Substantion Grounding Study Specification©

Introduction

A grounding study is required for *name of station*, a ______/______/______ kV substation located in *name of location* and connected to the following circuits:

- *number of lines* x ____ kV **overhead** lines
- *number of circuits* x ____ kV **buried** circuits
- …

Further details…

Station-Specific Attributes

Special attributes that can apply to some substations and should be mentioned, if known, are the following:

1. Nearby metallic urban infrastructure, water pipes in particular, cannot be ignored:
    a. Typically, for a distribution substation with multi-grounded neutrals, the water system acts as an extended grounding system and can considerably reduce touch and step voltages within and outside the substation periphery.
    b. For transmission substations that are isolated from the water system, earth potential gradients around the substation are exacerbated by the presence of nearby metallic water pipes or other such metallic infrastructure.
2. The same applies for major facilities next to the substation, such as power plants or industrial plants.
3. Large fault current levels.
4. Rock (at surface or shallow depth) or known high resistivity soil at site.
5. Geographic irregularities: significant slope, top of mountain/hill, nearby river/lake/quarry, etc.
6. The presence of one or more railroads, pipelines, fences, or other such long metallic structures running past the substation raises the concern of excessive touch and step voltages appearing along the metallic structures in question or even damage to these structures.
7. If the site is a brown field, measurements of soil resistivity on the substation property may be of limited value. In such a case, it is highly advisable to attempt to measure soil resistivity on larger adjacent tracts of land, if any can be found that are devoid of extensive buried metallic systems.
8. Below-grade power cables, especially on the high voltage side, which can have a considerable impact on fault current split and therefore upon the cost and performance of a substation grounding system, provided that the extent of these cables is sufficiently great.

General Requirements

A conceptual grounding design study is required that will satisfy the following requirements:

1. Provide a safe and cost-effective conceptual grounding system design for the substation by means of accurate calculations properly accounting for a realistic approximation of the soil structure (typically a multi-layered soil structure), attenuation along ground conductors (i.e., no equipotential conductor assumption for electrically large grounding systems), inductive coupling between ground conductors (if applicable), circulating currents in the grounding system, fault current split between the substation grounding system and power line ground return conductors, and interactions with outside metallic infrastructure.

2. Meet touch voltage and step voltage tolerable limits and conductor ampacity limits, determined in accordance with IEEE Standard 80, during worst case fault conditions. Touch and step voltage limits are to be met both inside the substation and around its periphery, including metallic infrastructure in close proximity to the substation.

Detailed Design Criteria

The study shall be carried out in conformity with the design guidelines listed below and the computer software used for the design calculations shall take into account all of the factors listed:

1. **Soil Testing.** Soil testing shall be made using the Wenner 4-pin method specified in IEEE Standard 81 Part 1. For each measurement traverse, pin spacings (between adjacent pins) shall begin at 6 to 12" and increase thereafter by a factor of approximately 1.5, up to the maximum pin spacing chosen for that traverse. It is highly desirable to have 2 to 3 traverses centered at different locations, whose maximum pin spacing (between adjacent pins) reaches a distance that exceeds the maximum extent of the substation, i.e., its largest diagonal dimension (and any other facility associated with the substation), preferably twice this diagonal dimension or more, while avoiding the influence of buried metallic structures. A number of additional shorter traverses (6" up to 20') are required to obtain data sufficiently representing soil conditions at shallower depths throughout the site. The equipment used shall be accurate to the maximum required pin spacings, for the soil conditions encountered at the site: equipment that can apply low frequency alternating polarity square wave pulses at voltages of up to 400 V and provide power of up to 200 W may be required.

   The recommended pin to pin spacings for a Wenner configuration are as follows:

Very Short Spacing (feet)	Short Spacing (feet)	Moderate Spacing (feet)	Large Spacing (feet)	Very Large Spacing (feet)
-	1	10	100	1000
-	2	20	200	2000
0.3	3	30	300	3000
0.5	5	50	500	5000
0.7	7	70	700	7000

Very Short Spacing (m)	Short Spacing (m)	Moderate Spacing (m)	Large Spacing (m)	Very Large Spacing (m)
0.1	1	10	100	1000
0.2	2	20	200	2000
0.3	3	30	300	3000
0.5	5	50	500	-
0.7	7	70	700	-

   Given the capital importance of the soil resistivity data for adequate grounding system design calculations, a well-defined quality control program is required in the field to demonstrate that readings are valid. This includes, as a minimum, reporting of the measured signal voltage, injected current, and standard deviation between pulses of alternating polarity, for each pin spacing and evidence that the instrument provides accurate results for the measured signal voltages and injected currents.

2. **Soil Resistivity Data Inversion.** The measured soil resistivity data shall be inverted in order to obtain equivalent multi-layer soils to be used in the subsequent grounding study. This interpretation shall account for electrode pin depth, any irregular pin spacings (due to obstacles in the field) and known buried metallic structures that mildly to moderately distort the measured values. One or more suitable soil models shall be chosen for the study from those obtained from all measurement traverses and the choice shall be explained in the final report. Any approximations to the soil model shall be justified. Soil structure model variations due to local and seasonal variations shall be accounted for by developing soil model structure limiting cases.

3. **Soil Model for Grounding Study.** Soil layers down to depths on the same order as the extent of the substation (and any associated facilities) can have a significant impact on its performance. It is anticipated that three or more soil layers may be required in the computer model to adequately represent the grounding medium. Provide graphs of measured apparent resistivity versus computer apparent resistivity curve for each measurement traverse, in order to demonstrate that the soil models chosen for the study adequately represent the actual soil's electrical structure.

4. **Grounding System Reactance.** Account for the attenuation along (i.e., longitudinal impedances of) grounding grid conductors, which can result in a reactive component of the grounding system impedance that is on the order of ten times the value of the resistive component for large substations. If applicable (e.g., GIS structures), take into consideration inductive coupling between grid conductors. These factors can have a considerable impact on the potential rise of the grounding grid and on the measured ground impedance.

5. **Circulating Currents and Voltage Drop in Grid Conductors.** Model circulating currents within the substation grounding grid and account for the voltage drop in grid conductors through which current is flowing, in order to correctly calculate touch and step voltages. The largest voltage drops will occur for faults occurring far from the transformers. For large substations, faults occurring at different locations within the substation shall be modeled in order to demonstrate that safety has been achieved for all fault locations studied.

6. **Conductive Coupling with Nearby Infrastructure.** Model interactions with surrounding metallic infrastructure (water and gas pipelines, railways, fencing, neighboring facilities, communications cables, etc.), which can considerably alter the substation grounding performance both favorably and unfavorably and also represent transferred potential concerns that must be investigated. Any nearby conductors that are imperfectly insulated from ground, such as coated pipelines and railways on ballast shall be included in the model, with their leakage resistances and longitudinal impedances properly represented. Note that inductive coupling with parallel power lines may also occur and must be considered if significant near-parallel exposure occurs.

7. **Fault Current Split Calculation.** A fault current split calculation shall be carried out based on a circuit model of the high and low voltage power line systems connected to the substation, including the remote substations whose transformers contribute fault current, in order to correctly determine the fault current distribution between the substation grounding system and power line ground return conductors, such as neutral and shield wires. The circuit model shall properly account for overhead and buried circuit characteristics, including conductor impedances, inductive coupling between conductors, leakage and ground impedances. The fault current split calculation shall consider faults occurring not only within the substation but also on circuits outside the substation, in order to determine the worst case fault location.

8. **Contingencies.** Consider the following contingencies and demonstrate that touch and step voltages remain satisfactory:

    a. One line down: phase and shield wires become disconnected from substation

    b. Loss of 10% of ground rods, evenly distributed throughout substation

9. **Conductor Ampacity Calculation**. Compute the required grounding conductor size, such that the maximum anticipated fault current can be carried, with the worst case asymmetrical transient offset

magnitude and backup fault duration, without damaging the conductor, based on the methodology specified in IEEE Standard 80.

10. **Touch and Step Voltage Limits**. Calculate tolerable safety limits in accordance with IEEE Standard 80 and demonstrate that they are met by the proposed grounding design.

11. **Grounding Design**. Provide a conceptual grounding system design for the substation, including specification of conductor size and depth, crushed rock or asphalt resistivity and thickness, in accordance with the above design criteria. The grounding design shall indicate the placement of horizontal grid conductors and ground rods for the grounding system: a DXF file from which exact dimensions can be obtained shall be provided such that detailed drawings can be made based on Owner's standard specifications.

12. **Recommended Software Packages**. The following industry standard software packages are strongly recommended. Alternative software packages can be used if it is proven that they have similar capabilities and that they can perform similar types of computations accurately.

    - **Classical Grounding Studies (Low Frequency, Equipotential Systems):** *MultiGround and MultiGround-Plus Software Packages.* This software is suited for grounding studies of electrically small installations where circulating currents within the grid are negligible, where above ground structures and busses are not relevant for the study and where extensive external metallic infrastructure does not exist close to the substation.

    - **Extended Grounding Studies:** *MultiGroundZ and MultiGroundZ-Plus Software Packages.* This software is suitable for grounding systems of any size. It accounts for the impedance of the conductors making up the grounding system and allows currents to be injected into the system at any number of locations, thus accounting for the effects of circulating currents. This software can also represent long insulated conductors, such as pipelines and railways. It does not, however, model overhead conductors, nor account for inductive or capacitive coupling effects between conductors: this can be done with MultiFields (see below)

    - **Electromagnetic Fields Based Studies (Grounding, EMI, Lightning and Transient Analysis).** *MultiFields and MultiFields-Plus Software Packages.* This software accounts not only for conductor impedance, but also for inductive, capacitive and conductive coupling between all conductors modeled, allowing the user to specify any number of horizontal soil layers and both overhead and buried conductors. Furthermore, in addition to the results computed by MultiGroundZ, this package also computes electric and magnetic fields in air and in soil. MultiFields can be used not only for grounding studies, but also for electromagnetic compatibility studies, safety studies involving induction or capacitive coupling, modeling of grounding grid impedance testing with long leads (and the associated inductive coupling between leads, grounding conductors and overhead conductors). It supports transformer models, cable conductors and GIS structure models.

13. **Final Report**. A final report shall be submitted summarizing the data, assumptions, computer models, computation results, conclusions and recommendations, including proposed conceptual substation grounding design. The final report shall include the following computation results:

    a. Effective substation grounding grid impedance (magnitude and angle) for fault current injection at high voltage transformer,

    b. Summary of fault current split calculation results,

    c. Summary of ampacity calculation results,

    d. Summary of tolerable touch and step voltage limit calculation results,

    e. Plan-view plots of substation grounding grid potential rise for all scenarios studied,

f. Plan-view plots of potential rise of any nearby metallic infrastructure modeled, for worst case scenario,

g. Plan-view plots of touch and step voltages throughout the substation and around its periphery, for all scenarios studied.

h. Plan-view plots of touch and step voltages associated with any nearby metallic infrastructure modeled, for worst case scenario,

i. Graphs comparing measured apparent soil resistivity data with values computed from soil model obtained from field data inversion.

Additional Situation-Specific Design Tasks

The following additional requirements apply to this grounding study:

1. **Substation Grounding Grid Test**. Provide a detailed methodology to test the grounding system after construction.
2. **Simulation of Grounding Grid Test**. Simulate the grounding system test, accounting for magnetic field induction between test leads and other conductors, such as transmission and distribution line ground return conductors, grounding grid conductors, water pipes, etc. Also account for conductive coupling between test electrodes, the grounding grid and surrounding infrastructure, in order to provide expected test results that will validate the study predictions.
3. **Zone of Influence**. Determine the extent of the 300 V contour line, accounting for the influence of transmission and distribution line structures and other nearby infrastructure.
4. **Construction Scenarios**. Safety calculations for various construction scenarios.
5. **Detailed Analysis and Mitigation for Nearby Infrastructure**. Design corrective measures for infrastructure on which a touch or step voltage concern has been identified, accounting for both conductive coupling with the substation (and nearby structure grounds) and any inductive coupling with power line circuits associated with the substation.
6. **EMI in Communications/Control Cables**. Calculation of electromagnetic interference in low voltage circuits.
7. **Transients.** Calculations related to steep wave front transients (as compared with 60 Hz fault conditions, with asymmetric component), such as those associated with lightning surges and switching operations.
8. **Lightning Shielding Study**. Create a 3-dimensional model of aboveground structures that must be protected from lightning strikes, along with intentional and non-intentional shielding structures (e.g., structural steel, shield wires, lightning masts, air terminals). Analyze the shielding effectiveness based on the electrogeometric method specified in IEEE Standard 998 and IEC EN 62305. Provide a conceptual shielding design that will yield the required protection.
9. **Gas-Insulated Substation**. Determination of current flow in GIS and assessment of required ground connections to substation grounding grid.
10. **Interactions between Buswork and Grounding Grid.** For very large stations, inductive coupling between phase conductors (lines or buswork) and the grounding grid can have a significant impact on the performance of the grounding system. These interactions are to be studied.

Owner's Responsibilities

Owner shall provide the following assistance:

1. Access to the substation site, for soil resistivity measurements, after final earth moving, but prior to installation of any substation equipment or structures, including fencing and reinforced concrete. This shall be at a time when no major construction activity is occurring.
2. Access to areas outside substation, for soil resistivity measurements: these areas are to be determined from study of local maps.
3. All data required to carry out the study (see below), except for soil resistivity measurements, which are to be carried out by Consultant.

Outline of Data to be Provided by Owner for Standard Grounding Study:

The following is a summary of the data that shall be provided by Owner for the study, with all maps and drawings to be provided in electronic format:

1. GPS coordinates of site.
2. General description of substation.
3. General equipment arrangement plan.
4. Single line diagrams of the transmission and distribution systems associated with the substation, both within and outside the substation, indicating buried/overhead components and distances between stations.
5. Fault current data: worst case horizon values. Provide breakdown of contributions from all circuits and substation transformers.
6. Fault clearing time and X/R ratio.
7. Transmission and distribution line details for fault current split calculation (e.g., typical circuit cross section, conductor/cable details, structure/manhole grounding, average span length, distance to each source of fault current, etc.).
8. Maps showing lengths of overhead/buried portions of transmission and distribution power lines connected to the substation, up to major transformer sources of fault current.
9. Plan and profile drawings of transmission and distribution lines associated with the substation, if requested by Consultant.
10. Maps, in electronic format, showing metallic or reinforced concrete infrastructure outside the substation: e.g., pipelines, railways, metallic fences, facilities, communications cables, etc.
11. Map showing areas around substation within radius of 1 mile where soil resistivity measurements can (or cannot!) be made.
12. Grounding and general arrangement plans of any major adjacent facilities.
13. Grading information, frost line.
14. If known, minimum resistivity, when wet, of available crushed stone.

Consultant shall compile a list of any additional data required, at the start of the study.

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