Overview on computational methods of *Gas Insulated Substation* grounding grid analysis

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***Abstract*—The following paper presents an overview of the current state of art on the subject of Gas Insulated Substation (GIS) technology in order to understand the necessity of the grounding grid design models. Furthermore, different studies regarding existing applied technologies are considered in order to create an accurate review on GIS grounding models. For a better understanding of current GIS modeling methods an evaluation of the procedures regarding GIS grounding system design is conducted. The focus was to identify a suitable model technique for the GIS assemble and to obtain a proper grounding grid design procedure.**

Keywords—Gas Insulated Substation;grounding grids; modelling methods.

I. Introduction

Gas Insulated Substations have found a gradually wide range of applications in energy industry over the last three decades, as a result of their high reliability, easy maintenance and reduced ground space requirements [1]. Moreover, recent studies confirm that the GIS substation has a lower environmental impact than the Air Insulated Substation [2].Beside the overvoltage applicable to conventional substation, GIS are exposed to different overvoltage and enforce additional mechanism of protection due to non-self-restoring characteristic of the insulating environment - SF6 gas.

Despite of the advancement of electrical measurement techniques and equipment, quantifying the very fast transient overvoltage (VFTO) remains a challenging subject. Digital simulations of overall substation behavior during these fast transients may be very helpful to investigate the problem and develop designing grounding systems procedures. Several digital models are adopted by different studies, mentioned in this paper. [1-7]

This paper presents the actual grounding grid design procedures for GIS used in practical cases including a new approach from electromagnetic compatibility point of view. From a constructive point of view GIS grounding grid design procedures can be classified in three categories: i) grounding grid for urban indoor Gas Insulated Substation (usually incorporated into a building with several floors); ii) grounding grid for Gas Insulated Substation situated outside of urban areas; iii) adapting GIS grounding grid to an existent grounding system.

The models adopted for electromagnetic simulations, including the earth effects, are based on following different approaches: 1) Electromagnetic field theory; 2) Transmission line theory; 3) Hybrid methods; 4) Circuit theory. This classification is not rigorous but is generally adopted in the literature. Three basic analytical concepts are used to simulate the transient behavior of grounding systems: circuit approach, transmission line approach, and electromagnetic field approach. The electromagnetic field approach describes the problem in frequency domain by rigorously applying the full set of Maxwell's equations, with minimal assumptions, and can be applied in both grounding grid design procedure and very fast transient analysis.

II. Fast and Very Fast Transients Overvoltage Influencing the Grounding Grid Performance

Very Fast Transient Overvoltage is generated during the switching operation and lightning stroke, as well as other events like operation of a circuit breaker, closing of grounding switch or phase to ground fault. The result is high-frequency interferences induced in GIS enclosure as travelling waves. Surge arresters cannot control these VTFO’s due to their extreme rise time [8]. An important amount of overvoltage enters in grounding network and causes transient ground potential rise (TGPR) and rise of transient enclosure potential (TEV) [3].

The standards IEEE 80-2000, IEEE Guide for Safety in AC Substation Grounding, briefly presents very fast transient and their mitigation, just in one chapter with very few theoretical recommendation and one mathematical condition [1]:

$$\sqrt{V_t^2 + (V'_{to\,max})^2} < V_{touch} (1)$$

V_t - is the maximum touch voltage as determined for the point underneath a person's feet

$V'_{to\,max}$ - is the (predominantly inductive) maximum value of metal-to-metal voltage difference between GIS enclosures.

Essentially, it offers just some brief quantitative engineering analysis.

A. State of the Art in Very Fast Transient Overvoltage caused by Disconnector Switch operations

When DS operating, contacts move slowly (1cm/s magnitude), the electric arc between contacts puts out and reignites for several times in SF6 gas. It is caused by adoption of SF6 of 0.4~0.5 MPa as insulating medium in GIS [3]. When the DS is operated, re-ignition and arc extinguishing can be observed for many times in gaps between the moving contacts and static contacts due to slow speed of switching on and poor quenching performance [3]. This event produces very fast transient overvoltage with steepest traveling-wave head, generally 1-20 ns, and with higher than several tens of MHz in GIS which are transmitted to both ends. Amplitude of the traveling waves depends on the potential difference between contacts, wave impedance of the bus before breakdown and the quantity of trapped charge remaining on GIS buses due to capacitive coupling between the phases. Part of travelling-wave can reach the peripheral equipment connected to GIS (control and protection equipment) [4]. The rest of the electromagnetic waves can form an equivalent circuit to the ground and can be transmitted along the GIS shell raising the Transient Enclosure Voltage (TEV) and making the potential to ground rise (TGPR) with dangerous levels of touch and step voltage [1].

Refraction and reflection will occur when VFTO reaches the substation enclosure due to discontinuities of wave impedance caused by the GIS junctions and flanges [2]. In addition, external high-frequency transient electromagnetic field related to Very Fast Transient Currents (VFTC) radiates into all directions from the shell and overhead lines.[4]

The waveform of internal VFTO is usually comprised by four components [2], [7]:

Step voltage;

b)The 100 MHz component as the highest level formed due to several slight changes of wave impedance, in the GIS busbar

c)The 30 MHz component as the highest level formed as a result of the reflection caused by significant changes of wave impedance;

d)The 0.1 MHz~5 MHz component produced by resonance caused by external equipment with large capacitance, such as capacitor voltage transformer and coupling capacitor of the power line carrier system.

In terms of computation procedures the it is recommended that TGPR induced by Very Fast Transient Overvoltage be computed using electromagnetic field approach, due to uncertainties related to circuit theory at frequencies above 10 MHz. [5]

B. State of the Art in Fast Transient Overvoltage caused by Lighthing Overvoltage

Lightning surge overvoltage is generally related on two cases, direct lightning stroke and back-flashovers, and can induce, in major parts of GIS, fast transient overvoltage. In order to prevent the damage caused on equipment it is important to establish an acceptable level of lightning protection, which can be achieved through lightning protection equipment (surge arrester) but also with adequate design of the grounding grid.

Lightning overvoltage waves travel along the transmission line and enter in the substation [6].Surge arresters cannot control entirely these transients due to their extreme rise time front component [7].

The significant frequency components of the lightning surge are all below 7 MHz. According to [5] the spectrum of lightning surge signal is dominated by its lower frequency component and can influence the TGPR of substation to oscillate at a resonance frequency of 1.05 MHz. However, in general, lightning stroke has a frequency range of about 100 kHz to an excess of 120 MHz in the worst-case scenario [6]. The resonance frequency and the time domain of TGPR in the presence of grounding grid is lower than in the absence of grounding grid [5], [7], the amplitude of the oscillation can be reduced up to 50 %. For an optimum design procedure it is recommended to model the response of the grounding system during lightning discharge. According to [12] effective grid area concept is an efficient and precise methodology for this type of analysis. The effective area is not directly related to the area of conductors that has a great significance in discharging the lightning stroke current. The area originates at the injection point at the lightning stroke and expands, with the speed of propagation of the current pulse, over the conductors.

Mitigation methods

Overtime many mitigation techniques were studied through experimental methods and digital simulations, but standardization of procedures was not achieved yet, neither a scalable efficiency for interactions with the grounding system. As examples which are considered the most economic solutions are: appropriate load side terminals, capacitance at transformer terminals, RC-filter, ferrite rings [4] [6]. Due to many GIS configurations and practical situations, the mitigation techniques should be used in accordance with the safety measures and special requirements included in further GIS grounding grid design procedures.

Taking into account the situations mentioned above we can conclude that it is important to emphasize VTFO analysis when elaborating a designing procedure for GIS grounding network, although is a challenging task which involves future research.

III. OVERVIEW OF GROUNDING GRID NETWORKS FOR DIFFERENT PRACTICAL SITUATIONS

A. Grounding grid for Gas Insulated Substation situated in suburban areasusing conventional method (IEEE 80-2000)

For suburban conventional substations, the perimeter is closed to the public; just professionals can access the substation. Therefore, the grounding system is satisfactory as long as it meets the national standard or guidelines [11].

The analysis is focused on a 33/11 kV indoor GIS substation with a fault level of 40 kA [15]. Fault current at substation is determined from system modeling and simulation, but in general practice there are different levels of fault current adopted for design purposes [14]. Note that the computations have been made in frequency domain at 50 Hz and harmonic current. The soil conditions considered are desert conditions and hence with poor resistivity. Soil resistivity measurement is done using Wenner 4 point method [15].The measured soil resistivity values are then analyzed using the Soil Analysis module of CYMGRD software. The conductor spacing and the ground rod quantity is calculated based on various simulations. Though manual calculation is still an accepted method by the literature, software tools ensure an optimal design of the grounding grid [15].

For an urban GIS substation, in most cases, the equipment is placed in a multi-story building. Recent studies [12] present a new approach regarding the grounding grid design procedure which states that a grounding system should be composed by three elements: main grounding grid (associated with fault current), equipotential grid (associated with VTFO) and lightning protection system (associated with lightning fault current). In this particular case the substation is embedded in a building with one floor situated in dessert area thus the method mentioned before is not applicable. Nevertheless, the worst case scenario should also include the influence of very fast transient overvoltage produced by common switching operations. Being a desert area the lightning stroke is unlike to happen. The authors in [12] have designed only the main grounding system accounting the designing procedure for conventional substations.

The grounding grid from this study is designed with 7 m horizontal conductor spacing resulting in 12 conductors each, along X and Y axes [15]. The grid is buried at a depth of 1 m below the ground and the ground rods being driven to a maximum depth of 12 m. This is adjusted based on contour plots from different simulations of potential contour which shows the distribution of surface potential. Rods along the grid periphery are encased with bentonite of 150 mm diameter.

The design grid confirms the IEEE 80-2000 standard but without special criteria analysis. Although the touch and step voltages are within the limits and the grounding grid meets the standard recommendations, additional analyzes are required regarding very fast transient overvoltage and its effects on GIS operation. It is important to mention that no induction between grid conductors and between grid and GIS enclosure is taken into account.

B. Grounding grid design model for GIS indoor substation using Electromagnetic Field Method

The Electromagnetic Field Method applied to grounding grid design, is an extension to low frequencies of the method of moment used in antenna theory, and is the most accurate approach. This method eliminates all of the assumptions adopted by the conventional methods and takes into account circulating currents along with aboveground bus bars. The GIS equipment has the metal enclosing gas-insulated switchgear and the inner high-voltage buses that are completely contained within the outer pipe type enclosures. Under fault conditions, especially when the fault is inside the enclosure, inductive coupling between faulted inner buses and associated enclosures can result in induced currents that may generate significant voltage drops [1], [3], [10],[16].

This approach takes induction effects fully into account resulting in computation outcomes which contain the combined effect of conductive, inductive and capacitive couplings.

As an example the study [16] is discussed. The substation operates as both a medium voltage distribution substation and a high voltage switching station. Operating voltages are 13.8 kV, 34.5 kV, 99 kV, 115 kV and 230 kV. A circuit model of115 kV and 230 kV existing overhead transmission lines and their related remote stations (terminals), that provide fault current contributions, was built to determine the actual fault current discharged into the earth by the grounding grid. The enclosure is grounded at its two ends outside the GIS building and also grounded in many points at various locations along their length. The fault situations that involve special attention and analysis are inside the enclosure because implies the inductive couplings between faulted inner bus and associated enclosure.

The method is based on field approach, therefore it was possible to include the entire assemble of the substations: underground cables, above ground bus bars and a part of the energy transmission and distribution network in the geometry, Fig. 1.

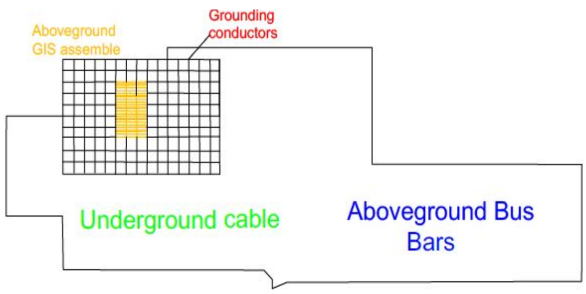

Fig. 1 Overall substation network

The maximum touch voltage is less than in the case when the fault is outside the GIS structure but near the GIS middle part. It is interesting to note that when the fault is inside the enclosure, the inductive coupling between faulted inner buses and associated enclosures evenly discharges the fault current through the enclosure everywhere in the soil and actually reduces the maximum touch voltage [16].

An advanced method is developed and used to analyze complex grounding systems. Although the IEEE 80-2000 recommendations are satisfied the study was carried out only for a 50 Hz fault current. In practice, the very fast transient overvoltage can create dangerous situations for personnel and harmful effects on the GIS secondary equipment. Therefore the grounding grid design procedure should include the presence of this type of overvoltage.

C. Grounding grid connected to metallic infrastructures of commercial buildings. Design model for GIS indoor substation using Electromagnetic Field Method

Generally, in an urban area, the low voltage distribution networks and the city metallic infrastructure, such as the residential water pipe network, are inevitably directly or indirectly connected to the substation grid, Fig. 2.

Recent studies have shown that connecting an urban substation grounding system to the urban city buried metallic infrastructures, in most cases, enhances the safety status inside the substation. We need to ensure that the transferred voltages to the metallic infrastructures will not endanger the safety of people in the zone of influence. Their omission in the computer model design can cause significant inaccuracies in the computed grounding performance depending on the topology of the electrical network [11].

The substation under study is situated upon approximately 3267 m^2 area and the highest operating voltage is 110 kV. The substation is situated inside a commercial building with metallic steel rebar of an indoor large parking lot and the rest of the building interconnected to the GIS grounding system. The computation takes into consideration a single-phase –to ground fault current of 60 kA at a 50 Hz frequency domain. The GIS is connected to two remote stations through underground uniform soil and above ground cables. The urban substation grounding grid performance is not very sensitive to the soil structure models due to the city buried metallic network and commercial building rebar, which are connected to the grounding grid providing a significant increase on the effects of soil characteristics changes [11].

The conventional methodology presented in IEEE 80-2000 standard cannot encompass such complex grounding grid system geometry. It is clear that an analytical approach is limited even for line-to-ground-fault current analysis due to assumption that the grounding grid is an equipotential surface and no mutual induction between grid elements it is taken into consideration as well as very fast transient overvoltage.

The computation method accounts for both the buried and above ground metallic components of the system which could be bare or coated conductors. Computer simulations have been performed using both Right-Of-Way module, based on a circuit approach, and Multi-Fields module, based on a field approach.

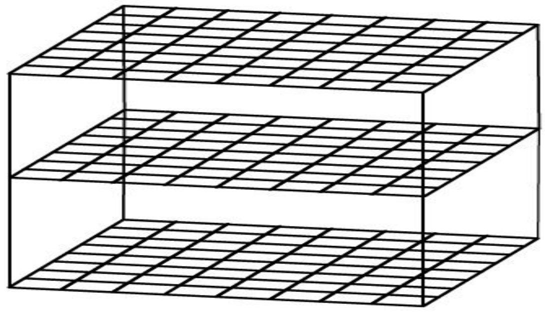

Fig. 2 GIS indoor grounding system

To be noted that the computations have been made in frequency domain at 50 [Hz] harmonic current only. According to [1], GIS substations imply special safety requirements and analysis, due to many reasons but especially because of electromagnetic coupling between substation elements which can cause very fast transients overvoltage. It is important to mention that when frequency increases the mutual coupling, soil parameters frequency dependence and propagation delay, cannot be neglected. Therefore the grounding grid is not analyzed from very fast transient overvoltage and lightning stroke fault current point of view.

To ensure that the response of grounding grid is effective in all possible worst scenarios, including combined effects, the designing procedure should take into consideration three types of analysis: fault events, very fast transient overvoltage and lightning stroke discharge. The electromagnetic field approach can be used also for high frequency domain analysis using the same procedures.

D. EMC Philosophy applied to Design the GroundingSystems for Gas Insulation Switchgear (GIS) Indoor Substation

In addition to IEEE 80-2000 recommendations, regarding special requirements for GIS grounding system and safety measures, recent studies have been developed using new approaches based on electromagnetic field philosophy applied to design procedure of gas insulated substation grounding system. In general, GIS urban indoor substation are situated in a several floors building and it is composed by: cable room (ground floor), GIS and power transformer room (first floor), HV cubicle room, relay room and control room (second floor), from Fig. 3.

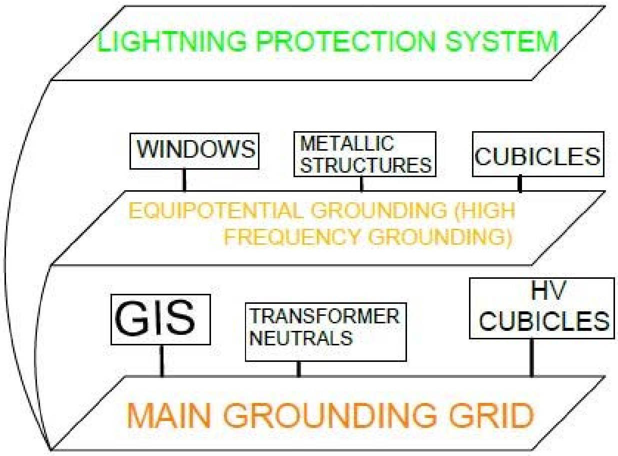

Fig.3 GIS indoor substation grounding system approach

According to [12],the grounding systems are characterized by three subsystems: main grounding grid (50/60Hz grounding systems), equipotential grounding grid (high frequency grounding grid) and lightning grounding system. All electrical installations are indoor and considering that all building has steel structure, there is an intrinsic connection between the various grounding system.

Main grounding grid is responsible for power frequency short circuit currents, is made of cooper to avoid corrosion, and is buried into soil. The conductors of the main grounding system are embedded in the concrete throughout the building floor. Besides the protection role, the main grounding grid is a reference to the potentials which arise inside the building. To be noted that after designing the main grid, it is necessary to evaluate the impulse impedance [12], [13].

Equipotential grounding grid is a system related to the existence of very fast transients occurring due to the switching operation of GIS, whose frequencies are of MHz order. As safety measure the design procedure requires a low-inductance of grounding system for GIS equipment as well as a minimization of the grid impedance. The purpose of equipotential grounding grid is to reduce the effects of very fast transients and to control the potential on the floors (touch and step voltages). Ideally, the equipotential grid system would be a flat metal plate, but this solution is not a cost effective one. According to [13] it is possible to compare the performance of a plate grid and metal grid made of thinner wires and small meshes.

Lightning protection system is responsible for dissipating the high frequency lightning currents. It is recommended to model the response of grounding grid under lightning discharge for an optimum design procedure. A very well-known method is to determine the impulse impedance of the grid through effective area concept [13].

Each grounding system is directly connected to the Main Grounding grid installed into the soil in several points. The expected voltage difference between such grid and the Equipotential Grounding grid is small, ensuring safety inside the building.

The safety criteria are established by GIS manufacturer in accordance with IEEE 80-2000 standard.

E. Gas Insulated Substation connected to an existent Air Insulated Substation grounding grid, using conventional grounding design method

Due to increase in power demand and non-availability of space, GIS extension provides a feasible solution to meet the necessity of additional power request. The design of grounding grid for air insulated substation is a different task comparing to the actual designing of GIS grounding system. According to [14] it is feasible to use the main grounding system of AIS as grounding system for a new GIS if the safety criteria recommended by IEEE 80-2000 is satisfied. The study states that if the concrete is used as the surface layer for GIS, the maximum permissible touch and step voltages are increased at high value and very small variation in touch voltage due to special criteria and no change in step voltage as compared to AIS [14], in some particular cases.

The study has been done with conventional assumptions (equipotential network as grounding grid and no inductive coupling between the grid elements is taking into account) and only for a worst case scenario of 40 kA harmonic fault current at 50 Hz [14]. It is well know that there are different switching operations taking place in the gas insulated substations (GIS). These switching operations generate the very fast transient overvoltages (VFTOs) which are dangerous to the substation equipment [1], [3], [4], [5], [6].Some of the problems are of more attention and require special analysis. Furthermore, because the two substations are connected to the same grounding system and essentially are part of the same circuit, it is possible that very fast transient overvoltage propagates through grid elements and affects the equipment of AIS. In the particular case mentioned above, the computation method respects the IEEE 80-2000 indications. The following primary parameters which influence the design of grounding grid are: magnitude of fault current, duration of fault current, grounding grid depth, soil resistivity, surface layer resistivity, grid geometry, system parameters [1], [14].The GIS had been placed in the area of AIS relying on the obtained results from [14].

IV. Discussions

The gas insulated substations represents a relatively new solution for the energy distribution and transmission networks. Due to their high reliability, easy maintenance and reduced ground space requirements main conclusions, regarding the design procedures for grounding systems of GIS, to be drawn from this review paper are as follows:

- Beside the overvoltages applicable to conventional substation, GIS are exposed to different overvoltages and enforce additional mechanism of protection due to non-self-restoring characteristic of the insulating environment, SF6 gas.
- Calculation models for electromagnetic simulations including the earth effects may be based on following different approaches: electromagnetic field theory,

transmission line theory, circuit theory and hybrid methods.

- The overvoltages affecting the grounding grid performance and contributing at worst cases scenarios faults are: very fast transient overvoltage produced by switching operations, internal and external GIS faults, lightning overvoltage;
- The grounding systems are characterized by three subsystems: main grounding grid (50 Hz grounding systems), equipotential grounding grid (high frequency grounding grid) and lightning grounding system;
- Beside IEEE 80-2000 standard recommendations regarding special requirements for GIS grounding grid system, additional analysis should be done;
- Connecting 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 metallic infrastructures will not endanger the safety of people in the zone of influence.

It can be conclude based on the studies mentioned in this paper that gas insulated substations grounding grid design procedures is not a mature research field yet and the subject is open to future research.

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