some overcharging does not appear to have detrimental effects on the structure. Because of the shape of the hysteresis curve, imposing a large change in current on the structure does not cause an equivalent increase in the pipe-to-soil potential. As a result of the self-regulating nature of well casing cathodic protection, an otherwise unregulated solar power system can be used as the energy source. Remember, the solar panel has its own upper limits on current capacity from full sunlight and lower limit in total darkness.

For a typical oil/gas well in northwest Oklahoma the constant current requirement may be six A. This current will often cause a pipe-to-soil potential shift at the surface of $-0.350$–$-0.400$ V. Once the well is polarized, if the current is removed an immediate relative increase in potential or partial discharge of the well casing is observed. Most of the increase in potential occurs during the first 24 h. The rate of change after 24 h decreases significantly. Actual well performance data are shown in Table II.

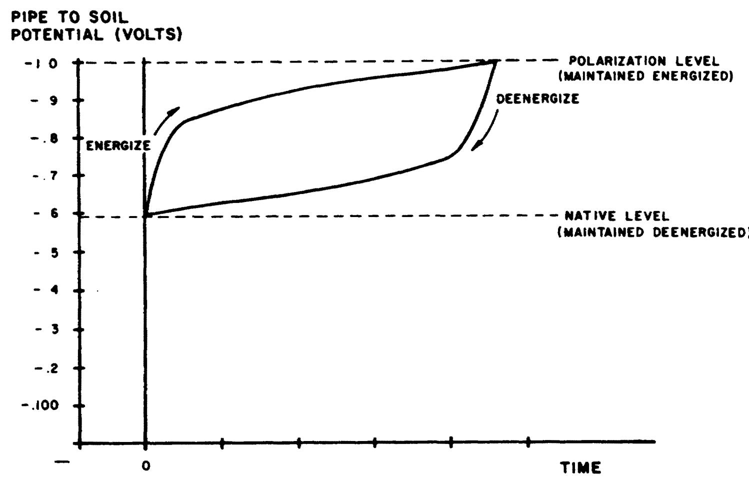


Fig. 4. Hysteresis effect. Pipe-to-soil potential change with time as current is applied and removed from well casing.

TABLE II
WELL CASING CATHODIC PROTECTION PARAMETERS[a]

| Well (Name) | Parameter | On (Steady) | Off (Immediately) | Off (24 h) | Back on (24 h) | Off (7-day) | Back on (7-day) |
|---|---|---|---|---|---|---|---|
| EL | V | 4.2 | 2.2 | 2.0 | 4.0 | 1.5 | 4.0 |
| | A | 5.5 | 0.0 | 0.0 | 6.5 | 0.0 | 7.0 |
| | P-S | 1.36 | 1.09 | 0.88 | 1.19 | 0.80 | 1.13 |
| RM | V | 8.0 | 2.5 | 2.5 | 7.5 | 1.5 | 7.0 |
| | A | 4.7 | 0.0 | 0.0 | 5.0 | 0.0 | 5.5 |
| | P-S | 1.25 | 1.09 | 0.94 | 1.12 | 0.88 | 1.03 |
| Mil 1 | V | 15.0 | 3.0 | — | — | 1.9 | 14.0 |
| | A | 3.5 | 0.0 | — | — | 0.0 | 3.0 |
| | P-S | 1.50 | 1.01 | — | — | 0.75 | 1.29 |
| Mil 2 | V | 9.5 | 2.0 | — | — | 1.5 | 8.5 |
| | A | 6.5 | 0.0 | — | — | 0.0 | 7.5 |
| | P-S | 1.98 | 1.11 | — | — | 0.70 | 1.70 |

[a] Typical well casing cathodic protection parameters change with time. All locations are in same area. Native pipe-to-soil (P-S) potential is less than $-0.65$ V. Voltage indications while off are residual readings on controller.

For the well with a 6-A requirement, approximately 9-A are needed to overcharge the well. This lowers the pipe-to-soil potential to a respectable $-1.4$ V. The potential typically reduces to $-1.1$ V immediately, if all power is removed, and to $-0.90$ V after 24 h with no current applied to the well. After a week the potential has only dropped to $-0.80$ V.

The immediate response potential (IRP) on de-energization after polarization appears to be the minimum constant potential required to maintain polarization and protection for the structure. This verifies that over $-1.0$ V is required on these particular wells to maintain protection.

The normalized data from a well with battery-free solar-powered cathodic protection is plotted in Fig. 5. This correlates actual pipe-to-soil potentials with applied current over time. As would be expected, the current from the solar panel sinusoidally follows the amount of daylight. It stays in the positive half-plane since it goes to zero at night. However, the pipe-to-soil potential has an asymptotic exponential decay in which the asymptote is increased with time. There is a delay in time between when the current reaches a peak and when the potential peaks. This phase shift results from the capacitive and discharging of the well casing.

The capacitive effect is also demonstrated from the filtering that is observed on cloudy days. The current output changes dramatically as the solar incidence is obscured. Again the potential change is less pronounced.

## System Current Requirements

A variety of techniques are used to determine the current needed to cause the pipe-to-soil potential to shift to the proper negative value. One method that has been used at various times and with various refinements for correlation has been the $E$-log $I$ curves. This is a plot of pipe-to-soil potential versus the log value of impressed current. Moreover, this corresponds with the hysteresis effect on the charging slope. Using this correspondence the additional current required to raise the potential more than it will discharge in one day can be estimated. Since some solar cell output is obtained every day to at least partially recharge the casing, one can use 24 h as the time frame to determine potential shifts and corresponding

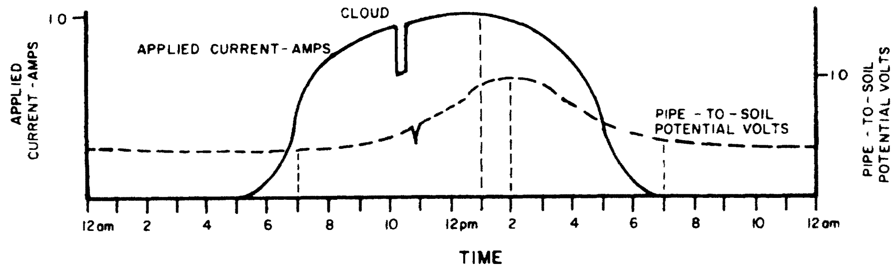


Fig. 5. Current-potential correlation.

current requirements. For a more conservative design this could be extended to the three days normally used for battery designs. However, the relatively flat slope of the discharge curve will result in very little change in the pipe-to-soil potential after 24 h.

There is another method of determining the system charging current. In a conventional solar system there is a difference between the energy required to charge the battery and the energy required for the well casing. The battery must be charged during the time of high solar incidence to a level that is greater than the average current required for the well. This incremental charging current must be designed into the solar panels.

Once the casing has been polarized, because of capacitive effects, it acts as a charge/discharge and storage device, very much like a battery. The current required to charge the battery is similar to that required to overcharge the well casing. Therefore the battery-free solar system can be sized as if it were to be used with a battery. However, rather than use a battery and controller, the current is applied directly to the well casing. A diode should be used in the circuit to prevent discharge of the well back through the solar panel.

## Solar Panel Design

To maintain reasonable power requirements on all power sources and in particular on solar systems, the circuit resistance must be as low as can be practically designed. This can be accomplished by adding more anodes to the *C–P* groundbed. For rectifier designed *C–P* systems, the anode-structure circuit resistance is typically established near 1 Ω. For solar systems the installation should be designed approaching 0.5 Ω, balancing the cost of the groundbed to reduce resistance and the cost of the solar panels to supply the incremental power to overcome the resistance.

With the current requirement established and the circuit resistance fixed by the groundbed, the solar panel system can be designed. Assume the well requires 6 A continuous and 9 A from solar power. The groundbed is designed for 0.5 Ω circuit resistance.

[1] Determine voltage requirements for the *C–P* circuit:

$$E_o = I_o \times R$$

$$E_o = 9\ \mathrm{A} \times .5\ \Omega$$

$$E_o = 4.5\ \mathrm{V}$$

where

$$E_o = \text{output voltage}$$

$$I_o = \text{output current}$$

$$R = \text{current resistance.}$$

[2] Determine power output to *C–P* circuit:

$$P_o = E_o \times I_o$$

$$P_o = 4.5\ \mathrm{V} \times 9\ \mathrm{A}$$

$$P_o = 40.5\ \mathrm{W}$$

where $P_o$ = output power.

[3] Determine panel amp multiplier from Fig. 1:

$$P_a = 6 \text{ for N.W. Oklahoma.}$$

[4] Calculate power input to solar panel:

$$P_i = P_o \times P_a$$

$$= 40.5\ \mathrm{W} \times 6$$

$$P_i = 243\ \mathrm{W}$$

where $P_i$ = input power.

[5] Select solar panel based on peak power rating (these are generic models):

| Model-5 | Model-16 |
|---|---|
| $V_{pp} = 5.2$ | $V_{pp} = 16.2$ |
| $I_{pp} = 6.7$ | $I_{pp} = 2.33$ |
| $P_{pp} = 35$ | $P_{pp} = 37.5$ |

where

$$V_{pp} = \text{peak power voltage}$$

$$I_{pp} = \text{peak power current}$$

$$P_{pp} = \text{peak power.}$$

[6] Determine current available per panel:

$$I_p = P_i / V_{pp}:$$

| Model-5 | Model-16 |
|---|---|
| $I_p = 243/5.2$ | $I_p = 243/16.2$ |
| $I_p = 46.7$ | $I_p = 15.$ |

where $I_p$ = panel current.

[7] Determine number of panels:

$$N_p = I_p / I_{pp}$$

| Model-5 | Model-16 |
|---|---|
| $N_p = 46.7/6.7$ | $N_p = 15/2.33$ |
| $N_p = 6.97$ | $N_p = 6.44 = 7$ |

where $N_p$ = number of panels.

Both models require seven panels to supply the current and power requirements. However, Model-16 would be a better design since the available voltage is significantly more than the circuit requirements. The other model has sufficient voltage at peak power but will not provide the required voltage most of the time.

## Conclusion

Solar panels are a viable economic source of power for cathodic protection installations where grid power is not readily available. Since solar power fluctuates with the level of sunshine, backup batteries have generally been used to provide a constant power level.

Because of hysteresis effects, some cathodic protected structures retain a significant charge when less than maximum current is applied. Structures with these characteristics may be adequately protected with solar panels without battery backup if the system is designed to overcharge the protected structure when energy is available. This design concept is particularly beneficial for installations in remote areas where maintenance and/or temperature are a problem.

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