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Challenges of Grounding When Upgrading Substations and Security Fences

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SUMMARY

As power systems strengthen in order to keep up with changing system operations, the system will be capable of higher available fault currents. Electrical equipment on lines and in substations in turn must have increased fault duty and interrupt ratings. In substations specifically, the grounding systems need to adapt to the increasing fault current on the power system.

At the same time physical security requirements are increasing, resulting in many older substations requiring new fence upgrades. Many of these older sites did not have fence grounding that would meet today's design practices, presenting challenges to properly ground the new security fence.

This paper presents the basics of grounding design and analysis to give the reader a brief background of the initial concerns. Some additional historical background on previous design approaches is included, which leads to some of the problems seen now as fault currents increase or as fences are upgraded. Based on an understanding of these concerns, several design approaches are presented both in new and existing substation grounding and security fence designs.

KEYWORDS

Grounding, fences, substation, security, touch voltage, faults

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IMPORTANCE OF A GROUNDING SYSTEM

Before beginning the design and analysis of a grounding system, one first needs to understand why grounding systems are so important. There are four major purposes to a grounding system:

- Provide personnel protection under fault conditions within a substation
- Protect equipment from high voltages and currents seen by the system during fault conditions
- Allow for proper system and equipment operation under both normal and fault scenarios
- Dissipate the current from surges and lightning strikes

One of the most important aspects of substation grounding system designs is for personnel protection within the substation during faults. IEEE Std 80 [1] and IEC TS 60479-1 [2] focus in on this fact. While the other purposes listed above are important as well, they will often be resolved in a system that is properly designed for personnel protection. However, for the grounding system to operate as designed, it must remain effective even as fault currents increase.

GROUNDING SYSTEM DESIGN AND ANALYSIS

Behavior of a Grounding System Under Fault Conditions

When a fault occurs, the current must return to its source. The purpose of the grounding system is to provide a low impedance path for the current to flow into the ground and use the earth as a return path. In the process, the current flows through the equivalent resistance of the grounding system and earth. As Ohm's Law indicates, when current flows through a resistance, it will result in a voltage equal to the product of those two values (V=I*R). This voltage of a grounding system is known as the Ground Potential Rise (GPR). This GPR presents an elevated voltage with respect to "remote earth", a point where there is no longer an effect from the fault.

IEEE or IEC Design Limits

IEEE Std 80 and IEC TS 60479 provide guidance on voltage limits based on scenarios presented in a substation environment and behavior of the human body when subjected to an electric shock. The basis for these voltage limits actually specify the calculated current that can flow through the body, particularly the heart, without causing a higher likelihood of death.

To take these body current limits and express them in a manner that can be more easily examined, these guides demonstrate approaches to evaluate two hazards: a touch voltage, and a step voltage. A touch voltage is simply the voltage difference between equipment being touched and the ground at your feet and typically assumes you can only touch something approximately one meter of where you are standing. Similarly, a step voltage is the voltage difference in ground between your feet as you are standing or walking, typically limited to a distance of one meter.

More background methodology can be found in the standards, but the compliance limits are determined primarily by the soil surfacing layer (and its relationship to the underlying soil), the maximum fault duration, and the X/R ratio of the fault.

Soil Data and Grounding Performance

The performance of the grounding system is greatly dependent on the soil structure in which the grounding system is installed. Soil structures typically consist of a few distinctive horizontal layers over a given area, with each layer having its own electrical characteristics based on soil composition and moisture content, as well as several other factors, including if the top layer of soil freeze in the winter. While all layers affect the performance, the bottom layer often drives the grounding system impedance, and therefore is very important to accurately determine. The layering and characteristics of the soil are determined by performing soil resistivity measurements. In order to measure all soil that affects the performance of the grounding system, the maximum probe spacing should be on the order of magnitude of the maximum dimension of the grounding system [3].

Soil data has one of the largest impacts on grounding system performance, but is often some of the worst available data. This is often due to inadequacies of equipment to perform the measurements, inexperienced people performing the measurements, or simply that they do not fully understand how the data they are gathering relates to the grounding analysis. The other major cause of soil model inaccuracies is simply a lack of data. If the probe spacings do not go as far as required, important data that affects the performance of the grounding system is not available. Further discussion on the importance of soil data acquisition and analysis, as well as the proper procedures for gathering the proper data is outside the scope of this paper.

Fault Current Data

When examining a fault scenario and its impact on a grounding system, one only need be concerned with ground faults. A three-phase or line-to-line fault results in no current flowing through the ground, and thus has no significant impact on the grounding system. Therefore, the typical concern is the single-line-to-ground fault scenario, which is the most common type of fault.

As discussed previously, the duration of the fault impacts safe levels for voltages; therefore, one needs to know the maximum duration that a fault could exist. To account for a "worst-case" scenario, typically the backup clearing time (due to protection failure or breaker failure) is used for the analysis. The longest possible delay with any one failure should be used.

In a substation with multiple voltages (such as a 230 kV/ 69 kV substation), the fault currents, clearing times, and X/R ratios will typically vary with a fault at all voltages. As a result, one must consider all scenarios and take the worst case combination of these three factors for the grounding analysis, as a fault anywhere in the substation will result in a GPR on all grounded objects.

Fault Current Split Analysis

The most conservative assumption for substation grounding analysis is to assume that all of the maximum fault current will enter the grounding system and return to the source through the ground via the grounding system. In practicality, there are often, but not always, numerous other return paths to the fault source through shield wires and distribution neutrals, including the associated structure grounds. Various methods exist for computing an equivalent current split of this fault current distribution, allowing the true amount of fault current into the grounding system to be determined. As a result, the maximum calculated touch and step voltages within the substation will decrease to a more realistic value.

The methods to determine the split of fault current include those described in IEEE Std 80. More advanced and accurate computations are achievable with extended power system data using the various software packages, but can be more time consuming and may require additional data.

The effects of a fault current split are most significant where poor soil exists in the vicinity of the substation, resulting in a high grounding system impedance. In this scenario, the multiple parallel paths provide the current a lower impedance path, and much more current will flow through grounds other than the substation.

Grounding System Design and Analysis

The performance of a grounding system under fault conditions is primarily characterized by the Ground Potential Rise (GPR), the electrical impedance of the grounding system, and the touch and step voltages used to evaluate compliance according to IEEE Std 80 during fault conditions. In addition, the ampacity of the grounding conductor is determined to verify that the equipment leads will not be destroyed (fuse) during fault conditions. The ampacity depends on the conductor material, the maximum fault duration, and the X/R ratio of the fault. Finally, everything needs to connect all items that need to be grounded to the main grounding system. All connectors must be rated for the maximum current the connector could see.

When designing a new grounding system design, there are many items to keep in mind. Typically, the entire substation area should be encompassed, including an area of at least three feet beyond substation fence, including outward swing of gates. Doing so will help lower the overall grounding system impedance (as it is proportional to area of grounding system) and provide good protection to the fence as well. In many older stations, the fence was not externally grounded, or may not have been grounded at more than a couple places where it tied to the main grid, resulting in significant touch voltages along the fence.

Typically, a new main grounding system is laid out in a square horizontal grid conductors covering station with typical spacings that vary from 10 feet to 50 feet between parallel conductors. This spacing depends on soil, fault current, station size, and the location of the equipment. The higher the fault current, the denser the main grid spacing needs to be, all other factors remaining the same. As a result, older substations may not have a dense enough grid if the system has strengthened significantly. Large areas without equipment can be left uncovered if there are no step voltage issues since there is nothing to touch in those areas.

When selecting a conductor to use for the grounding system, the conductor must be sized to carry worst case fault without fusing. The rating of a given conductor is known as ampacity and depends on the conductor size and material. The conductor must be sized such that it can carry the maximum fault current that could flow through a given segment for the longest duration of the fault, while also taking into account the fault X/R ratio (increases fault's impacts due to asymmetry). Typical conductors are copper or copper clad steel due to their high conductivity. For a main grounding system, these conductors are usually size #2/0 AWG or #4/0 AWG, or an equivalent. However, typically a #4/0 AWG conductor is only rated for a little over 40,000 amperes for a fault clearing time of 0.5 seconds. As fault currents increase above this value, larger conductors need to be considered.

A substation will typically have a high resistivity surface layer added throughout the station. The goal of this layer is to add additional impedance to current flowing through body, thereby increasing allowable touch and step voltages. This layer is typically two to six inches (five to fifteen centimeters) thick, and the benefits of a thicker layer rarely outweigh the cost, not to mention the difficulty in driving though a very thick layer of gravel. The layer should extend no less than three feet beyond the grounding system in order to reduce touch and step voltages near the fence.

MITIGATION ANALYSIS

When upgrading an older substation, there are several techniques for improving the performance of a grounding system to meet the IEEE or IEC compliance limits, should the initial analysis of the main grounding grid system indicate that the compliance limits are exceeded. The use of additional horizontal ground conductor, ground rods, ground wells, and improved surfacing are all techniques that can be analyzed. Careful analysis of the reasoning behind the non-compliance, as well as understanding how the soil structure affects the grounding system performance, can result in a more feasible grounding system mitigation plan.

One major goal in substation grounding designs it to provide a low impedance path for fault current. In order to obtain this, the grounding conductors need to be in the lower resistivity soil at the site. Considering this goal can help determine whether additional ground grid conductor, ground rods, or ground wells are more effective as a mitigation technique.

Adding horizontal conductor to a grounding system works especially when upper soil layers are lower resistivity. By installing most copper in the lower resistivity upper soil layer it keeps the surface closer to equipotential and provides equipment ties that are needed.

Ground rods are most effective when top layer is higher resistivity, but lower resistivity layers accessible to the ground rod below. Specifically, rods can be very useful where a water table is less than 20 feet deep. Ground rods are typically 8 or 10 feet (2.5 to 3 meters) long and can be coupled for greater lengths, but usually this will not extend further than 20 to 40 feet (6 to 12 meters) as driving can become difficult. In addition, if ground rods are placed at the perimeter of the station, they also extend effective size of substation and reduce touch voltages. Because of their behavior in dissipating current, rods typically are not be placed closer together than length of rod as the effectiveness decreases.

Ground wells are the most expensive option of these three techniques, but may provide the most efficient grounding design. A ground well involves drilling a hole (typically six inches in diameter) to a significant depth (can vary from around 50 to over 500 feet). The goal is to reach a deeper lower resistivity layer (or water table), or may be used to get below frost depth in very northern sites. The drilled hole may use a steel casing to prevent cave-ins from the surrounding soil or be free standing (in stable/firm soils). A run of copper is inserted the entire length of the well and the hole is then typically backfilled with low resistivity material (bentonite, carbon, concrete/bentonite slurry, etc.).

If installing additional grounding material is ineffective or not cost efficient, improving the surfacing layer can provide a significant benefit. This approach may be as simple as adding clean crushed rock surfacing to a substation that presently has native soil, particularly in older stations. In a new substation built in very poor soil conditions, switching from gravel surfacing to asphalt can have a similar benefit, as the resistivity of asphalt is usually at least three times that of gravel.

FENCE UPGRADES

One of the common issues with older substations relates to grounding along the fence. As previously noted, many older substations did not have grounding outside the fence which is often the location with the highest touch voltages. If additional property allows, simply adding grounding loop(s) outside the fence and the area below the swing of outward opening gates will often resolve these issues. Other solutions may include adding an insulating surface layer (gravel or asphalt) within three feet of the fence.

However many older substations placed the fence on the property line and do not allow the installation of grounding or surfacing material outside the fence. In some instances, the fence can be moved inward a few feet into the existing substation, allowing grounding and surfacing outside, but in many instances existing equipment and clearances prevent this option.

Alternative Fence Designs and Grounding

Most traditional substations were built with basic chain link fencing topped with barbed wire. Due to various reasons including aesthetics and physical security requirements, several new types of fencing are being implemented. Some of these options are electrically similar (bare metal) to chain link fencing, but others present different challenges as they may be partially or fully non-conductive.

Coated Metallic Fences

A common type of partially-conductive fence includes fences coated with vinyl, paint, powder coating, or a similar type of environmental protective coating. These types of coatings pose challenges when it comes to grounding the fence as they do not always allow a proper metal-to-metal bond. As a result, proper connections must intentionally be made through connections such as self-tapping bolts, pre-welded bare metal grounding tabs, or by simply sanding and removing the coating prior to making a metallic bond.

The coatings may not provide significant insulation to protect an individual contacting the fence under fault conditions as the coating may fail at fairly low voltages, or provide no insulation if the coating is damaged. Because the coatings cannot be relied upon, coated fences should be grounded similar to traditional fences, but with additional care. Where a chain-link fence is naturally bonded together by typical construction techniques, care must be taken that each post, panel, and section of barb wire is properly electrically bonded. This may require grounding from the top of each post to the grounding system and adding intermediate bonds to the various components of the fence.

Non-Conductive Fences

A common form of a non-conductive perimeter to a substation is a concrete, block, or brick masonry wall. These fences provide significantly more security, possibly better aesthetics, and have the benefit of likely not requiring grounding. Therefore, masonry walls can be used on the property line with all grounding contained within the substation.

Several manufactures also produce non-conductive fencing material typically made of fiberglass and/or plastic materials. These materials do not present touch voltage scenarios due to the non-conductive construction possibly avoiding any external grounding requirements. These fences are generally more secure than traditional chain-link fencing, but may be less secure than high-security metallic fences or masonry walls.

With either non-conductive option, care must be taken at gate locations if the gate remains metallic and can be touched outside. Often the driveway area will allow either surfacing and/or grounding conductor installation to mitigate touch voltages on the gate if required. Non-conductive gate materials are also an option.

Barbwire is typically installed at the top of substation fences. Non-conductive fence materials pose a challenge as this barb wire can often still be contacted and therefore may need grounded. Solutions to this include non-conductive barbwire equivalents or placing the barbwire on the inside of a wall or at a height where it could not be contacted from outside and grounding it.

SUMMARY

Electrical system modifications resulting in increases of fault current require grounding designs to be reconsidered and often upgraded. Similarly, fence upgrades for physical security, or any other reason, to sites with inadequate grounding can pose significant challenges in constructing a practical and safe design. This paper identifies the main aspects of concern, mitigation design approaches, and security fence options to address these concerns.

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