Design Practice for the Earthing System of the 400 kV Gas Insulated Switching Station at Lavrion

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Abstract: The paper presents the situation of the gas insulated 400 kV switching station at Lavrion of Public Power Corporation, Greece as a part of a power station expansion project and gives details of the ground grid design.

Although the ground grid design was carried out according to the American Standard IEEE 80 "Guide for safety in AC substation grounding", there is a cross reference to the German Standard DIN VDE 0141 "Earthing systems for power installations with rated voltages above 1 kV" and the upcoming European Standard EN 50179 "Erection of electrical power installations in systems with nominal voltages above 1 kV AC".

Besides the analysis of soil resistivity and the selection of conductor sizes, the determination of fault current distribution in the grounding system is a key step for the design of an effective and economically feasible grounding system.

Finally, the test procedure for verification of effectiveness of the earthing system after completion of erection is given.

Keywords: Grounding system design, Gas insulated switchgear, Electromagnetic compatibility

I. Introduction

A closed type, metal enclosed, SF_6 gas insulated 400 kV switching station, has been constructed and put in operation in 1998 at the area of Lavrion, to serve the new Lavrion 550 MW combined cycle power plant with three gas and one steam turbine units, as well as the existing 300 MW old steam turbine unit. One, already existing, double circuit overhead line together with a new one single circuit under construction transmit the power into metropolitan Athens area. The switching station with double busbar and nine 400 kV bays in total is the first in that voltage level in Greece. A simplified layout of the switching station is presented in Fig. 1.

Apart from the above units, there are also in operation at site one 150 MW oil fired steam turbine and one combined cycle unit with total rating of 175 MW feeding power at 150 kV voltage level through an air insulated 150 kV substation.

The limited dimensions of the available space, almost 9000 m^2, as well as the great industrial and sea pollution problems at site, made the decision of constructing a compact closed type gas insulated switchgear (GIS) substation obligatory.

GIS substations offer a lot of advantages to utilities. They need only small areas compared to outdoor conventional type switchgear, they are independent from environmental conditions and can be considered very reliable. Therefore, they are found in load and generation centres, where the level of short circuit capacity is high.

These facts have an impact on the ground grid design, which has to guarantee a safe substation with regard to step and touch voltages. Also the interference with other systems nearby, like control systems, has to be minimised in order to maintain operation under fault conditions and to secure the quality of power.

All the above mentioned units and the related switchgear are close together forming a unified power complex of 1200 MW occupying an area of about 400 000 m^2. Consequently the earthing network of the new closed type GIS substation could be assumed as a part of the larger earthing network of the whole complex. Nevertheless for safety reasons, it is faced as an independent selfstanding network suitable to assure alone safe operation and the protection of the staff in case of earth faults.

In this paper description and details of the grounding grid design both outdoor and indoor, together with the foreseeable electromagnetic compatibility measures, are given. Although the design was carried out according to the American Standard IEEE 80 "Guide for safety in AC substation grounding" [1, 2], there is a cross reference to the German Standard DIN VDE 0141 "Earthing systems for power installation with rated voltages above 1 kV" [3] and the upcoming European Standard EV 50179 "Erection of electrical power installations in systems with nominal voltages above 1 kV AC" [4].

The paper especially discusses the determination of soil resistivity, the selection of material and cross section of ground conductors, the tolerable touch and step voltages, the expected ground potential rise, the design details and the test procedure for verification of effectiveness of the earthing system after completion of the erection.

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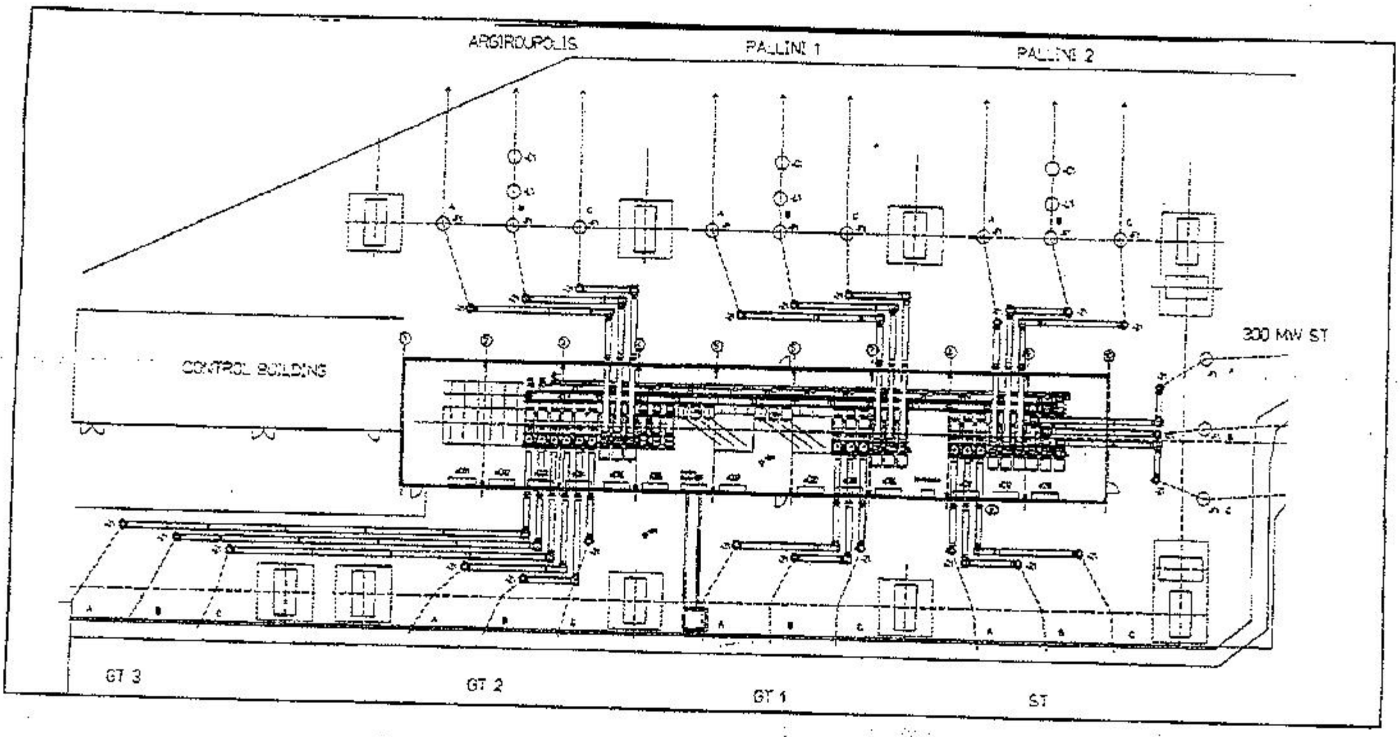

Fig. 1. General layout of the 400 kV gas insulated switching station at Lavrion

II. Determination of Soil Resistivity

In order to design the earthing system of the substation, the resistance to earth has to be calculated in advance. This value depends on two parameters which can hardly be influenced by the designer. The area covered by the installation and the specific soil resistivity beneath. As the specific soil resistivity varies considerably with type and structure of soil the reliable determination of effective soil resistivity is essential for a safe and economic design.

In order to determine the soil structure also in deeper layers, the Wenner method, which uses 4 electrodes at the surface to measure soil resistivity also in larger depth, has proved to be a useful tool. The resulting diagram of apparent soil resistivity is the basis to identify top and bottom layer resistivity as well as top layer thickness.

For the Lavrion site out of 4 sequences with spacing up to 30 m the decisive parameters were taken.

ρ_T	=	160	Ω·m	top layer resistivity
ρ_B	=	60	Ω·m	bottom layer resistivity
h	=	13	m	top layer thickness

Considering the area of the interconnected earth grid of substation and power station of more than 160 000 m², the effective equivalent resistivity for a homogenous soil comes to 68 Ω·m.

III. Thermal Design

The task of earthing conductors is to carry the line to ground fault current from the faulted component and distribute it to the buried earth electrodes. The sizing has to be done in a way that no damage or melting will occur even in case of auto reclosure or subsequent faults in short sequence.

The design for the 400 kV equipment was based on the following parameters:

I_{K1}	=	40	kA	maximum line to ground fault current
t_c	=	1	s	fault duration for thermal design
T_A	=	40	°C	ambient temperature
T_m	=	300	°C	maximum allowable temperature

For copper conductors this results in a required minimum cross section of 220 mm². For earthing conductors of equipment which is connected at least twice or for the meshed part of the grid a split up of current can be considered. In this case a copper cross section of 150 mm² is sufficient.

IV. Tolerable Touch and Step Voltages

In case of a line to ground fault a person in or outside the substation can be subjected to a potential difference between hand and feet, hand and hand or foot and foot. This potential difference will lead to a current through the body, which has to be limited to a safe level not causing ventricular fibrillation of the heart. Based on the current limit found by Dalziel, the IEEE standard 80 gives formulas to determine tolerable touch and step voltages under consideration of body and feet resistance's as well as fault duration:

t_S	=	0.5	s	shock current duration
ρ_S	=	2000	Ω·m	resistivity of crushed rock surface layer
h_S	=	0.3	m	thickness of surface layer

Based on these data the tolerable touch voltage is $U_{t\,tol}$ = 792 V and the tolerable step voltage $U_{s\,tol}$ = 2500 V.

V. Determination of Expected Ground Potential Rise

In case of a line to ground fault in the substation area the fault current will return on different path. Part of the fault current will flow through the interconnected earth grid to the grounded neutrals of the generator transformers. Another part will return due to inductive coupling through the ground wires of the outgoing overhead lines. The rest will be split up according to the ratio of resistance's between substation earth grid and power station earth grid.

The resistance to earth of an earth grid lies in between the value of a solid plate and a single earth electrode surrounding the area. The formula according to IEEE 80 considers the actual density of the meshed grid by taking into account the length of the buried conductors.

ρ_E	=	68	$\Omega\cdot$m	soil resistivity
A	=	8400	m^2	area of substation
L	=	2000	m	length of buried conductors
h	=	0.6	m	burial depth of earth grid

The resistance to earth of the substation comes to $R_{sub} = 0.36\ \Omega$. The impedance to earth of the parallel earthing systems such as existing earth grids and tower foot chain impedance of outgoing overhead lines was found to be $Z_{parallel} = 0.1\ \Omega$.

In the area of the interconnected earth grid there are transformers with rated power between 140 MVA and 360 MVA. Based on a short circuit calculation the summary of transformer neutral currents gave $I_{\Sigma N} = 12$ kA.

The earth wire reduction factor for the outgoing 400 kV overhead line with two steel earth wires was taken as $r_E = 0.87$.

From the above listed data the grid current flowing between substation earth grid and remote earth (Fig. 2) was calculated to be $I_{Grid} = 5.4$ kA resulting in a ground potential rise of $U_{GPR} = 2$ kV.

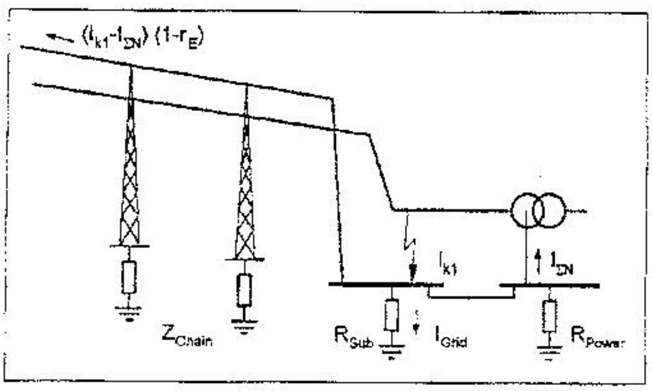

Fig. 2. Fault current distribution and resistance's to earth

VI. Check of Design regarding Touch and Step Voltages

Based on the expected ground potential rise it was decided to install in the substation area not covered by foundations a buried earth grid with rectangular meshes having a maximum mesh width of 10 m. The calculation of mesh voltage according to the formulas of IEEE 80 gave $U_{mesh} = 422$ V. As this mesh voltage is smaller than the tolerable touch voltage, the design requirements with respect to touch voltages are fulfilled. The analysis of step voltages gave $U_{step} = 278$ V, which also satisfies the requirements of tolerable step voltages.

VII. Details of Earthing System Design

The main components of the earthing system are the meshed and buried outdoor earthing grid, the foundation ground electrode of the buildings and the indoor earthing system. The structure is given in Fig 3.

In order to form a foundation ground electrode steel bars are welded together and embedded in the concrete of the lowest floor. The steel bars are wrapped to the reinforcement mats and have risers to the indoor earthing system.

A main earthing conductor which runs along the wall is the backbone of the indoor earthing system. All components which can carry the fault current are connected via earthing conductors to the main earthing conductor at least twice. There are several connections to the outdoor earthing system.

High voltage gas insulated switchgear causes transient potential differences when isolators are switched. In order to prevent arcing between grounded metal structures and to reduce interference on secondary equipment, additional measures with respect to electromagnetic compatibility are considered.

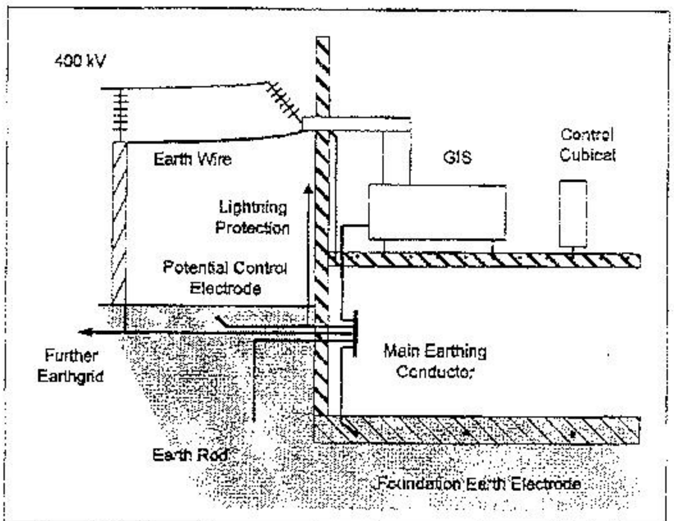

Fig. 3. Main components of earthing system of GIS building

Equipotential bonding for high frequencies
Enclosure earthing in a low inductive manner
Secondary wiring with suitable screens

Rooms of the control building with sensitive equipment are shielded in order to minimise interference from electromagnetic fields radiated from 400 kV outdoor bushings during isolator switching.

There are earth wires between the metal support of the surge arrestors and the 400 kV bushings of the outgoing overhead lines.

Each building is surrounded by a potential control electrode in 1 m distance to the building. The lightning protection system is interconnected with the earthing system.

VIII. Current Injection Test

In order to check the effectiveness of the earthing system it is intended to carry out a current injection test after completion of the erection. For this purpose an outgoing overhead line will be short circuited and grounded in about 6 km distance. In the substation a single phase current source will be connected between the three phase conductors of the overhead line and the substation earth grid (Fig. 4). The test current will be about 150 A. During the test the following data are recorded

Ground potential rise
Touch voltages and transferred potential
Step voltages
Potential differences within the earth grid
Zero sequence impedance of test line

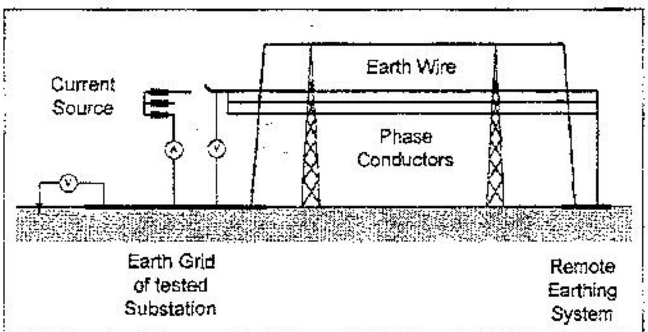

Fig. 4. Test circuit for current injection test

IX. Design Procedure according to German Standard

The DIN VDE standard 0141 requires a design of the earthing system with respect to thermal and mechanical stresses, as well as a design to meet touch voltage requirements. While the thermal design gives almost the same results as IEEE 80, the approach to meet touch voltage requirements is different.

It is presumed that the calculation of ground potential rise is far more accurate and easy to handle than the theoretical determination of touch voltages.

The tolerable touch voltage can be taken from a diagram giving the tolerable touch voltage as a function of fault duration. This diagram is based on the body current limits given in IEC 479 [5]. In VDE it is stated that the correct operation of protection and circuit breakers can be presupposed. As the tolerable touch voltage according to VDE is not considering feet resistance's, the value is smaller than the IEEE value.

There is no step voltage limit given in VDE 0141.

The criteria to decide whether a substation will be safe is therefore based on the relation of ground potential rise U_E and tolerable touch voltage $U_{t\,tol}$:

If $U_E \le U_{t\,tol}$:
⇒ Substation is safe in general

If the substation is located in an industrial or densely build area :
⇒ Substation is safe in general

If $U_E \le 2 \cdot U_{t\,tol}$:
⇒ Substation is safe as based on experience no untolerable touch voltages are to be expected

If $U_E \le 3000$ V and fault duration $t_F \le 0.5$ s :
⇒ Substation is regarded as safe if certain specified measures to prevent excessive touch voltages are applied

If $U_E > 3000$ V :
⇒ Substation has to be tested after erection to prove that the tolerable touch voltages are kept

X. Earthing requirements of upcoming European Standard

With the upcoming European Standard EN 50179 the requirements for earth grid design of a substation will be part of a general standard for the erection of high voltage installations.

The thermal design will be similar to the procedure known from IEEE and VDE.

The design with respect to touch voltages is based on the VDE approach. There is a diagram giving the tolerable touch voltages in dependence of fault duration. Additional curves give limits for touch voltages under consideration of foot and shoe resistance's. As there is no formula to calculate touch voltages there are certain circumstances listed under which the earth grid can be considered as sufficient to keep touch voltage limits.

If $U_E \le U_{t\,tol}$:
⇒ Substation is safe in general

If the substation is part of a global earthing system :
⇒ Substation is safe in general

If $U_E \le 2 \cdot U_{t\,tol}$:
⇒ Substation is safe as based on experience no untolerable touch voltages are to be expected

If $U_E \leq 4 \cdot U_{t\,tol}$:

⇒ Substation is regarded as safe if certain specified measures to prevent excessive touch voltages are applied

If $U_E > 4 \cdot U_{t\,tol}$:

⇒ Substation has to be tested after erection to prove that the tolerable touch voltages are kept

Besides the general rules it is mentioned that touch voltages resulting from transferred potential have to be considered.

XI. Summary

The careful design of an earthing system for a substation is necessary to assure not only the protection of the staff, but also the safe operation, in case of earth faults. Substations with gas insulated switchgear need even more efforts because of their limited dimensions.

The closed type, metal enclosed, SF_6 gas insulated 400 kV switching station at Lavrion, the first in that voltage level in Greece, has been constructed and put into operation in 1998.

As some of the main components of the earthing system are integrated into the civil works, it was essential to design the earthing system at the very beginning of the project.

Details of the design, which was carried out according to the American Standard IEEE 80, are given in the paper. As a cross reference the requirements of the German Standard DIN VDE 0141 and the upcoming European Standard EN 50179 are given. The aspect of electromagnetic compatibility in the surrounding of the GIS was considered.

Finally the test procedure for verification of the effectiveness of earthing system after completion of erection is given.

XII. References

[1] ANSI/IEEE Std 80-1986 "Guide for Safety in AC Substation Grounding"

[2] ANSI/IEEE Std 81-1983 "Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System"

[3] DIN VDE 0141-1989 "Erdungen für Starkstromanlagen mit Nennspannungen über 1 kV"

[4] prEN 50179-1996 "Erection of electrical power installations in systems with nominal voltages above 1 kV AC"

[5] IEC 479-1/1984 "Effects of current passing through the human body"

XIII. Biographies

Georgios J. Georgantzis was born in Piraeus, Greece in 1953. He received the diploma in Electrical and Mechanical Engineering from the National Technical University of Athens, the MSc in System Engineering from the City University, London, UK and the PhD degree in Electrical Engineering from the University of Patras, Greece in 1976, 1978, 1992 respectively. From 1981 he is with Public Power Corporation of Greece, currently in charge of special transmission substation studies. He is a member of the Technical Chamber of Greece, CIGRE WG 14.20 and Gen. Secretary of Greek National Committee for CIGRE.

N G. Gagaoudakis was born in Athens, Greece in 1945. He received the diploma in Electrical and Mechanical Engineering from the National Technical University of Athens in 1968. He joint Public Power Corporation, Engineering and Construction of Transmission Projects Department in 1969. For the last three years he is manager of the Engineering and Construction of HV Substation Branch. He is a member of the Technical Chamber of Greece and CIGRE

Theodor Connor was born in West-Berlin, Germany in 1953. He received his degree in Electrical Engineering (Dipl. Ing.) from the Technical University of Berlin in 1980.

He joined the system planning division of Siemens AG, Erlangen in 1980. Currently he is in charge of the network engineering, earthing and interference section in the Power Transmission and Distribution Department.

Theodor Connor is a member of VDE and DKE K222