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ELECTRICAL GROUNDING CASE HISTORIES

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ABSTRACT

Traditional copper grounding systems may create excessive demand on cathodic protection systems. Three case histories demonstrate the significant differences in current demand for CP of underground piping systems as a result of the design of the electrical grounding systems. Compatible electrical grounding system design is shown to be a clear advantage.

Keywords: alternatives to bare copper, bare copper, conflict, cross bonding, copper grounding, galvanic couple, impressed current, resistance-to-remote earth.

INTRODUCTION

Traditionally, most underground structures have been electrically bonded in common to reduce hazardous voltages associated with lightning and man-made fault currents or induced currents in the earth.[1,2] A common grounding system provides a more economical and a lower resistance-to-remote earth than does several individual earthing connections. This assures a low resistance return path for power system earth return currents and fault currents. It also tends to reduce step and touch voltages at the surface of the earth. Redundancy is very desirable in electrical grounding and earthing circuits for safety reasons if one or more conductors are cut or otherwise damaged.

The USA National Electrical Code (NEC)[3] does not require copper grounding; instead, it requires that "permanent" metallic earthing electrodes and conductors must be used for earthing connections. The United States electrical practice does not make a clear distinction between "earthing" and "grounding" as is common in European practice. In this paper we will make a clear distinction. "Earthing" refers to a grounding electrode or grounding conductor in direct contact with the soil environment which makes an electrical connection to that environment. When measured, it is an expression of the ohmic resistance between the total contributions of all of the various grounding members and the soil environment to which they are connected. "Grounding" refers to the practice of providing metallic bonding conductors (conduit, ground wires, etc.) which are deliberately connected between various pieces of equipment and the earthing electrodes/conductors making up the plant's grounding grid. The term "grounding grid" encompasses all electrically common grounding conductors, earthing conductors, earthing electrodes, ground mats and process piping that make up the overall, electrically continuous, plant grounding system. To distinguish these elements of the grounding system from a "cathodic protection groundbed," we will use the term "anode-bed" for the latter.

Common bonding of underground ferrous structures to massive copper grounding grids creates problems for corrosion engineers attempting to apply cathodic protection (CP) to associated ferrous structures in the facility.[4] CP is routinely employed to overcome soil instigated corrosion cells on power plants, industrial facilities and on crude oil or natural gas production and transportation facilities. In most instances, the underground piping is provided with a dielectric coating to create a corrosion control barrier between the pipe surface and the local soil or water environment. These coatings are supplemented with CP to prevent corrosion at holidays or voids in the protective coating. The combination of dielectric coatings supplemented with CP produces a low cost corrosion protection system with minimum current demands. When such a system is directly connected to a bare copper earthing system, total CP current demand may increase by several orders of magnitude. This creates a serious design conflict between CP engineering design and electrical engineering safety design.

In some instances current demand by the copper grounding system may exceed 90% of the total current output of the impressed current system.[4] At any time that the impressed current CP system is out of service or is not functioning, a strong galvanic couple is created between the underground ferrous piping and the copper grounding grid. This leads to accelerated corrosion of all of the ferrous structures that are in direct soil contact. Even with the CP systems operating within their rated capacity, serious corrosion losses may still be experienced in localized areas where low pipe-to-soil potentials exist.

Acceptable alternatives to bare copper do exist in the form of stainless steel (SS) groundrods, sacrificial anodes in cast, rod or ribbon shapes, rebar or other iron rods in concrete, galvanized steel groundrods and galvanized steel cables as well as the use of cathodically protected iron and steel shapes.[2] Grounding grids have been constructed of wrought iron or mild steel rod and bar shapes for many decades in China, Germany and Russia. CP is frequently applied to these ferrous grounding grids. Many others have been successfully installed without the benefit of CP. The integrated grounding/CP design with a fully cathodically protected grid may very well provide a significantly longer useful life for the ground grid.

CASE HISTORIES

The following three case histories are presented to demonstrate the principles discussed in the paper. Case History Number 1 is an aircraft maintenance facility built to modern cathodic protection and grounding standards that exhibits a very low cathodic protection current density per unit area.[5] Case History Number 2 is an oil and gas production facility with excessive amounts of bare copper grounding.[6] Case History Number 3 is an electrical generating station with a bare copper grounding grid typical of late 1960's construction practices.[7] This paper discusses the new concept of cathodic protection current density per unit area as an indicator of the efficiency of cathodic protection systems.

Case History 1 -American Airlines Alliance Maintenance & Engineering Base

The American Airlines Alliance Maintenance & Engineering Base (M&E) was designed and constructed in December 1989 through mid summer 1992. The M&E is a wide body jet aircraft overhaul facility capable of hangaring seven jets simultaneously. The underground metallic matrices at M&E consists of the following components:

1. HDPE plastic natural gas lines with welded steel, dielectrically coated risers on the larger service lines and "anodeless risers" on the smaller service lines.
2. Welded steel, dielectrically coated compressed air lines.
3. Large diameter ductile iron pipe (DIP) fire water and potable water lines are bonded and are dielectrically coated. Twelve inch and smaller diameter lines are PVC with DIP risers, valves, tees and 90's.
4. Welded steel dielectrically coated jet fuel (JP-4) lines and several underground day tanks.
5. Various control lines and electrical conduits.
6. Foundation rebar.
7. Stainless steel grounding electrodes and insulated copper cable grounding grid.

The author was commissioned to design the CP systems for all underground utilities and the electrical grounding grid. For this particular grounding scheme, all building steel was tied in common with the grounding grid. The grid is a complete network of PVC insulated copper cables with a few driven SS groundrods at selected locations. By taking full advantage of building steel and foundation rebar, the maximum acceptable plant grounding grid resistance of 1 ohm was easily met in the low resistivity 1,000 ohm-cm (10 ohm-meter) soil environment typical of North Texas. This type of grounding system is very compatible with CP systems.[8] Current demand for SS grounding electrodes is generally in the range of about 1 milliampere per square foot (0.1 milliampere/m^2) of surface area exposed to the soil. Current demand for structural steel members encased in concrete is generally in the range of about 0.1 milliampere per square foot (0.01 milliampere/m^2) due to the passivation effect of the portland cement concrete on the steel.

The impressed current CP system consists of conventional, vertically installed distributed anodes powered by transformer/rectifier (T/R) units sited in individual buildings throughout the facility. In the case of large diameter DIP firewater/potable water mains, distributed anodes were installed in the middle of the company streets. Distributed anodes were also installed in areas of congested piping, around underground jet fuel day tanks and around the perimeter of aboveground water storage tanks. In other areas conventional remote vertical anode groundbeds were employed. There are a total of eleven CP rectifiers installed to protect the underground plant piping. Total output capability of the eleven rectifiers is 439 amperes. At the time a recent survey,[9] these eleven rectifiers were putting out a total of 106.5 amperes. This total does not take into account isolated coated DIP fittings which are protected by sacrificial anodes. The M&E facility covers a surface area of approximately 199 acres. Therefore, the average current density per unit area is approximately 0.5352 amperes per acre for essentially all of the underground plant, including the grid.

Case History 2 – Pakistani Oil & Gas Production Facilities

Union Texas Pakistan (UTP) operates six major oil and gas production facilities and a number of smaller facilities in the Badin Block, Sindh Province, Pakistan. The production facilities separate oil and gas, knock out water, ship natural gas via pipeline and store oil and distillate production in aboveground tank farms for later transport to refinery by tanker truck. Electrical power is obtained from on-site generator sets with diesel or natural gas prime movers. The production facility (P.F.) discussed in this paper handles both crude oil and natural gas and was brought on-line about 1990. There were three functioning T/R units. T/R Numbers 1 and 2 power a total of thirty (30) vertically installed distributed anodes around the perimeter of nine production tanks. T/R Number 3 powers a conventional remote vertical anode-bed and is dedicated to CP of the incoming flow lines and trunk lines from remote production facilities. All three of these T/Rs are rated at 25 volts 75 amperes DC each. They were capable of protecting the underground piping, as originally installed.

The original electrical grounding grid was constructed utilizing PVC coated stranded copper conductor ranging in size from 16 mm^2 to 95 mm^2 conductor. The 16 mm^2 conductor is used for equipment grounding. Grid conductors are 70 mm^2 or 95 mm^2 and are connected to driven copper clad groundrods at 61 m (200 foot) to 122 m (400 foot) spacing around the perimeter of the plant with supplemental ground rods at major equipment.

At some point within the five year period prior to this study, a grounding system upgrade was undertaken to “improve” the electrical grounding at each of the P.F.s. This was considered necessary at the time to assure adequate fault current protection should a motor winding or similar electrical element go to ground. The grounding system upgrade consisted of bare stranded copper 70 mm^2 or 95 mm^2 cable laid in parallel with the existing insulated cable grounding grid. The bare copper grid was supplemented with additional copper groundrods and a total of four “deep well groundbeds” were installed. The deep well groundbeds consist of a copper plate approximately 1 m^2 and buried approximately four meters deep. Three separate 95 mm^2 stranded bare copper conductors were exothermically welded to the copper ground plate and were brought up to a bus bar installed in an aboveground manhole. Given the very low electrical soil resistivity at this site, ranging from 90 to 200 ohm-cm (0.9 to 2 ohm-meter), the grounding system upgrade did not seem to be necessary.

Following installation of the grounding system upgrade, corrosion failures became a serious problem at most of the production facilities. In a few instances, perimeter fencing fell down when the supporting poles corroded in two at grade level or underground due to their being bonded to the bare copper perimeter grid. It was reported that numerous corrosion leaks had been repaired, mostly on flow lines due to active corrosion. In some instances, entire segments of a pipeline were replaced with new pipe. Annual CP surveys by the company and in-country subcontractor personnel indicated that the vast majority of the buried plant piping (BPP) was not adequately cathodically protected following the grounding system upgrade. The majority of the underground piping exhibited pipe-to-soil potentials less negative than –0.85 volts referenced to copper-copper sulphate electrode. In late summer 1996, the author in collaboration with in-country CP subcontractors and UTP personnel, conducted a detailed CP/electrical grounding survey of the major production facilities and most of the minor production facilities in Sindh Province.

Prior to the initiation of our study, the company and contractor personnel disconnected essentially all of the bonds to the perimeter fencing and disconnected most of the bare copper perimeter ground loop from the plant grid. Perimeter fence bonding is required at electrical generating stations and at locations where external power is brought into a facility via overhead conductors.[10] This is necessary in order to protect personnel in the event of a falling conductor. Since neither of these conditions exist at the production facilities, with on-site power generation, perimeter fence grounding is not required. A perimeter grounding conductor with or without supplemental driven electrodes would be beneficial if one needed to lower the resistance-to-remote earth of the overall grid. That was not the case for these P.F.s.

Resistance-To-Remote Earth Measurements. An attempt was made to measure the combined plant/electrical grounding grid resistance-to-remote earth at one of the P.F.s via the IEEE fall of potential method.[11] The resistance-to-remote earth of the existing composite grounding grid and plant piping network was so low as to preclude measurement with the available instrumentation. Neither of the two AC ohm meters available at the time of the survey could accurately measure a value of less than 0.005 ohms. Therefore, an alternative DC method was used. The differences in potential (ΔE) between the "on" and the "off" remote pipe-to-soil potentials measured while simultaneously cycling the T/R units were used to calculate the resistance of the entire plant grounding grid to remote earth. These measurements were taken using a single, remote copper-copper sulphate reference electrode established at 2,590m (8,500 feet) remote from the plant site. When the interrupted pipe-to-soil potential survey was conducted, the close pipe-to-soil potential and the remote pipe-to-soil potential were measured and recorded at each test site with the T/Rs in both the "on" and in the "off" condition. An average of the remote pipe-to-soil ΔEs was divided by the portion of the T/R outputs that were contributing CP current to the plant piping only. This procedure properly disregarded the CP current that was applied to the flow lines that were electrically isolated from the grid.

Calculated resistance-to-remote earth of the P.F. was 0.001294 ohms prior to removing the additional copper grounding. Approximately 890 lineal feet (271m) of additional large diameter bare copper grounding conductor was physically disconnected from this plant grid. The perimeter grid conductor was abandoned in place by disconnecting connections to individual fence posts and all ties back to the common plant grid. As a result of the additional excavation work carried out during these studies, neither the perimeter fencing nor the perimeter bare copper grounding loop remained connected to the plant grid. Grid resistance was 0.00139 ohms after removing as much of the additional copper grounding as was safe and practical. This represents a 7.7% increase in overall plant resistance. However, the final overall plant grid is still more than three orders of magnitude lower in resistance-to-remote earth than is required to operate a safe system. For on-site electrical power generation, an overall plant grounding grid resistance up to 5 ohms may be adequate for safe touch and step potentials. Therefore, the extensive grounding system upgrade was not necessary.

The existing CP system was preferentially protecting the fire water loop and not providing enough CP current flow to the varied plant piping which contains the valuable production fluids and gases. During the electrical grounding system dig-outs, deliberate cross bonds were made between fire water piping and plant piping and between insulated plant grounding grid conductors and buried plant piping. This was done to assure adequate electrical continuity between the various systems; that is, grounding grid conductors, buried production piping and various fire water mains. It is important to overcome cathodic interference problems between various segments of the underground systems. Cathodic interference was noted at more than one location within the plant site. Notably, this was usually occurring on the grounding grid which had not previously been deliberately connected to the BPP but was interconnected only via aboveground connections at the various equipment skids.

During the second survey, we noted an acceptable decrease in pipe-to-soil potential magnitudes on the F.W. lines because of the deliberate cross bonding between the F.W. system, the buried plant piping and the electrical grounding grid. At the same time, improvements were noted in BPP and grid conductor potentials. Since we can not take the grounding grid out of the equation, a better choice is to bond the grid in common with the balance of the piping system to eliminate stray current cathodic interference problems and to produce more uniform pipe-to-soil potentials. The net result of the improved cross bonding and the elimination of some of the bare copper grounding was more uniform and somewhat improved pipe-to-soil potentials on the buried plant piping and elimination of cathodic interference between various elements of the underground system.

Recommendations. Based upon the extensive investigations carried on throughout the Badin block production facilities, specific CP system upgrade recommendations were made for each facility.[12] These upgrades ranged from a few zinc anode and test lead installations in one remote production facility to the installation of as many as two additional and much larger T/R units at some of the larger facilities. No upgrade in ICCP capacity was deemed necessary for many of the facilities. Just removing excessive bare copper grounding at these facilities was sufficient to restore effective levels of CP. The data shows significant improvement in the level of potential of the buried piping at test point locations which had previously been difficult to protect due to their closeness to buried bare copper conductors. We also prepared an "Engineering Design Manual For Cathodic Protection and Grounding Facilities" for future work by in-house staff.

Recommendations were made for two additional T/R installations at the P.F. under discussion in this paper. T/R Number 4 is a 10 volt 100 ampere unit powering a split horizontal anode-bed containing 11 anodes. It is installed on the west side of the plant. This anode-bed is not truly a remote anode-bed but almost could be considered a distributed anode installation. T/R Number 5 is a 10 volt 150 ampere oil cooled T/R on the east side of the plant. This unit powers 16 anodes in a horizontal anode bed which is fully remote from the plant piping. Thus, T/R unit capacity for the BPP in the P.F. was increased from 100 amperes to 350 amperes even after removing as much of the excessive bare copper grounding as was practicable. Negative connections were made to BPP, F.W. lines and the plant grounding grid on all new T/R installations. This was essential to remove any probabilities of cathodic interference on underground plant, including the grid.

In addition, we made recommendations for additional cross bonds and for removal of some of the resistor junction boxes (RJB) that were used to cross connect some of the plant piping. Some of the RJBs are appropriate to control pipe-to-soil potentials on flow lines and other isolated piping. However, within the plant site itself, these RJBs introduce unacceptably high resistances in the bonding circuits. This leads to uneven pipe-to-soil potentials and always presents the possibility of cathodic interference on some of the underground structures.

Results of the CP P.F. Upgrade. The installation work for the recommended CP system upgrades started at the end of 1997 and was finished by the end of 1998.

All of the final data were gathered within a week of commissioning the upgrade at each P.F. which did not allow sufficient time for full polarization.[13] Nevertheless, the vast majority of the BPP was adequately protected with a combined T/R output of 196.4 amperes, excluding current to the flow lines. The P.F. covers a surface area of approximately 29.5 acres. Therefore, the final average current density per unit area is approximately 6.658 amperes per acre. Future CP system upgrades, necessary to protect a few small areas of low potential, were expected to marginally increase the average current density.

Case History 3 – A Steam Electric Station

A large, 2 unit lignite fired Steam Electric Station (PLANT) was designed and constructed in the mid to late 1960s in East Texas. Underground utilities at the plant site include at least the following components:

1. Welded steel dielectrically coated natural gas lines, compressed air lines and service water lines.
2. DIP, firewater and potable water lines. These lines may or may not be coated.
3. Various control lines.
4. Electrical conduit.
5. Foundation rebar.
6. Driven sheet piling
7. An extensive bare copper grounding grid with numerous driven copper ground rods.

There was no intentional electrical isolation between any of the underground structures. Some cathodic protection was provided for the underground plant at the time of initial construction. A few additional rectifiers and groundbeds were installed in the 1980s.

The author became involved with upgrades to the plant's cathodic protection system in the mid 1990s after a number of fire water lines and water lines had been replaced due to corrosion failures. At that time, the cathodic protection system was found to be in a general state of disrepair plant wide. The first course of action was to make repairs to the existing rectifiers and/or anode-beds. This was accomplished over a period of four years, as maintenance funds have become available. A total of six additional units have been installed to address specific low potential areas. For all new T/R units in this facility, negative connections are always made to the grounding grid or to building steel. Negative connections are also made to nearby BPP, where practical. Individual negative output shunts are provided whenever two or more negative outputs are employed. Some rectifiers have as many as four negative output terminals.

During one of the comprehensive plantwide surveys, a remote reference electrode was established and the output of the largest T/R was interrupted.[14] On and off potentials were measured and recorded to both the remote and a close reference electrode. The remote readings clearly showed several major electrical discontinuities in the plant grounding grid. A revised plant grounding grid drawing was prepared calling for insulated bonding cables ranging from Number 2 AWG up to 500 MCM. Overall plant grid resistance-to-remote earth has not been measured since the repairs have been completed. It is estimated that the resistance will be less than 1 milohm.

After that survey, additional T/Rs and anode-beds have installed. At the time of the most recent survey there were a total of fourteen operational T/R units and associated anode-beds with a total rated current output capability of 810 amperes protecting the BPP within the plant facility. At the time of the most recent survey, the fourteen rectifiers were putting out a total of 730.1 amperes. The plant covers a surface area of approximately 113 acres. Therefore the average current density per unit area at that time was approximately 6.461 amperes per acre.[15] Recognize that in the congested areas of the plant, the current density per unit area quite probably is at least an order of magnitude higher.

CONCLUSION

For both case histories involving extensive bare copper grounding grids, the CP current requirement is more than an order of magnitude higher on a per unit area than is the case for a properly coordinated and integrated electrical grounding and CP design. This implies that these older designs, employing bare copper grounding, are at best ten percent efficient, from a CP standpoint.

Case History Number	Grounding Grid Configuration	Average Current Density per acre (amps) for effective CP
1	SS ground rods & Ufer grounds	0.5352
2	Excessive bare copper grid	6.658
3	Bare copper grid	6.461

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