A Study of Grounding Grid Characteristics with Conductive Concrete

Chun-Yao Lee and Siang-Ren Wang

Abstract—The purpose of this paper is to improve electromagnetic characteristics on grounding grid by applying the conductive concrete. The conductive concrete in this study is under an extra high voltage (EHV, 345kV) system located in a high-tech industrial park or science park. Instead of surrounding soil of grounding grid, the application of conductive concrete can reduce equipment damage and body damage caused by switching surges. The focus of the two cases on the EHV distribution system in a high-tech industrial park is presented to analyze four soil material styles. By comparing several soil material styles, the study results have shown that the conductive concrete can effectively reduce the negative damages caused by electromagnetic transient. The adoption of the style of grounding grid located 1.0 (m) underground and conductive concrete located from the ground surface to 1.25 (m) underground can obviously improve the electromagnetic characteristics so as to advance protective efficiency.

Keywords—Switching surges, grounding gird, electromagnetic transient, conductive concrete.

I. INTRODUCTION

THE switching surge in the EHV substation is always a topic for discussion, security in particular. The grounding system has to ensure personnel security and equipment security under ground fault, lighting and switching surges [1]. This paper aims to study switching surges of the two cases based on power delivery and distribution system in a high-tech industrial park. Due to high-frequency transient characteristics of switching surges, the injection of switching surge current will result in some electromagnetic transient phenomena on grounding system. For example, the value of Earth surface potential, Ground potential rise (GPR), Step voltage and Touch voltage may increase, and the magnitude of conductor with current and electromagnetic field strength will be changed.

The application of a novel high conductive concrete [2] for setting and arranging the soil materials is focused. The conductive concrete surrounded the grounding grid is applied to reduce the damage of grounding equipment and accident of personnel and effectively improve the reliability and quality of power system in high-tech industrial park.

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II. DESCRIPTION OF SYSTEM STRUCTURE

A. System Structure in EHV Substation

This paper discusses the two cases related to the switching surge in a typical EHV substation, as shown in Fig. 1. In this diagram, a 345kV balanced three-phase sources connects to a 345kV bus, and the 345kV bus connects four transmission lines, including the first circuit, the second circuit, the third circuit and the backup circuit, and supplies the four main transformers. Every main transformer makes the voltage drop from 345kV to 161kV and supplies to the load through the 161kV bus. The system structure also considers the 161kV equivalent sources which supplies to the secondary side through 161kV bus [3]. The six injecting points of the switching surge on grounding grid assumed in this paper is to observe electromagnetic transient phenomena, as shown in Table I. According to Fig. 1, this paper uses transients program of electromagnetic transients program to simulate the model in the EHV substation. The simulated model contains source, bus, cable, breaker and 345kV main transformers. We can use the program to calculate the capital parameter of transmission line and simulate the geometric position of conductor, the conductive resistivity and the number of conductors.
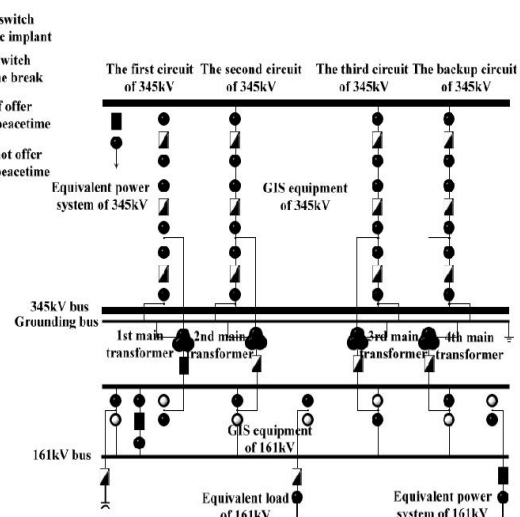

Fig. 1. Single-line system in the EHV substation.

TABLE I
GROUNDING POINTS OF EQUIPMENT IN THE EHV SUBSTATION

Grounding point	Grounding equipment
grounding point 1	neutral point of 1st main transformer
grounding point 2	neutral point of 2nd, 3rd and 4th main transformer
grounding point 3	345kV cable shielding conductors of the first circuit
grounding point 4	345kV cable shielding conductors of the second circuit
grounding point 5	345kV cable shielding conductors of the third circuit
grounding point 6	161kV cable shielding conductors

B. Grounding Grid in EHV Substation

In this paper, we assume six injection points on grounding grid in the EHV substation, as shown in Fig. 2. Grounding grid area is 120m×85m and a mesh area is 5m×5m. The conductive material is composed of copper and sectional area of conductor is 100mm^2. The grounding grid contains 18 parallel conductors and 25 vertical conductors located under ground 1m in the bottom of the EHV substation [3].

Generally speaking, the soil composition is complex, and the soil resistivity is slightly diverse in different environment, such as moisture, humidity, temperature, etc. The parameter of soil and air characteristic assumption is shown in Table II [2, 4]. In this paper, the material of conductive concrete is composed of cement, aggregate, water and metal fiber. The advantages of the conductive concrete are good conductivity, durability and without environmental pollution. This paper divides different soil material into four styles to analyze the characteristics of grounding grid.

a. The soil material style I : All soil is a general soil layer from ground surface to unlimited depth.

b. The soil material style II : The conductive concrete is applied from ground surface to 0.5m underground and a general soil layer from 0.5m underground to unlimited depth.

c. The soil material style III : A general soil layer from ground surface to 0.75m underground and from 1.25m underground to unlimited depth. The conductive concrete is applied from 0.75m underground to 1.25m underground.

d. The soil material style IV : All conductive concrete is applied from ground surface to 1.25m underground and a general soil layer from 1.25m underground to unlimited depth.
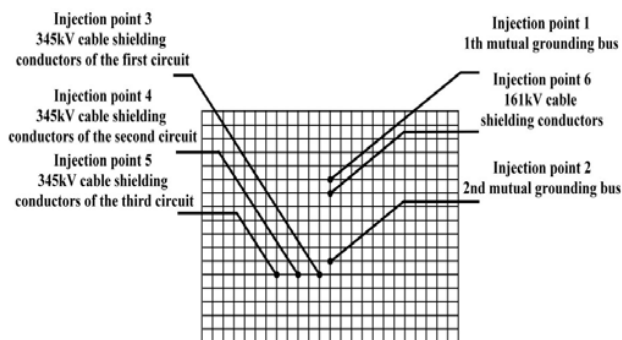

Fig. 2. Position of injection points on grounding grid.

TABLE II
PARAMETER SETTING OF GROUNDING GRID IN THE EHV SUBSTATION

Matter	Resistivity (Ω-m)	Relative permeability	Relative permittivity
air	10^{18}	1	1
general soil	200	1	1
conductive concrete	5	2.5	2

III. PROBLEM OF SWITCHING SURGES AND ANALYSIS METHOD OF ELECTROMAGNETIC TRANSIENT PHENOMENA

A. Problem Analysis of Switching Surges

The injection of surge current on grounding system can be calculated, and the diagram of equivalent circuit is shown in Fig. 3. S_a, S_b and S_c are three-phase switches. E_a, E_b and E_c are the balanced three-phase sources. Z_s is zero-sequence impedance of the transmission line. C_{1g}, C_{2g} and C_{3g} is the equivalent capacitance corresponding to a, b and c phase respectively. I_g is the equivalent current of injecting grounding system, namely, surge current. R_{g0} and R_{g1} are equivalent grounding resistance of the source side and injection side of current respectively. The switch-close S_a, S_b and S_c occurs simultaneously called three-poles operation and also termed three-phase synchronous operation. And, the only one-phase switch-close is called single-pole operation. Both three-poles operation and single-pole operation can utilize the second-order equivalent circuit to analyze surge current I_g.

Fig. 3 can be simplified to R L C series second-order equivalent circuit as shown in Fig. 4 and further inferred the current i_g [1].
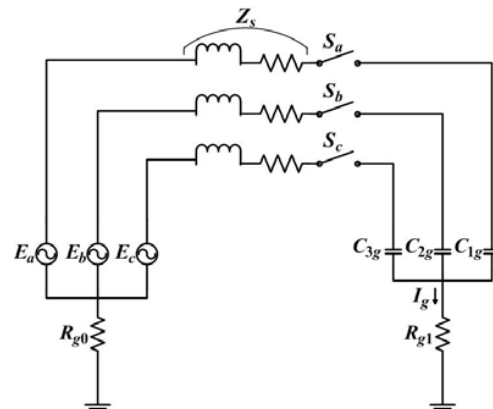

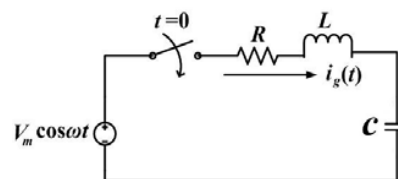Fig. 3. Three-phase equivalent circuit of switching surge current.

Fig. 4. R L C series second-order equivalent circuit.

$$i_g(t) \approx \frac{1}{\omega_d L}(V_m - V_o)e^{-\alpha t}\sin\omega_d t - \omega C V_m \sin\omega t \tag{1}$$

$$\omega_d = \sqrt{\omega_0^2 - \alpha^2} \tag{2}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{3}$$

$$\omega = 120\pi \tag{4}$$

$$\alpha = \frac{R}{2L} \tag{5}$$

where

ω_d : resonant frequency (rad/sec)

ω_0 natural frequency (rad/sec)

ω : angular frequency of voltage sources (rad/sec)

α : decay constant

The values of R, L, C and amplitude of the voltage source V_m will be changed under different switching mode, and the initial value should also be considered.

B. Analysis of Electromagnetic Transient Phenomena

The operation of switch-open or switch-close will cause the switching surge of the voltage and current which leads to a high magnetic field strength, GPR, step voltage and touch voltage. Based on grounding bus on injecting grounding grid in the EHV substation, the following formulas are employed to estimate the values.

(1). Earth Surface Potential and Magnetic Field Strength

To analyze earth surface potential and electromagnetic field distribution, the analysis methods of electromagnetic theory is applied in this paper [5]-[7]. When the range of grounding system is large, grounding conductor should be divided to several small parts by using this method. Firstly, the current distribution of every part will be analyzed, and then scalar potential Φ and vector potential $\bar{A}$ are computed. Finally, both the electric field strength $\bar{E}$ and the magnetic filed strength $\bar{H}$ can be estimated as follows:

$$\bar{E} = -\bar{\nabla}\Phi - \frac{\partial \bar{A}}{\partial t} \tag{6}$$

$$\bar{H} = \frac{1}{\mu}\bar{\nabla}\times\bar{A} \tag{7}$$

where

$$\bar{\nabla} = \left[\frac{\partial}{\partial x}\hat{x} + \frac{\partial}{\partial y}\hat{y} + \frac{\partial}{\partial z}\hat{z}\right] \tag{8}$$

μ : permeability of the media (H/m)

The electric field strength and magnetic field strength are sum of the entire conductor's effect. Formula (6) and (7) are applied to analyze any waveform. Once obtaining Φ, $\bar{E}$ and $\bar{H}$, we can further analyze earth surface potential, electric field strength and magnetic field strength, that is, we compute potential distribution of conductor and electromagnetic field distribution corresponding to every point of ground one by one.

(2). Conductor with the Maximum Current and GPR

Choose the serious one to analyze the switch mode caused by surge current, and compute switching surge current I_g. The fault decrement factor D_f of duration calculation is considered to estimate the current I_G. The grounding resistance R_g and conductor with the maximum current I_G can be estimated as the following formulas according to IEEE Std. 80-2000 [8]:

$$GPR = R_g \cdot I_G \tag{9}$$

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \tag{10}$$

$$I_G = D_f \cdot I_g \tag{11}$$

where

ρ : soil resistivity (Ω-m)

L_T : total effective length of grounding system conductor (m)

A : total area enclosed by of grounding grid (m²)

h : depth of grounding grid conductors (m)

GPR : ground potential rise (V)

(3). Maximum Step Voltage and Maximum Touch Voltage

According to IEEE Std. 80-2000 [8], maximum step voltage E_s can be estimated as the following formulas for grounding grid of the rectangular uniform mesh:

$$E_s = \frac{\rho \cdot I_G \cdot K_i \cdot K_s}{L_T} \tag{12}$$

$$K_i = 0.644 + 0.148n \tag{13}$$

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{n-2}\right)\right] \tag{14}$$

$$n = \frac{2L_c}{L_p} \tag{15}$$

where

K_i : correction factor for grounding grid geometry

K_s : spacing factor for step voltage

n : geometric factor

D : spacing between parallel conductors (m)

L_c : total length of grounding system conductor (m)

L_p : the peripheral length of grounding grid (m)

According to IEEE Std. 80-2000 [8], maximum touch voltage E_{touch} can be estimated as the following formulas for grounding grid of the rectangular uniform mesh:

$$E_{touch} = \frac{\rho \cdot I_G \cdot K_i \cdot K_m}{L_T} \tag{16}$$

$$K_m = \frac{1}{2\pi}\left\{\ln\left[\frac{D^2}{16\cdot h\cdot d} + \frac{(D+2+h)}{8\cdot D\cdot h} - \frac{h}{4\cdot d}\right] + \frac{K_{ii}}{K_h}\ln\left[\frac{8}{\pi(2n-1)}\right]\right\} \tag{17}$$

$$K_h = \sqrt{1 + \frac{h}{h_0}} \tag{18}$$

$$K_{ii} = \frac{1}{(2n)^{\frac{2}{n}}} \tag{19}$$

where

K_m : spacing factor for mesh voltage

K_h : corrective weighting factor that emphasizes the effects of grounding grid depth

K_{ii} : corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh

d : diameter of grounding grid conductor (m)

h_0 : reference depth of grounding grid ($h_0 = 1\text{m}$)

IV. CASE STUDY AND RESULTS

A. Analysis of Switching Surge Current

According to (1), the switching surge current could be estimated; however, too many factors would lead a quite large error of current value. This paper mainly uses the program model to simulate the magnitude of switching surge current in these two cases.

Case 1: The power supplies to load in the EHV substation. In this situation, the third circuit of EHV supplies power to the 345kV bus and the switch-close is not synchronization. The application of the program model simulates the switching surge current characteristics on grounding system as shown in Table III.

Case 2: The power supplies to load in the EHV substation. In this situation, the 345kV bus supplies power to the No. 4 main transformer and the switch-close is not synchronization. The application of the program model simulates the switching surge current characteristics on grounding system as shown in Table IV.

B. Analysis of Electromagnetic Transient characteristic

The program model is applied to simulate the value of surge current in every grounding bus and the maximum surge current in different conditions of switch mode is obtained. Moreover, the switching surge current of injecting grounding system is analyzed and various electromagnetic characteristics on grounding grid including earth surface potential, touch voltage, step voltage, conductor with the current, magnetic field

TABLE IV
SURGE CURRENT CHARACTERISTICS ON GROUNDING SYSTEM FOR CASE 2

Injection point	Maximum value of current (A)	Degrees (°)	Frequency (Hz)
Injection point 1 (1.8-j6.87)	7.1	-75.25	20700
Injection point 2 (36.4-j195.7)	7.1	-75.25	20700
	7.1	-75.25	20700
	185	-79.78	20700
Injection point 3 (-17.3+j72)	74	103.5	20700
Injection point 4 (-17.3+j72)	74	103.5	20700
Injection point 5 (-17.3+j72)	74	103.5	20700
Injection point 6 (1.9-j7.8)	8	-76.49	20700

strength and GPR are observed. All the analyses consider different styles of soil layers. The EHV substation in the vicinity of earth surface potential and magnetic field distributions can be estimated as shown in (6) and (7). The magnitude of switching surge current on injecting grounding system in the EHV substation is simulated according to the program model. By employing (11), the fault decrement factor D_f of duration calculation should be considered to estimate conductor with the maximum current I_G.

Based on the grounding grid structure and the parameters (area, depth, total length of conductors and soil resistivity) in the EHV substation, the equivalent grounding resistance of grounding grid R_g is computed according to (10), and then the magnitude of GPR is computed according to (9). Similar to the description mentioned above, based on grounding grid structure and the parameter, (13) to (15) and (17) to (19) are employed to compute every factor value on grounding grid structure, and the reference of its grounding grid depth is 1m. From (12), (16) and conductor with the maximum current of estimation I_G, the magnitude of step voltage and touch voltage are estimated. The analyzed result of electromagnetic transient phenomena in different styles of the soil material for case 1 is presented in Table V and for case 2 is presented in Table VI.

TABLE III
SURGE CURRENT CHARACTERISTICS ON GROUNDING SYSTEM FOR CASE 1

Injection point	Maximum value of current (A)	Degrees (°)	Frequency (Hz)
injection point 3 (129-j41.7)	136	-17.86	41760
injection point 4 (129-j41.7)	136	-17.86	41760
injection point 5 (212-j150.5)	260	-35.36	41760
injection point 6 (-5-j2.1)	5.45	-156.9	20700

TABLE V
ELECTROMAGNETIC TRANSIENT PHENOMENA
ON GROUNDING SYSTEM FOR CASE 1

Electromagnetic transient phenomena	Soil material style I	Soil material style II	Soil material style III	Soil material style IV
ground surface potential (V)	483	426	465	384
touch voltage (V)	260	232	204	118
step voltage (V)	31	28.5	22.8	19.8
conductor with the current (A)	59	55	57.5	51
magnetic field strength (A/m)	9.4	14.8	12.9	8.9
GPR (V)	490	428	444	339

TABLE VI
ELECTROMAGNETIC TRANSIENT PHENOMENA
ON GROUNDING SYSTEM FOR CASE 2

Electromagnetic transient phenomena	Soil material style I	Soil material style II	Soil material style III	Soil material style IV
ground surface potential (V)	61.5	55	60	51
touch voltage (V)	72	65.5	64	51.5
step voltage (V)	21.9	21.2	21.1	14.7
conductor with the current (A)	46.1	44	45.5	43
magnetic field strength (A/m)	9.9	25.9	17.3	9.4
GPR (V)	111.5	85	97.5	65

TABLE VII
THE DECREASED PERCENTAGE FOR ELECTROMAGNETIC TRANSIENT
PHENOMENA IN DIFFERENT SOIL MATERIAL STYLE

Electromagnetic transient phenomena	Type of cases	Soil material style II	Soil material style III	Soil material style IV
ground surface potential (%)	Case 1	11.80	3.73	20.50
	Case 2	10.57	2.44	17.07
touch voltage (%)	Case 1	10.77	21.54	54.62
	Case 2	9.03	11.11	28.47
step voltage (%)	Case 1	8.06	26.45	36.13
	Case 2	3.20	3.65	32.88
magnetic field strength (%)	Case 1	-57.45	-37.23	5.32
	Case 2	-161.62	-74.75	5.05
GPR (%)	Case 1	12.65	9.39	30.82
	Case 2	23.77	12.56	41.70
conductor with the current (%)	Case 1	6.78	2.54	13.56
	Case 2	4.56	1.30	6.72

V. DATA ANALYSIS AND DISCUSSION

The two cases demonstrate that the grounding grid is located 1.0(m) underground. The switching surge current of high frequency transient on injecting grounding grid affect the values of earth surface potential, touch voltage, step voltage, magnetic field strength, GPR and conductor with the current. The soil material style I can be seen as a general soil layer, that is, the soil material style I is a reference compared to every soil material style in this paper. Table V and Table VI indicate that when the soil material is style I, the magnitude of various electromagnetic transient characteristics is the largest value. When the conductive concrete is applied around the grounding grid, it can effectively improve the magnitude of earth surface potential, touch voltage and step voltage. Table V and Table VI also reveal that the soil material style II decreases the degree of value more than the soil material style III in earth surface potential, GPR and conductor with the current. Since the conductive concrete is firstly applied under ground surface in the soil material style II and its soil resistivity is low and conductivity is great, the switching surge current of injecting grounding grid spreads to earth quickly. The magnitude of electromagnetic transient characteristics is lower than the soil material style III. Due to the conductive concrete is located in the grounding grid 0.25m above and 0.25m below that makes current spreading rate lower than conductive concrete located from ground surface to 0.5m underground, the fact that the style III of voltage difference is closer style II, and the magnitude of touch voltage and step voltage is smaller than the soil material style II. The soil material style III improves effectively than the soil material style II in touch voltage and step voltage parts.

The soil material style IV improves obviously for grounding system. The magnitude of earth surface potential reduces 20.50%, the touch voltage reduces 54.62% and step voltage reduces 36.13%. It is noted that the soil material style II and style III make magnitude of magnetic filed strength a little higher than the reference value (The soil material style I). Particularly, the percentage of soil material style II in case 2 is higher about 161.62% than reference value. The decreased percentage of the four soil material styles for analyzing the results of the two cases is shown in Table VII. Therefore, we have to evaluate the magnitude of magnetic field strength and to confirm if it is consistent with security standards before setting.

VI. CONCLUSION

Grounding grid in the EHV substation is an important facility for both the security of personnel and operating reliability in power system. The magnitude of grounding resistance is the main technical parameter for grounding grid. Therefore, this paper indicated the two cases of the EHV substation in a high-tech industry presented to analyze switching surges make some electromagnetic transient phenomena on grounding system. The results have shown that the conductive concrete applied around grounding grid not only makes the value of grounding resistance decrease in the whole grounding system but also improves the magnitude of electromagnetic transient phenomenon effectively. It is difficult for grounding resistance to meet the security standards when we set a higher soil resistivity in the EHV substation. Both the decrease values of touch resistance between grounding grid and the soil, and resistance of the current spreading to earth could achieve this purpose. Thus, the conductive concrete applied around grounding grid is workable. The advantages of this method are small and stable value of grounding resistance, long lifespan and decreased maintenance cost, which can be promoted to the practical application of grounding engineering in the area of high soil resistivity. For a better adoption, the cooperation with the arranging and programming of grounding grid will meet the standards of grounding resistance and decrease cost effectively.

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