WHITEPAPER:
Substation Grounding
Identifying and Implementing Cost-Saving Design Practices
INTRODUCTION
Substation grounding is critical to personnel safety and protection of electrical equipment. A ground fault event gives rise to a potential gradient within and around the substation. As a result, there is concern for the safety of people who may come within the influence of this potential gradient. This voltage potential gradient should not exceed the tolerable human body limit. Therefore, most utilities spare no expense when designing and implementing their substation ground grids. However, there are several aspects of ground grid design that can lend themselves to severe over design or under design, which could lead to unnecessary construction and materials costs, or could result in inadequate performance and unsafe conditions. A strong understanding of these aspects can result in a final design that is more optimized, and in which there is more confidence in the degree of uncertainty in the design performance results, so that additional design margin does not need to be applied excessively.

MAJOR INFLUENCING DESIGN FACTORS
There are many factors that influence the performance and cost of a substation ground grid. However, three of the most influential are soil resistivity, fault magnitude, and fault duration.

SOIL RESISTIVITY
The resistivity of the soil in the area of the substation must be properly characterized in order to accurately model and design the ground grid. It is probably the biggest source of uncertainty in a ground grid analysis due to the many variables involved, from testing to data interpretation and implementation.

Testing
There are many firms who perform soil resistivity testing, and like many things, everyone has their own way of going about it. Among the things that can differ from firm to firm are testing techniques and specifications (number and orientation of tests, pin spacing, test method, lead coupling), how to handle site physical accessibility constraints, and awareness and consideration of external influencing objects (buried metallic objects or overhead power lines). Without proper planning and consideration, all of these items can introduce errors in the data and add costs to a design.

Data Interpretation
Once the data has been obtained from the field, the data must be analyzed and interpreted. If multiple tests were performed, the data sets should be compared to one another, against the site plan, and against any available geotechnical data. Any questionable results should be investigated further. If the data is deemed invalid, new tests should be performed. Obviously, this can have impacts to schedule and budget.

Data Implementation
After the data has been scrutinized, an equivalent soil model must be created for use in the computer model. Selection of this model can introduce additional errors, depending on the type of model used (uniform soil, multi-layer, etc.). If poor or conflicting soil data is used from the interpretation phase, multiple soil models may be necessary during the analysis to create design boundaries. Seasonal variations (e.g., frozen soil) and their impacts on soil resistivity should be considered at this stage. Improper selection of the soil model will result in an improperly designed ground grid.

Because there are so many variances in the way soil data is obtained, interpreted, and modeled, there is no way to completely eliminate the uncertainty introduced by soil data. However, an experienced engineer can systematically reduce the uncertainty and increase confidence in the final model. By involving the engineer early in the process, he or she can evaluate the site prior to soil testing, specify the soil testing methods (or perform the tests themselves), and analyze the test results in real-time to quickly identify possible testing errors or effects from external sources.
FAULT MAGNITUDE
The magnitude of the fault current into the earth via the substation ground grid is directly proportional to the ground potential rise (GPR) at the substation. Therefore, this number should be as close to the real-world, worst-case scenario as possible, while accounting for future system growth. However, getting the correct earth current magnitude requires careful consideration and some analysis.

Data Quality and Applicability
All too often, the grounding design engineer utilizes maximum substation equipment fault ratings, or uses a number provided in a generic substation design criteria. Many times, three-phase fault data is provided, when in reality single- and double-line-to-ground fault data is what is required. These numbers are not provided in the context of a grounding analysis, so while they may be worst-case for one aspect of design, it may be the opposite for grounding, or vice versa.

For substations with multiple voltages, fault levels must be known at all voltage levels. The data should be specifically requested by the grounding design engineer, and he or she should specify exactly what is needed. Data should be provided by a system planning department, and should account for reasonable future growth. Fault data should include X/R ratios for all contributions.

Knowing what data to ask for, how to ask for it, and from whom, is critical to get the right data for the grounding analysis.

Split Factor and Contribution Analysis
It is not uncommon for grounding design engineers to take a conservative approach and assume 100% of the fault current goes into the earth, instead of analyzing the fault and other potential paths for the current to flow, such as shield wires and distribution neutrals. While this results in a conservative design, it does not represent what will happen in reality and therefore results in over-design. In some instances, the over-design may be marginal. However, most designs benefit greatly by accounting for the current division (or split) factor, and there are some facilities that cannot be made safe without it.

The split factor analysis requires quite a bit of additional data about the surrounding system, such as transmission and distribution line lengths and geometries, footing resistances, conductor types, remote substation grid impedance, etc. The grounding design engineer must assess the system and request the necessary information.

There are additional current contribution analyses that should be performed, aside from the individual contributions from transmission lines. Autotransformers play a unique role during a substation fault, and require a separate calculation for various fault locations to determine their effects. It is the obligation of the grounding design engineer to identify these scenarios and properly account for them in his or her design.

Fault magnitude is an important piece in grounding analysis. The data itself can come from different departments within a utility, using different software packages. Utilizing an engineer with experience in fault studies and system planning provides a single point of contact that is knowledgeable in the day-to-day activities of the various departments involved. An experienced engineer will also be able to properly identify and account for substation equipment that may positively or negatively impact the total earth current magnitude.

FAULT DURATION
The duration of the fault impacts the safe voltage thresholds for step and touch – the faster the fault clears, the less stringent the grounding design constraints will be. As with fault magnitude, there are many factors to consider in getting the appropriate fault clearing time. A good understanding of system protection principles expedites the process and aids in proper selection.

Data Applicability
Under normal circumstances, faults at any point in the system should be cleared by a primary protective device. The clearing time of the fault depends on the protective device settings and protection scheme, as well as mechanical characteristics of the interrupting device. Clearing times can vary dramatically throughout the system, on the order of tens of milliseconds to tens of seconds. During a grounding analysis, the fault duration should never be less than this normal operation clearing time.
In the event that primary protection fails, something in the system will eventually clear the fault. If there is a backup device for the failed equipment, the clearing time may be the same or similar to normal operation. However, common practice in grounding design is to assume the interrupting device itself failed (breaker failure), and a different (often remote) device must clear the fault. Since protective device margins must exist to allow for sectionalizing during faults, there is often an intentional delay built-in when a backup device will clear a fault outside its zone. If the clearing time is simply requested without context, it may not be known if the value is a normal operation or backup. The grounding design engineer should frame his or her request for clearing time information with these considerations in mind. He or she must also be aware of all reasonable possibilities of clearing times (particularly for different voltage levels within a substation), and properly consider all scenarios in the grounding design.

**Variable Clearing Time**

For lower voltage levels, inverse time-overcurrent protection is often implemented. The nature of this protection means the clearing time is inversely dependent on fault magnitude. Therefore, the grounding design engineer should be cognizant when performing a parametric analysis involving fault magnitudes, as lower fault levels could actually make things worse in these scenarios.

The fault duration can be affected by a number of factors, and there may be multiple fault durations to consider in a single substation. Utilizing an engineer with experience in system protection will provide additional insight into what factors should be considered when selecting a clearing time, in order to prevent choosing an overly conservative and unrealistic contingency case or an overly optimistic and risky normal operation case.

**CONCLUSION**

Substation grounding design is a complex process with many influencing factors. Some are fixed characteristics of the site or the system (e.g., grounding system size and geometry, electrical system network), or may be driven by utility standards (e.g., surface layer thickness and composition). While soil resistivity, fault magnitude, and fault duration can also be classified similarly, there is engineering judgment involved in determining the appropriate values to be used for these factors. Because of the uncertainties associated with determining these factors, there is often additional design margin added to cover the uncertainties, or worse, they may go un-considered and the design may be inadequate. The cost of over-design is simply the cost of unnecessary equipment installed in the ground, and associated construction and engineering labor. The cost of under-designing a substation can be more severe, if equipment or personnel are harmed during a fault event.

Experience in performing substation design analyses and calculations provides intuition into the detailed considerations to be made, questions to be asked, and ultimate design decisions that will result in a more optimized design. Using an engineering firm with the breadth and depth of knowledge in substation grounding and related areas can significantly reduce the chances of over or under design, ultimately providing cost savings for the end user.

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