Grounding of Urban GIS Substation Connected to Commercial Buildings and Metallic Infrastructures

Zhang Jinsong, Qian Feng, Guo Bing, Yexu Li, and Farid Dawalibi

***Abstract*—This paper examines various aspects of the design process of an urban Gas insulate Switchgear (GIS) complex substation grounding system. The study shows how advanced simulation approaches can be used to study complex grounding systems involving gas-insulated substations and massive connected metallic infrastructure in an urban environment by following the IEEE 80-2000 recommendations and requirements. It describes why it is important to model accurately the GIS structure, ground conductors, massive reinforced steel rebar, residential neutrals, surrounding commercial buildings and residential water pipe infrastructures as well as correctly simulate fault currents and circulating currents in order to determine touch voltages accurately and avoid overestimating or underestimating them. A parametric sensitivity analysis are performed. It is shown that bonding of an urban substation grounding system to the urban city buried metallic infrastructures, in most cases, enhances the safety status inside the substation while ensuring that the transferred voltages to the city metallic infrastructures will not endanger the safety of people in the zone of influence. Furthermore, this paper suggests that the grounding grid installed beneath the GIS system does not have a major influence on the grounding grid or GIS performance. However, the method of bonding the GIS to the rebar or to the grounding system can significantly modify the building and GIS safety status. Finally, the paper demonstrates that the urban substation grounding grid performance is not very sensitive to the type of soil structures in which the system is buried due to the surrounding city buried metallic network and building rebar which are typically directly or indirectly connected to the grounding system providing thus a significant damper on the effects of soil characteristics changes.**

***Index Terms*—Urban substation, GIS, grounding, metallic infrastructures, touch & step voltages, ground potential rise (GPR).**

I. Introduction

The grounding system is the fundamental component that controls excessive overvoltages and ensures safety within a substation in the power system. It is directly related to the stability of the power grid, the integrity and operational safety inside or nearby the substation. Surveys show that in China of several power network devices and the safety of personnel many accidents and incidents occur due to inappropriate grounding system design, i.e., the substation grounding system does not meet the operational and safety requirements. Every incident caused by the grounding system can cause not only immediate and direct financial losses, but also more serious indirect economic losses related to social and economic development.

On the other hand, with the rapid growth of China national economy, the power system grid is expanding rapidly and short circuit current levels are increasing significantly. As a result, appropriate substation grounding system must be designed, tested, and implemented in order to ensure the safety of the substation personnel and to enhance the life expectancy of the substation equipment and infrastructure. Consequently, the design and construction of conventional grounding systems are mandated to follow various criteria (e.g., IEEE Guide 80 and GB50065-2011). Various national and international guidelines and standards have also been widely recognized and applied.

Meanwhile, in order to minimize the required substation area and enhance the aesthetic look of the substation construction, gas-insulated substations (GIS) are widely used, mainly in urban city nowadays. A GIS is a high voltage substation in which the major structures are contained in a sealed environment with sulfur hexafluoride gas as the insulating medium. GIS technology was developed to make substations as compact as possible. The clearance required for phase to phase and phase to ground for all equipment is much lower than that required in an air insulated substation. The total space required for a GIS is probably only 10% of that needed for a conventional substation. Furthermore, Gas insulated substations offer other advantages in addition to the reduced space requirements. Because the substation is enclosed in a building, a GIS is less sensitive to pollution, as well as salt, sand or large amounts of snow. Although the initial cost of building a GIS is higher than building an air insulated substation, the operation and maintenance costs of a GIS are less.

For suburban conventional substation, the perimeter is closed to the public. Few personnel, most of them are professionals, can access the substation. Therefore, the grounding system is satisfactory as long as it meets the national standard or guidelines. For urban substation, however, the substation grounding system is connected directly or indirectly to the surrounding civilian facilities (such as residential neutrals and pipes, commercial buildings, etc.). In this case, the grounding system is extended to a much larger area and the grounding impedance is reduced. However, in the event of a short circuit, earth fault current can in the surrounding buried metallic infrastructure where it will be dissipated into the soil. It is therefore legitimate to determine if this will threaten the integrity of adjacent civilian facilities and become a concern to public personnel safety.

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An urban GIS substation grounding system design is a complicated task in order to provide an adequate system that meets specific criteria with regards to personnel safety and integrity of equipment during a fault condition. There are a few additional challenges unique to GIS grounding computer simulation approaches. First, given an urban location, the site offers limited space for the grounding system and requires that the grounding analysis accounts for interactions with the metallic infrastructure outside the substation, such as water and gas pipes. Second, for GIS, induction between faulted phase conductors and associated enclosures can result in circulating currents that generate sufficient voltage drop between switchgear enclosures and the grounding grid to warrant special analysis. Third, due to large fault current levels that exist nowadays, the grounding design should be satisfactory for a total single-phase-to-ground fault current of 60 kA and preferably more. Finally, often, an urban GIS station is connected to other substations through underground cables. Sheaths, vaults and ground continuity conductors of the cable circuits that connect to the GIS station must be analyzed to account for the current returning back to the remote sources as well as dissipating into the earth through the existing grounding systems installed along the cable circuits.

Therefore, how to accurately model the GIS structure, ground conductors, massive reinforced steel rebar and adjacent infrastructures and correctly simulate fault currents become crucial. Previous studies have already been carried out on this related subject [1]-[7]. This paper presents a grounding study for such an urban GIS situation using an advanced grounding and EMF analysis software package [7] based on the safety criteria provided by IEEE Standard 80-2000 [1] and GB/T 50065-2011[2].

II. Computation Methodology

The computation is performed in the frequency domain for a single 50 Hz harmonic current. The computation method accounts for both the buried and above ground metallic components of the system which could be bare or coated conductors and considers the electromagnetic interactions between all elements and supports multilayer soils with arbitrary characteristics. A field theory approach is used to solve Maxwell's electromagnetic field equations. The field theory approach used in the computation module is an extension to power frequencies of the Moment Method used in antenna theory. This approach takes induction effects fully into account. In other words, the computation results contain the combined effects of the inductive, conductive and capacitive interference.

The method approach is an exact method that eliminates all of the assumptions in the conventional method, such as equipotential, and takes into account circulating currents and modeling exact cables as well. It accounts for attenuation, phase-shift and propagation effects in the electromagnetic fields when moving away from the current sources. It models correctly and accurately the GIS phase conductors and enclosures that play a major role in discharging more realistically and accurately the fault current along the GIS structure ground bonding locations that are connected to the grounding grid through the steel rebar in concrete.

III. System Studied

The substation under study is situated upon approximately 66m by 49.5 m land. The substation functions as a medium voltage distribution substation. The highest operating voltage is 110 kV. The station is inside a commercial building. The metallic steel rebar of an indoor large parking lot and the rest of the building are interconnected to the GIS station grounding system. Fig. 1 shows a perspective view of the system under study. Fig. 2 shows a three-dimensional view of a portion of the GIS structure.

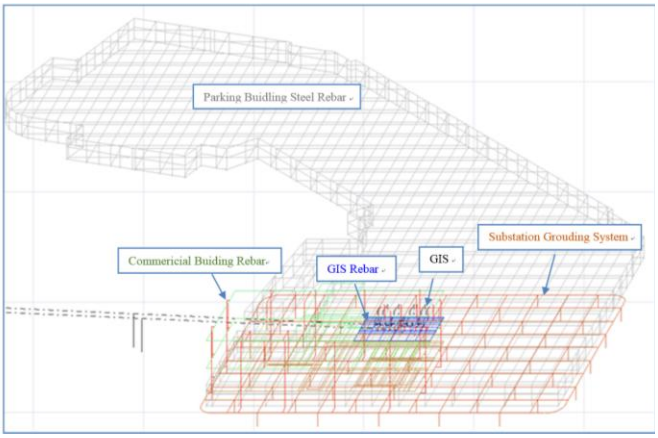

Fig. 1. Perspective view of the system under study.

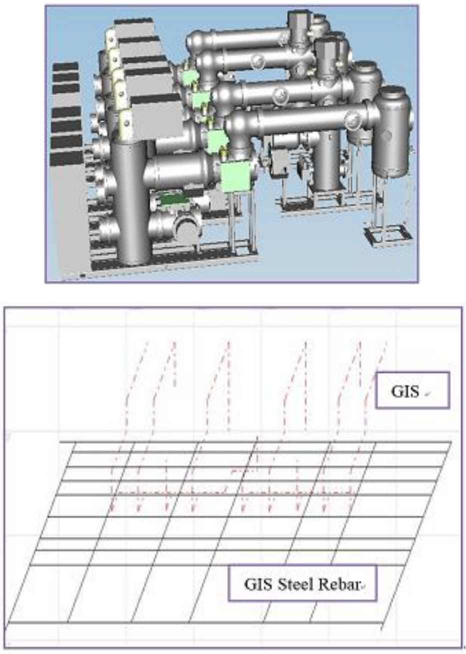

Fig. 2. Three-dimensional view of a portion of the 110kV GIS structure and its computer model equivalent.

Soil resistivity measurements constitute the basis of any grounding study. Soil resistivity measurements were made at a few representative and accessible locations in the substation area. An interpretation of the soil resistivity measurements was carried out and analyzed. For simplicity, a resistivity of 28 ohm-m uniform soil was used in most computation results presented in this paper.

IV. Fault Current Distribution

The objective of the fault current split calculations is to obtain the earth current (current discharged by the grounding system to earth). Under most conditions, the total fault current doesn't discharge entirely in the substation grounding system. Part of the fault current, which does not contribute to the average ground potential rise (GPR) of the grounding system, will return to remote source terminals and to transformer neutrals through shield wires, neutral wires or conductors of the grid.

It is well known that the GPR and the touch and step voltages associated with a grounding network are directly proportional to the magnitude of the fault current component discharged directly into the soil by the grounding network. It is therefore important to determine how much of the fault current returns to remote sources via overhead ground wires and neutral wires of the transmission lines and distribution lines connected to the substation.

TABLE I: Fault Current Split Calculation Results

	Station #1	Station #1
Remote contribution	11.94 ∠-85°kA	11.45 ∠-85°kA
Current returning via OHGW	10.89 ∠13.6°kA	10.42 ∠13.6°kA
Earth current discharged in grid	2.62 ∠-61.8°kA	2.79 ∠-61.8°kA

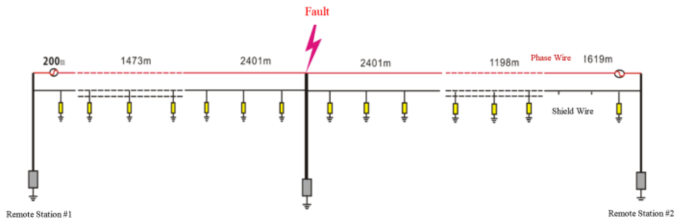

Fig. 3. Fault current distribution computation circuit model.

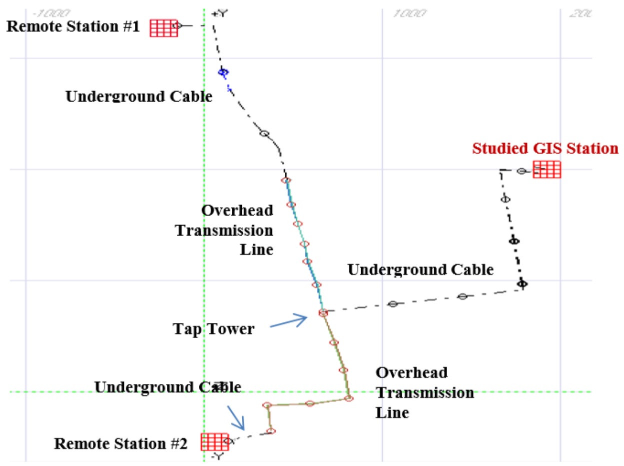

Fig. 4. Fault current distribution computation field approach model.

Computer simulations have been performed using both Right-Of-Way (based on a circuit approach) and MultiFields (based on a field approach) software packages described in [7]. The results are shown in Fig. 3 and Fig. 4, respectively, representing the scenario of a 110 kV single-line-to-ground fault at the GIS station. Fig. 3 and Fig. 4 also show the fault current contributions from the two remote sources. Table I provides the results of fault current distribution calculation. The values shown in Table I have been used in the grounding grid analysis. The earth currents discharged by the grounding systems were determined to be about 22 to 24% of the total fault current.

V. Grounding System Performance Analysis

GPR, touch and step voltages are important quantities when a substation is assessed for safety during fault conditions. In order to consider the infrastructure outside the substation, a full network computer model was built for the grounding system. Fig. 5 shows the model considering all grounding systems, including GIS, commercial building rebar, parking lot rebar, cables and water pipes, etc.

Various cases have been analyzed and touch and step voltages all over the substation and residential water pipes have been examined. However, in this paper, only the results for a typical case are reported to illustrate the system performance.

Fig. 5. Complete computer model for safety evaluation at the substation.

TABLE II: Safety Evaluation

Maximum Value (V)	Grounding Grid	GIS	Parking Lot	Building	Water Pipes
GPR	246	243	245	246	175
Touch Voltage	37.0	16.3	27.0	45.9	88.4
Step Voltage	35.0	10.7	34.5	7.7	35.0
Earth Potential	257.2	243.4	246.2	242.3	257.2

Fig. 6 shows the touch voltages computed throughout the substation when the fault is outside the GIS building but near the GIS end. The maximum computed substation touch voltage is 29.5 V and it occurs at the commercial building of the station. This value is well below the touch voltage limit of 132.7 V. Furthermore, the touch voltages outside the substation, near water pipes for example, are also below the 132.7 V safe limit. Fig. 7 shows the touch voltages along waters pipes within an area of about 5 km outside the GIS substation.

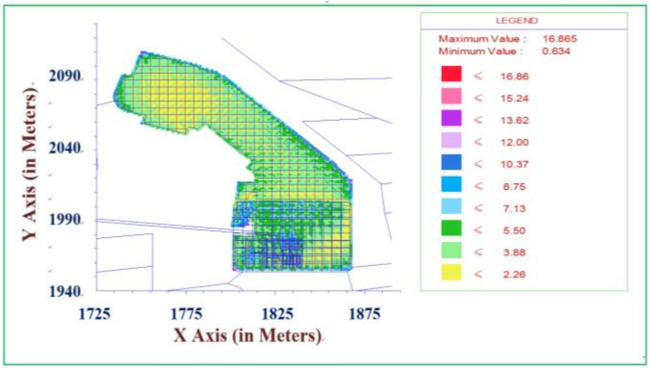

Fig. 6 . Touch voltages at the GIS substation (Volts).

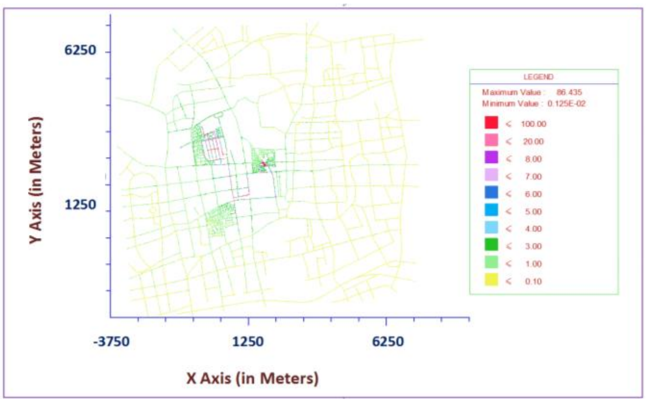

Fig. 7. Touch voltages on pipes 5 km around the GIS substation.

VI. Sensitivity Analysis

In this section several grounding network features and parameters that are often related to an urban GIS substation performance were analyzed to demonstrate their effects on the results due to uncertainty on some basic data or alternative design options and contingency conditions.

A. Bonding of the Grounding System to City Buried Metallic Infrastructures

In general, in an urban area, the low voltage distribution neutrals and the city metallic infrastructure such as the residential water pipe network are inevitably directly or indirectly connected to the substation grid. Their omission in the computer model can cause negligible or significant inaccuracies in the computed grounding performance depending on the topology of the electrical network. This is because the power line fault currents can dissipate easily in the metallic infrastructures, a situation that, in most cases, enhances the safety status inside the substation. On the other hand, the transferred voltages to the city metallic infrastructure may endanger the safety of people in the zones outside the substation.

Realistic computer models including a skeleton of the extensive urban business and residential metallic pipe network (see Fig. 5) were modeled. In order to examine the effect of the pipe network on the system performance, a study was conducted with and without the metallic pipes included in the model. The results are presented in Table III. As can be seen, the GPR, touch and step voltages can be very different if water pipes are not considered. The maximum GPR with water pipes is about 33% less than when the water pipes are ignored.

TABLE III: GPR, Touch and Step Voltages with & without Considering Water Pipes TABLE IV GPR, Touch and Step Voltages with & without Grid Under GIS Rebar

Scenario	Maximum GPR (V)		Maximum Touch Voltage (V)			Maximum Step Voltage (V)
	Grounding Grid	GIS	Grounding Grid	GIS	Parking Lot	
With Water Pipes	246	243	37.0	16.3	27.0	35.0
Without Water Pipes	511	498	90.6	22.1	56.4	80.3

B. Effects of Installing a Grounding Grid under the GIS Enclosure

A study regarding the effects of installing a grounding grid under the GIS enclosure was carried out. The grounding grid beneath the GIS rebar was removed and the performance of the grounding system was evaluated. Table IV presents the results for scenarios that include or exclude the grid under the GIS rebar. As can be seen, adding a grid under the GIS enclosure will only improve slightly the overall performance of the grounding grid system. In other words, this grid beneath the GIS does not have a major influence on the grounding grid or GIS performance.

TABLE IV: GPR, Touch and Step Voltages with & without Grid Under GIS Rebar

Scenario	Maximum GPR (V)		Maximum Touch Voltage (V)			Maximum Step Voltage (V)
	Grounding Grid	GIS	Grounding Grid	GIS	Parking Lot	
No Grid under GIS Rebar	246	243	37.0	16.3	27.0	35.0
With Grid under GIS Rebar	253	245	37.5	17.1	27.1	35.2

TABLE V: GPR, Touch and Step Voltages with Building Rebar Connected and Disconnected from the Grounding Grid

Scenario	Maximum GPR (V)		Maximum Touch Voltage (V)			Maximum Step Voltage (V)
	Grounding Grid	GIS	Grounding Grid	GIS	Parking Lot	
Building Rebar Connected	246	243	37.0	16.3	27.0	35.0
Building Rebar Disconnected	263	267	49.4	20.9	28.0	48.2

C. Connecting or Disconnecting the Commercial Parking Lot Rebar from the Grounding Grid

The steel rebar in the GIS enclosure is usually bonded to the grounding system. The bonding method is one of the challenges in the GIS design. In order to assess the feasibility and efficiency of the bonding method as well as for the purpose of comparison from a safety perspective, two scenarios were analyzed: 1) rebar connected to the grounding system; 2) rebar not connected to the grounding system.

Table V shows that the GPR and touch voltages higher when the rebars are disconnected from the grounding system.

D. Equations Soil Uncertainty

It is known that grounding system performance and safety are closely related to soil characteristics. The performance of the grounding grid is heavily dependent on the soil structure. This study focuses on the effects of possible variations of soil structure on the studied urban substation grounding performance. Three soil models were used to carry out the soil sensitivity study. Soil Model 1 is a 28 ohm-m uniform soil; Soil Model 2 is a two-layer model with a low soil resistivity top layer over a high soil resistivity bottom layer. Soil Model 3 is also a two-layer soil model but with a high soil resistivity top layer over a low soil resistivity bottom layer. Table VI describes the three soil model structures.

The computed results are shown in Table VII. The touch and step voltages are safe everywhere for all three soil cases. As can be seen, the urban substation grounding grid performance is not very sensitive to the soil structure models. Note that normally soil variations should remain within narrow limits, and will not change as dramatically as shown in this paper. This is due to the fact that the city buried metallic network and commercial building rebar which are connected to the grounding grid provides a significant damper on the effects of soil characteristics changes.

TABLE VI: THREE SOIL MODELS USED IN SOIL SENSITIVITY STUDY

Soil Model Number	Layer	Soil Resistivity (Ohm-m)	Thickness (feet)
1	1	28	∞
2	1	20	1.5
	2	500	∞
3	1	500	1.5
	2	20	∞

TABLE VII: GPR, TOUCH AND STEP VOLTAGES WITH THREE DIFFERENT SOIL MODELS

Soil Model Number	Maximum GPR (V)		Maximum Touch Voltage (V)			Maximum Step Voltage (V)
	Grounding Grid	GIS	Grounding Grid	GIS	Parking Lot	
1	246	243	37.0	16.3	27.0	35.0
2	899	891	31.3	17.7	32.5	28.9
3	557	550	177	40.2	121.1	156.0

VII. SUMMARY

The performance of an urban GIS substation grounding system has been analyzed using modern computer techniques. The paper shows how advanced simulation approaches can be used to study complex grounding systems involving gas-insulated substations and massive connected metallic infrastructure in an urban environment by following international standards recommendations and requirements. It is necessary to model accurately the GIS structure, ground conductors, massive reinforced steel rebar, residential neutrals, surrounding commercial buildings and water pipe infrastructure as well as correctly simulate fault currents including circulating currents in order to determine touch voltages accurately and avoid overestimating or underestimating them.

For an urban GIS substation, bonding of an urban substation grounding system to the city buried metallic infrastructure, in most cases, will enhance the safety status inside the substation. However, it is important to ensure that the transferred voltages to the surrounding city metallic infrastructure will not endanger the safety of people in the zones of significant influence. The grounding system located under the GIS building does not have a major influence on the overall grounding grid or GIS performance. However, connecting or disconnecting the GIS building rebar to the grounding system can significantly alter the building and GIS safety status. Finally, the urban substation grounding grid performance is not very sensitive to the soil structure models due to the fact that the city buried metallic network and commercial building rebar which are connected to the substation grounding grid provides a significant damper on the effects of soil characteristics changes.

REFERENCES

[1] *IEEE Guide for Safety in AC Substation Grounding*, IEEE Standard 80-2000.

[2] GB/T 50065-2011, *Code for Design of AC Electrical Installations Earthing*, China planning press, December 5, 2011.

[3] F. P. Dawalibi and D. Mukhekar, "Ground electrode resistance measurement in nonuniform soils," *IEEE Transactions*, vol. PAS-93, no. 1, pp. 109-116, Jan. 1974.

[4] G. Yu, J. Ma, and F. P. Dawalibi, "Effect of soil structures on grounding systems consisting of steel conductors," in *Proc. the International Conference on Electrical Engineering (ICEE'2001)*, Xian, China, July 22-26, 2001.

[5] Y. Li, J. Ma, and F. P. Dawalibi, "Power grounding safety: Copper grounding systems vs. steel grounding systems," in *Proc. the International Conference on Power System Technology (POWERCON2006)*, Chongqing, China, October 22-26, 2006.

[6] J. Liu and F. P. Dawalibi, "Gas insulated substation grounding system design using the electromagnetic field method," in *Proc. 5th International Conference on Electricity Distribution*, CICED, Shanghai, China, September 5-6, 2012.

[7] CDEGS Software Package, *Safe Engineering Services & technologies ltd.*, Laval, Quebec, Canada, Version 15, June 2014.

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