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A Cathodically Protected Electrical Substation Ground Grid

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Abstract—A discussion is presented on the design of a cathodically protected electrical substation grounding system in which a steel ground grid and steel ground rods were used in place of the commonly used copper ground grid and copperweld ground rods. Several electrical constraints are presented which discuss common electrical utility requirements, safety considerations, and economic factors. The grounding system materials chosen are discussed along with the means of cathodic protection. Finally, the design, construction, and testing considerations are presented as an aid to others who wish to design a similar system.

INTRODUCTION

AN ELECTRICAL substation was required for the Natural Gas Pipeline Company of America's Canyon Compression facility located near Evanston, WY. The substation, which was to consist of two 138–4.16-kV 12/16/20-MVA transformers, was to be used to supply four 5500-hp synchronous motors. The synchronous motors in turn were to supply power to four compressors which were to be used to pressure natural gas from Amoco Production Company's Whitney Canyon plant into the Trail Blazer Pipeline.

During the preliminary design stages of the electrical substation, the design engineers of the substation questioned the advisability of using an extensive copper grounding system in close proximity to the Trail Blazer Pipeline and its associated cathodic protection system. At that time, a decision was made not to use the conventional copper grounding system and an alternative system was developed.

The substation design engineers and Natural Gas Pipeline Company's cathodic protection engineers reviewed the grounding system requirements for the electrical substation. The result was the design of a steel grounding system which used sacrificial anodes to control the corrosion of the ground grid and ground rods. In order to monitor the cathodic protection afforded by the sacrificial anodes, test stations were installed to monitor the current being supplied by the sacrificial anodes.

ELECTRICAL SYSTEM CONSTRAINTS

The proposed substation was to be placed on Utah Power and Light Company's (UP&L) 138-kV system. Although for legal purposes UP&L limits the amount of control placed on a customer-owned substation, they are quite interested in the grounding system. This is due in part to the fact that their personnel may be involved in activities within the substation such as switching, meter reading, and inspection. Therefore, the substation grounding design had to meet the rigid requirements of the local utility.

ELECTRICAL SYSTEM CONSTRAINTS

The 138-kV system was supplied by a single 138-kV transmission line being fed from UP&L's Naughton Power Plant. The available fault current from the 138-kV system was approximately 2100 A. The secondary of the substation was supplied by two delta-resistance grounded wye transformers with a normally open bus tie breaker. Either of the two 138–4.16-kV 12/16/20-MVA transformers could supply the entire load (Fig. 1).

Each of the grounding resistors was rated 6Ω and 400 A for 10 s. LOD TRAK II relaying was provided for each of the motor feeders and instantaneous ground relays were provided on each 1000-kVA auxiliary service transformer. High-speed bus differential relays were provided for 4.16-kV bus fault protection, and high-speed harmonically restrained transformer differential relays were provided for each 138-kV–4.16-kV transformer. Bus and transformer ground backup overcurrent relays were also installed in such a manner that all 4.16-kV ground faults would be cleared in less than 1.0 s.

SAFETY REQUIREMENTS

Grounding for electric supply stations is covered in [2, sec. 9]. The purpose of that section is "... to provide practical methods of grounding as one of the means of safeguarding employees and the public from injury that may be caused by electrical potential."

Within an electrical substation, a person can be placed in an unsafe situation by the following three potentials when an energized conductor comes in contact with a structure or some other object within the substation.

1) Touch potential is the potential difference between the hands and feet commonly caused by a person touching a structure which has come in contact with an energized conductor and in which there is a voltage drop between the hands and feet.

2) Step potential is the potential difference between the two feet when spread apart as in a walking position and which is caused by an electrical gradient within the earth while ground fault current is flowing.

3) Transfer potential is the potential difference between two separate locations caused by a difference in earth

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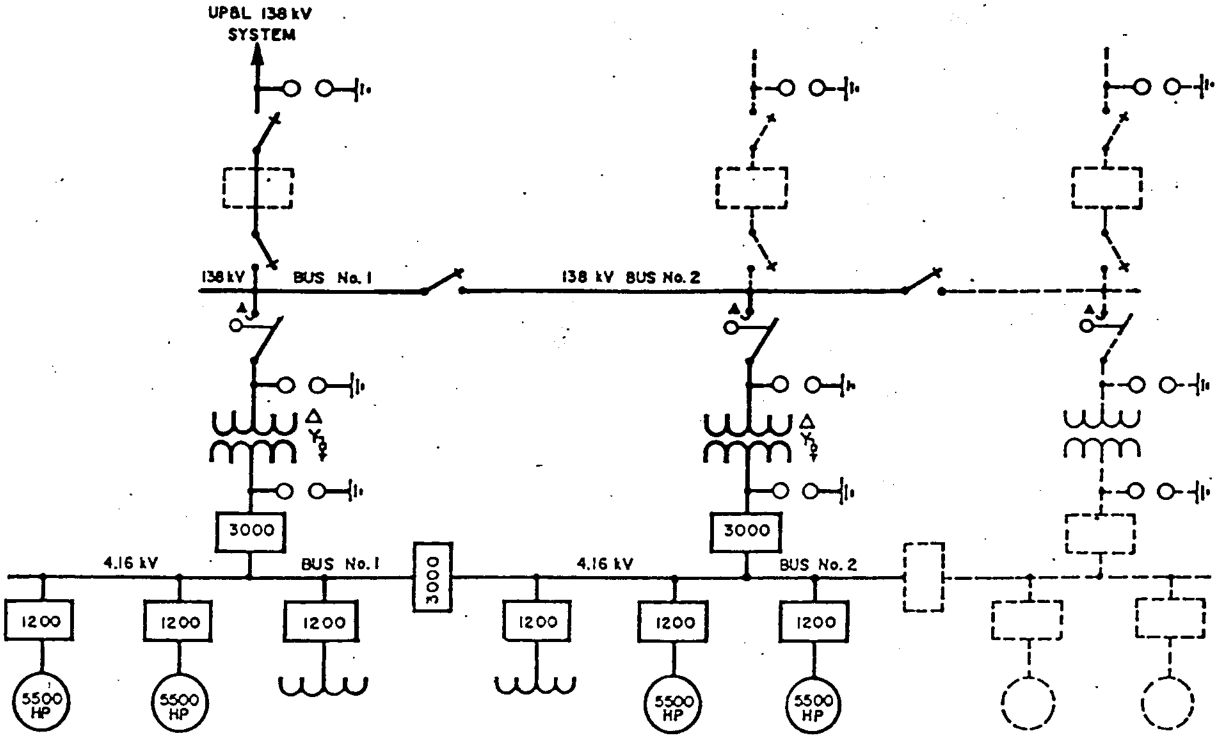

Fig. 1. Canyon Compression substation.

potentials and transferred via some electrical conductor such as a conduit.

Although not as directly related to safety, a good grounding system tends to reduce the fault impedance which tends to reduce the fault clearing times. Likewise, a good grounding system also provides a good path to ground for switching and lightning surges passing through surge arresters.

EXPANSION REQUIREMENTS

Provisions were necessary for the expansion of the substation due to the possible future growth of the compression plant or to the 138-kV system. The initial concern was the possibility of providing a third 138-kV–4.16-kV transformer which would have little effect on the grounding system except for allowing a larger substation plot. This, because of the increased surface area, would help reduce the ground resistance of the substation. The second concern was that of the expansion and growth of the 138-kV transmission system which would ultimately increase the available ground fault current. The expansion possibility of the 138-kV system was used as one of the design constraints.

The initial fault availability of 2100 A from the 138-kV system is indicative of a relatively weak system. The substation was located approximately 32 mi from UP&L's Naughton Power Plant which was the only 138-kV source in the area. However, a 138-kV loop system and a new 230-kV–138-kV substation were being considered to boost the capability of the 138-kV system in the area. Each of these possibilities could increase the available fault current by approximately 2000 A so that the available fault current could approach 6100 A in the foreseeable future. A design constraint of 8000 A of ground fault current was used which allowed slightly over a 30-percent growth factor beyond the expected 6100 A.

SOIL CONDITIONS

A series of six soil resistivity tests was conducted. Four tests were conducted for a 4.6-m (15-ft) depth and two for a 3.0-m (10-ft) depth. The following is a summary of those tests:

Test	Depth		Resistivity (Ω·cm)
	m	ft	
T1	4.6	15	5231
T2	4.6	15	5655
T3	4.6	15	5853
T4	3.0	10	4449
T5	4.6	15	5966
T6	3.0	10	5750

Based on a review of the test data, the 4449-Ω·cm test value was considered an anomaly and was neglected. The average of the remaining five tests was 5691 Ω·cm. The design criteria was then set at 6000 Ω·cm

CATHODIC PROTECTION REQUIREMENTS

Ground Grid and Ground Rod Material

The grounding system material was an important consideration in the design of the substation grounding system. Copper was excluded because of the concern that a copper grounding system in close proximity to the pipeline could cause additional corrosion problems.

The projected fault current of 8000 A dictated that a large amount of material would be required to keep the step and touch potentials within tolerable limits. The approximate length of buried conductor was determined by

$$L=\frac{Km \cdot Ki \cdot p \cdot I \cdot t}{116+0.17p_s}.$$

where

L length of grounding conductor (m),
Km coefficient based on the ground grid design,
Ki irregularity correction factor,
p average resistivity ($\Omega \cdot m$),
I total rms ground fault current (A),
t maximum duration of shock (s) (assumed maximum relay operating time),
p_s resistivity of surface ($\Omega \cdot m$) (may take into account special surface treatment such as crushed gravel).

For the Canyon Compression substation, the following constants were determined.

$Km = 0.4041$ (calculated)

$Ki = 2.0$ (calculated)

$p = 60\Omega \cdot m$ (test)

$I = 8000$ A (projected)

$t = 1.0$ s (assumed maximum fault clearing time)

$p_s = 1000\Omega \cdot m$ (crushed gravel).

The length of conductor was found to be

$$L = \frac{(0.4041) \cdot (2.0) \cdot (60) \cdot (8000) \cdot (1.0)}{116 + 0.17(1000)} \text{ m}$$
$$= 1356 \text{ m} \quad (4407 \text{ ft}).$$

With 1356 m (4407 ft) of ground conductor, it was important that an economical material be used. This is the point where a steel conductor ground grid was considered. The steel conductor and ground rods for the grounding system were economical and readily available. The main disadvantage of the steel grounding system was that of corrosion.

The below grade ground conductor was chosen to be 1.27-cm (1/2-in) seven-strand galvanized steel conductor, and the ground rods were chosen to be 1.91-cm (3/4-in) diameter × 3-m (10-ft) galvanized steel ground rods. The 1.27-cm (1/2-in) steel conductor closely approximates the cross sectional area of 3/0 conductor, and the 3-m (10-ft) ground rods were chosen due to the fact that the frost line typically extends to 1.8 m (6 ft) below grade.

Corrosion Prevention

A means of reducing corrosion of the grounding system was not only an attractive option but was a requirement of the National Electrical Safety Code (NESC) [2]. The NESC requires that

> "In all cases, the grounding conductors shall be made of copper or other metals or combinations of metals which will not corrode excessively during the expected service life under the existing conditions, and, if practical, shall be without joint or splice."

The first means of corrosion prevention chosen was that of using a galvanized coating of the steel. Knowing that the galvanized coating would provide only a limited amount of protection, a primary means of supplying continuous protection was necessary. The common means of providing such protection consisted of using cathodic protection rectifiers, sacrificial anodes, or a combination of the two.

In choosing the type of protection to be used, the rectifiers were eliminated from consideration due to the high electrical gradients which could be present during ground fault conditions. The ground grid potential rise was calculated to be 1282 V initially and 4070 V ultimately. This calculation was based on

$$V_{\text{rise}} = I_{\text{fault}} \times R_{\text{grid}}$$

where

$$I_{\text{fault}} = 2513 \text{ A initial}$$
$$= 8000 \text{ A ultimate.}$$
$$R_{\text{grid}} = \frac{p}{4 \cdot r} + \frac{p}{L}$$
$$= 0.51\Omega$$

and

r radius of a circle with area equal that of the substation ground grid (m^2),
p soil resistivity ($\Omega \cdot m$),
L length of grounding conductor (m).

Therefore, the use of sacrificial anodes was chosen to provide corrosion protection for the steel ground grid.

Sacrificial Anodes

An anode is one of four components in a basic corrosion cell. The other three components consist of 1) the cathode, the material being protected; 2) the connecting conductor between the anode and cathode, and 3) the electrolyte, the earth (Fig. 2). A sacrificial anode is an electrically negative metal which corrodes and provides current flow to the cathode, maintaining a potential which is negative to the soil. The sacrificial anode thus assures the integrity of the grounding system. While in theory any metal which is more active than the steel ground grid could be used, zinc and magnesium are the two materials commonly used in practice for sacrificial anodes.

The more evident distinction between magnesium and zinc as anodes lies in the driving voltages (Table I). While in theory magnesium and zinc have potentials of -2.37 V and -0.76 V to a hydrogen reference, respectively, actual voltages are usually much less. With reference to a copper sulfate solution, the driving voltage of magnesium and zinc are 1.55 V and 1.1 V, respectively. These voltages closely simulate actual soil conditions. The lower driving voltage of zinc has been shown to work well where the soil resistivity is less than 1000 $\Omega \cdot cm$, while the use of magnesium is quite effective in soils in the 5000-$\Omega \cdot cm$ resistivity range, and as high as 10 000 $\Omega \cdot cm$ for well coated material.

The efficiency of the two anodes is quite different. Zinc is approximately 90-percent efficient in metal being consumed for cathodic protection, while magnesium is only 50-percent, the difference being in the amount of material being consumed

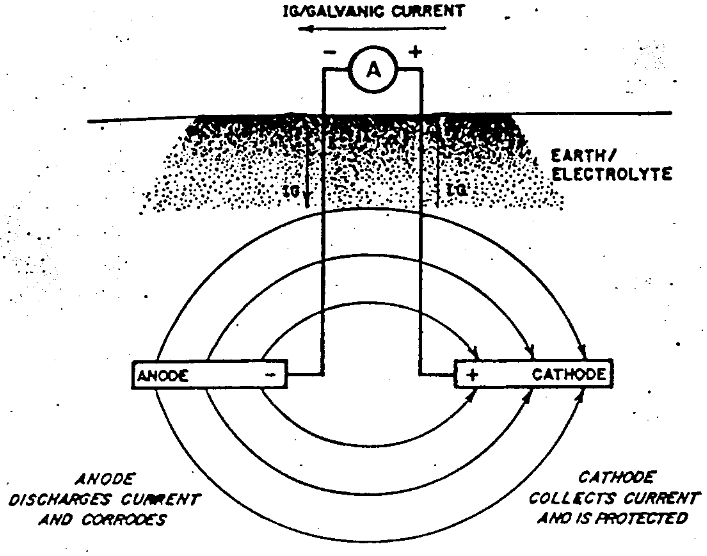

Fig. 2. Basic corrosion cell.

TABLE I
ELECTROLYTIC POTENTIAL WITH REFERENCE TO HYDROGEN AT 25°C IN AN AQUEOUS SOLUTION

METAL	ELECTRODE POTENTIAL VOLTS
Magnesium (Mg)	−2.37
Aluminum (Al)	−1.66
Zinc (Zn)	−0.76
Iron (Fe)	−0.44
Tin (Sn)	−0.14
Stainless steel	−0.25
Hydrogen (H_2)	0
Copper (Cu)	+0.34
Silver (Ag)	+0.80
Gold (Au)	+1.36

in self-corrosion. Assuming that the normal rate of consumption of material is dependent on the magnitude of generated current, magnesium and zinc will be consumed at the rates of 4.0 kg (8.7 lb) and 10.7 kg (23.6 lb) per ampere year, respectively. In actuality, the consumption rates of each are 8.0 kg (17.4 lb) and 11.9 kg (26.2 lb), respectively.

Since the soil resistivity was in the 5000–6000-Ω·cm range, magnesium was chosen as the material for the sacrificial anodes due to its higher driving voltage. A special backfill was desired consisting of a mixture of gypsum, bentonite, and sodium sulfate. This special backfill serves four purposes:

1) provides uniform soil around the anode in order to assure uniform corrosion of the anode,
2) minimizes the resistance between the anode and the earth,
3) retains moisture which aids in minimizing the resistance, and
4) aids in depolarizing any film buildup, which would reduce the flow of the galvanic currents.

Prepackaged magnesium anodes weighing 14.5 kg (32 lb) were chosen that were over 98 percent pure magnesium (Fig. 3). Each prepackaged magnesium anode included a backfill mixture consisting of 75-percent gypsum, 20-percent bentonite, and five-percent sodium sulfate packaged in a cotton bag. A 2/0 copper AWG copper wire insulated with high molecular polyethylene was specified for each sacrificial anode to assure adequate current-carrying capacity during fault conditions and for the adequate conductor size for the exothermic connections.

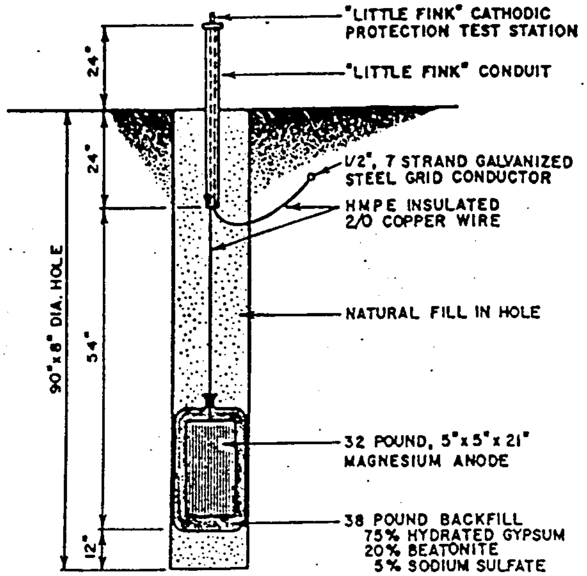

Fig. 3. Sacrificial anode installation.

The approximate resistance of each sacrificial anode was found to be 45 Ω based on the following equation:

$$R=\frac{p}{2L}\left(\ln\frac{4L}{a}-1\right)$$

where R is the resistance of one ground rod and

p soil resisitivity (6000 Ω·cm),
L length 53.3 cm (21 in),
a radius 6.4 cm (2.5 in).

Assuming the worst case, a ground potential rise of 4080 V, the current flowing to the anode under fault conditions was only 91 A. Therefore, the 2/0 copper conductor was more than adequate for the fault current flow of 91 A.

Testing Facilities

The sacrificial anode provides a continuous current flow to the grounding system. Individual test stations were installed in the lead conductor from each anode to the grounding system. Each test station was provided with a 0.1-Ω shunt and test terminals so that periodic tests could be made on the cathodic protection system. The test currents can be recorded and used to calculate the amount of anode remaining. The calculated life expectancy of the anodes was 39 years.

DESIGN CONSIDERATIONS

Below Grade Connections

Exothermic connections were used below grade on all connections. No special precautions were required on the steel-to-steel connections on the cross connections, tee connections, or the ground grid-to-ground rod connections. However, special precautions were taken when copper-to-steel connections were made.

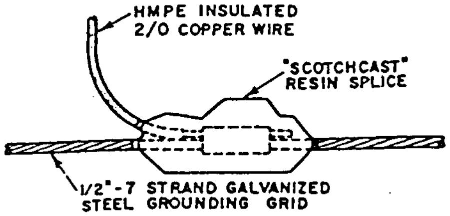

Fig. 4. Below grade connection.

Copper leads from above grade ground conductors and below grade anode leads were connected to the grounding system. At these points, there was concern about the galvanic action which would take place between the copper and the iron. To minimize this galvanic action, Scotchcast splice kits were specified to assure a moisture tight seal at the connection, Fig. 4.

Concrete-Encased Rebar Grounding Electrode

Several structures were required within the substation for 138-kV switch stands, bus supports, and terminating structures. The rebar was spot welded to the anchor bolts to provide supplemental grounding electrodes. Concrete below grade typically has a resitivity of $3000\ \Omega\cdot\mathrm{cm}$ which is lower than the average resistivity in the substation. Although not taken into consideration in the grounding calculations, the concrete-encased rebar grounding electrodes will provide a larger safety margin especially during winter conditions with a deep frost line.

SUMMARY

Substation grounding systems are extremely important, especially in close proximity to an industrial plant. The most common material used for that grounding system is copper because of its noncorrosive characteristics. However, for the same reason that it is noncorrosive, i.e., its galvanic potential, it causes additional corrosion with metals such as iron and aluminum when set up in the basic corrosion cell.

As an alternative to using copper as the primary grounding system material, a steel ground system can be used and is acceptable under [1] and [2]. However, precautions must be taken to assure that the grounding wires and electrodes are of an adequate size and will not corrode excessively.

The use of zinc or magnesium anodes for cathodic protection of the grounding system appears to satisfy the corrosion requirement of the codes. It also alleviates the possibility of losing the anode because of high ground grid potential rises under fault conditions. However, the life of the anodes are finite, and a means of monitoring the anode through test stations is desirous.

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