IOP Conf. Series: Earth and Environmental Science **121** (2018) 042023 doi:10.1088/1755-1315/121/4/042023

Research on electromagnetic environment characteristics of 500 kV full-scale substation based on BEM

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Abstract. Aiming at the electromagnetic environment of 500kV substation, a full-scale simulation model is proposed to calculate the electric field and magnetic field distribution using the boundary element method (BEM). To improve the simulation accuracy and convergence of computation, the structure of original electrical equipment is simplified, and then simplification principles are put forward. Finally, the full-scale model including the full outdoor equipment is established. Electric field and magnetic field distribution of the substation is obtained and compared with the measured value, and the excessive area is determined.

1. Introduction

Electromagnetic environmental of power substation is an essential factor for designing and building a new substation, which can ensure the safety of the staff. At present, the most common method[1-2] is to examine the electromagnetic field whether it is under the limited for the constructed stations, but this method cost too much, and it cannot be used to predict other stations with different layouts. There are few research studies the 500kV full-scale substation model and simulation. Tan Chen[3] used the CDEGS software to calculate, just establish a linear cylindrical conductor composition model. In this paper, a full-scale simulation model is proposed to calculate the electric field and magnetic field distribution using the boundary element method (BEM[4]), and the simulation results are discussed.

2. Derivation of the basic equations of BEM

Indirect boundary integral equation is based on the elementary solution to point charge and the principle of superposition. The charges of the charged surface are distributed as surface-density $\sigma(x, y, z)$ according to the single source view. When the charged body is located in a limited space, both regard infinities as a potential reference point, and the conductor surface $D_n = \sigma = -\varepsilon \frac{\partial \varphi}{\partial n}$, then the potential of any point M in the field according to the superposition principle can be written as follows,

$$\varphi_M = \int_s \frac{(\partial\varphi / \partial n)dS}{4\pi\varepsilon r_1} \tag{1}$$

The formula is the single source of indirect boundary integral equation; it is suitable for the isotropic and homogeneous linear medium. For double equivalent source, the relationship between it and the potential can be derived as follows: let the dipole moment of the dipole electric[5] is $p = q\Delta l$, as Figure 1 shows. Where the Δl is the small distance between the two charges of the equal amount but opposite sign. Moreover, its direction from the negative charge pointing to a positive charge. Then, the potential for the point M is,

$$\varphi_M = \frac{q}{4\pi\varepsilon}\left(\frac{1}{r_2} - \frac{1}{r_1}\right) = \frac{p}{4\pi\varepsilon\Delta l}\left(\frac{1}{r_2} - \frac{1}{r_1}\right) \tag{2}$$

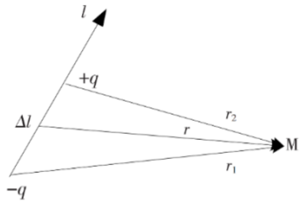

Figure 1. Electric dipole.

Since the Δl is very small, which can be replaced with differential, and the equation (2) can be represented as shown in the blow.

$$\varphi_M = \frac{p}{4\pi\varepsilon}\frac{\partial}{\partial l}\left(\frac{1}{r}\right) = \frac{p}{4\pi\varepsilon}\frac{\cos(\boldsymbol{r},\boldsymbol{l})}{r^2} \tag{3}$$

Thus, the potential generated by the dual-level areal of dipole moment density with surface density σ_p is in the following.

$$\varphi_M = \frac{1}{4\pi\varepsilon}\int_S \sigma_p \frac{\cos(\boldsymbol{r},\boldsymbol{l})}{r^2} dS \tag{4}$$

When the field point and source point has overlapped, there will appear singularity in equation (5), and this singularity is a removable singularity.

$$\varphi_M = \frac{1}{4\pi\varepsilon}\int_S \sigma_p \frac{\cos(\boldsymbol{r},\boldsymbol{l})}{r^2} dS = \frac{1}{4\pi\varepsilon}\int_S \sigma_p \frac{\boldsymbol{n}_p \cdot \boldsymbol{r}^0_{p,M}}{r^2_{p,M}} dS \tag{5}$$

3. Simplified method of substation model

In this paper, the BEM is used to study the distribution of electromagnetic environment in 500kV substation. Based on the characteristics of the rapid attenuation of the electromagnetic field with the distance, the central electrical equipment (current transformer, voltage transformer, circuit breaker and arrester) in the substation is suitable with the problematic modeling and calculation of the substation total station simulation. Moreover, the simulation of a simplified model to verify the accuracy of the simplified simulation. Take TYD500 series capacitive voltage transformer as an example.

Table 1. Material properties table.

Element	Capacitor	Steel	Silicone Rubber	Copper
Permittivity	81	1×10^{8}	3.45	1×10^{8}
Resistivity（Ω·mm）	3.4×10^{-6}	1.007×10^{-4}	1×10^{17}	2.898×10^{-5}

Since the voltage transformer structure is symmetrical along the Y axis, the right half is modeled using the X-Rotational Symmetric pattern in detail, where the blue part is the capacitor, the dark part is the electromagnetic unit, the yellow part is the composite insulator (Silicone Rubber), the red part is the voltage ring, the gray part is the cement pillar. The related material properties are shown in Table 1.

The external composite insulator umbrella skirt of the current transformer was simplified as a smooth cylindrical surface, ignoring the gas and porcelain jacket, the capacitor, the electromagnetic unit and other structures, which was simplified as a whole cylinder. Since the simplified cylinder is composed of a mixture of various materials, the equivalent relative permittivity and resistivity are loaded with the material properties of the cylinder. As shown in the Figure 2-6.

Figure 2. The voltage transformer of TYD 500.

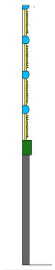

Figure 3. A fine model of the voltage transformer.

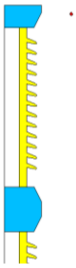

Figure 4. A partial enlargement of the fine model.

Figure 5. A simplified model of the voltage transformer.

Figure 6. A partial enlargement of the simplified model.

The actual operating voltage of the 500kV switch-yard area is 500kV power frequency voltage, in the case of low frequency AC, we used the quasi-static field to calculate. In the calculation, the maximum working voltage value of 303kV is loaded on the high-voltage side and the voltage-bearing ring. The medium-voltage end is loaded with 208kV; the low-voltage side is loaded with 113kV; the electromagnetic unit is loaded with 57kV; plus zero potential on the ground. The simulation results are shown in Figure 7 and Figure 8.

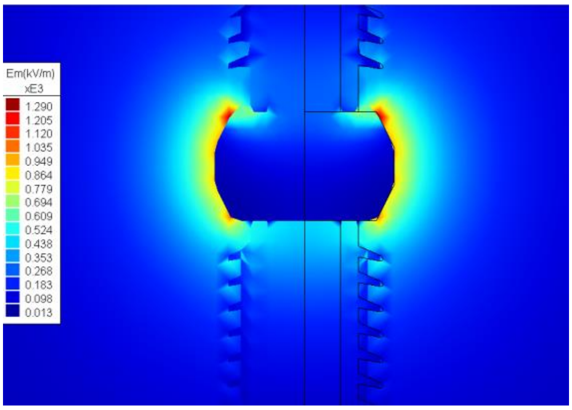

Figure 7. Electrical field distribution near the voltage divider of the fine model.

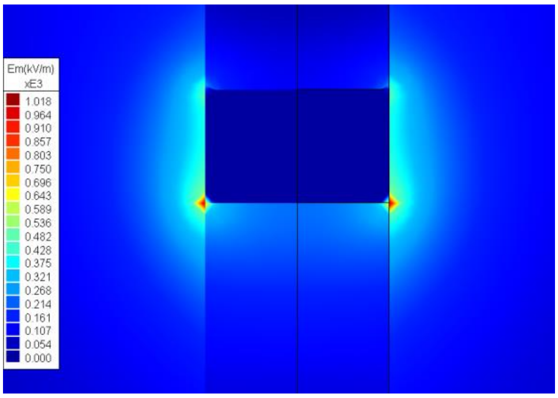

Figure 8. Electrical field distribution near the voltage divider of the simplified model.

From Figure 7-8, we can get some conclusions in the following.

- The effect of the voltage ring in the surrounding electric field is substantial, the maximum field intensity of the equipment is located at the voltage equalization ring;
- The shape of the model has a significant influence on the electric field distribution on the surface of the device. The distortion of the electric field around the pre-capacitor divider is simplified and becomes smaller.
- As the distance from the high voltage side increases, the electric field intensity step is attenuated.

This paper studied the electric field attenuation curves of the circuit breaker and arrester, and verifies the feasibility of the simplified simulation method. The results are shown in Figure 9 and Figure 10.

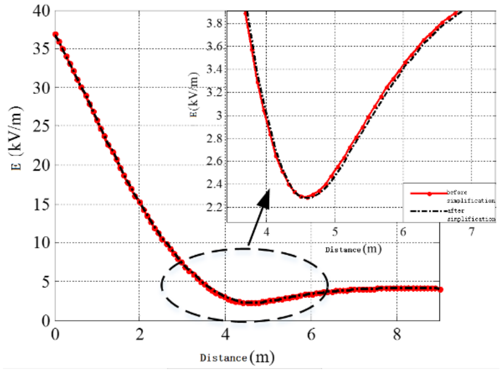

Figure 9. Comparison of the electric field intensity of two 500kV circuit breaker models.

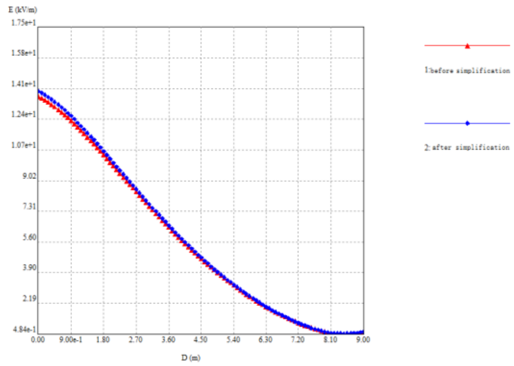

Figure 10. Comparison of the electric field intensity of two 500kV arrester models.

The above research shows that the error of the device model used in this paper is very small and almost negligible in the vast field application. After this, we can use this method to simplify the calculation.

4. The calculation modeling of 500kV substation

4.1. Modeling of 500kV substation

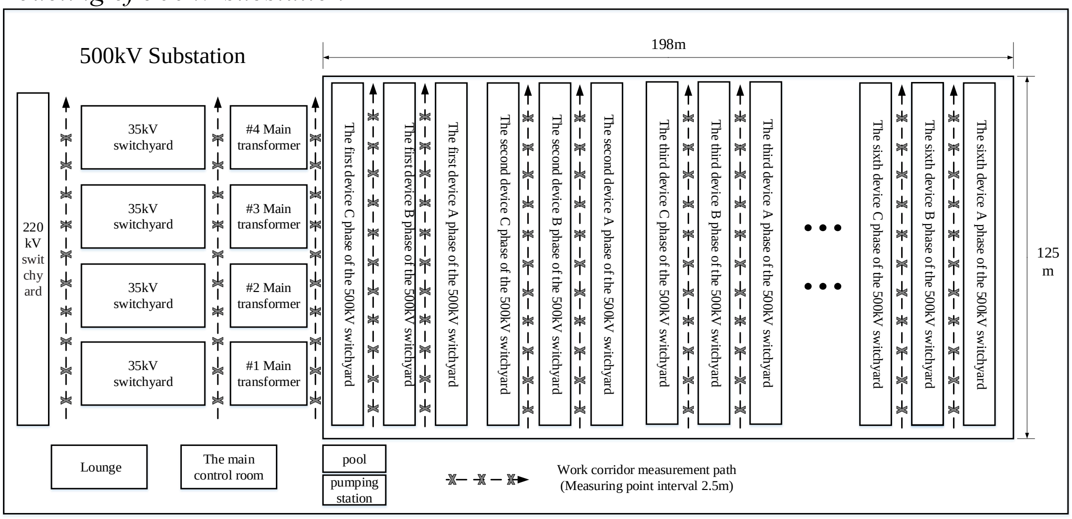

Figure 11. The schematic diagram of the 500kV substation.

In this paper, a 500kV outdoor substation is simulated. There are four transformers in the station. According to the voltage level of the different switch-yard, we can divide the substation area into four parts. Including 500kV switch-yard area, 220kV switch-yard area, and 35kV switch-yard area. The schematic diagram of the substation is shown in Figure 11. The relevant parameters of the wire model are as follows.

- The busbar of 500kV switch-yard area is the LGKK-600 and LGJQT-1400/120;
- The busbar of 220kV switch-yard area is the LDRE-130/116;
- The wire of equipment connection is the LGJ-300/40;

The busbar of 35kV switch-yard area is the NRLH58GJ-1440/120.

The electromagnetic field distribution of substation is very complicated because of distortion of equipment and wires in the switch-yard area. The BEM calculation will spend a lot of the electromagnetic field simulation of computer resources, and the result is not easy to convergence. The distance between each switch-yard is far away, and the influence is small. Therefore, the substation is divided into four parts for independent simulation. Based on the modeling principle of substation described in chapter 3, simulation modeling of 500kV switch-yard equipment is carried out according to the distribution device drawing and related drawings, a 500kV HGIS equipment model shown in Figure 12, reach a single string device simulation diagram is shown in Figure 13, from left to right in turn for HGIS equipment, circuit breaker, the wave resistance, post insulators and lightning arrester.

The overall modeling results of the 220kV switch-yard and 35kV switch-yard are shown in Figure 14 and Figure 15.

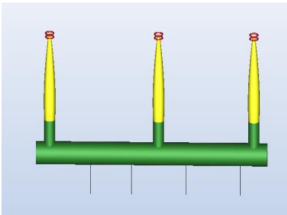

Figure 12. 500kV HGIS equipment model.

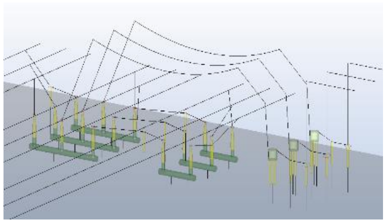

Figure 13. Single-string device model.

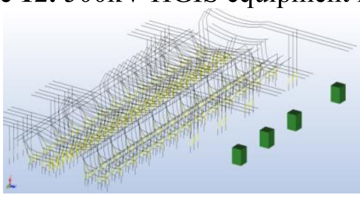

Figure 14. 220kV switch-yard model.

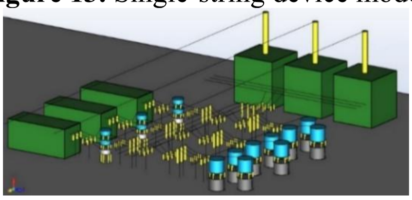

Figure 15. 35kV switch-yard model.

4.2. Calculation result of 500kV substation

Based on the simulating principle of substation described in section 3. The distribution of the electric field intensity at the plane of 1.5m was obtained. As a result, as shown in Figure 16-17.

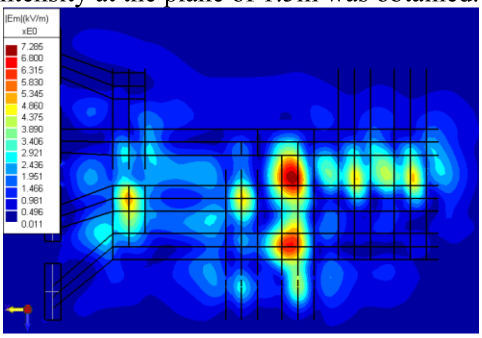

Figure 16. The electric field intensity distribution of the 500kV switch-yard. (From the ground 1.5m)

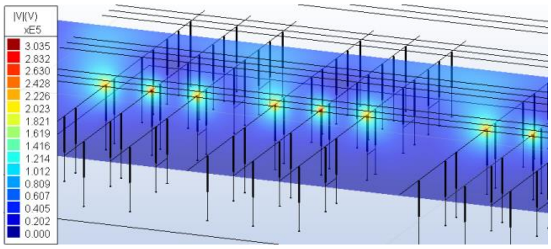

Figure 17. The potential distribution in the rectangular region.

Table 2. The electric field intensity distribution of the 500kV switch-yard

Element	Electric field intensity
Maximum value	14.6kV/m
Mean value	1.30kV/m
Excessive area proportion	15%

The distribution of the frequency electromagnetic field in the switch-yard of 500kV substation was obtained by the simulation results, as shown in table 2. The electromagnetic environment exceeded the main reference of the ICNIRP Guidelines[6] (2010) standards in IEEE(Institute of Electrical and Electronics Engineers). According to the ICNIRP Guidelines, the electric field intensity of public exposure value is 5kV/m, and the occupational exposure limit is derived for 10kV/m.

4.3. Calculation result of 220kV switch-yard and 35kV switch-yard

The actual operating voltage of the 220kV switch-yard area is 220kV power frequency voltage, in the case of low frequency AC, we used the quasi-static field to calculate. In the calculation, the maximum working voltage value of 133kV is loaded on the high-voltage side and the voltage-bearing ring, the potential of the ground is 0V. Moreover, the equipment material properties and voltage, boundary conditions are set before the calculation and analysis. We can get the electric field intensity distribution of the 220kV switch-yard in substation as shown in Figure 18. Similarly, we can get the electric field intensity distribution of the 35kV switch-yard in substation as shown in Figure 19.

It can be seen from Figure 18 that the maximum of the electric field intensity in the 220kV switch-yard is 3.659kV/m, located under the busbar. The overall electromagnetic environment in the region is right, and all electric field intensity is below the limit.

5. Verify the validity of the model

A working corridor in 220kV switchyard was set as an example to verify the accuracy of the calculation model in this paper. The sampling line whose centre position is 65m long and 1.5m high was selected to compare the results of simulation analysis. The blue and red lines in Figure 20 represent the measured and simulated values on the sample line, respectively.

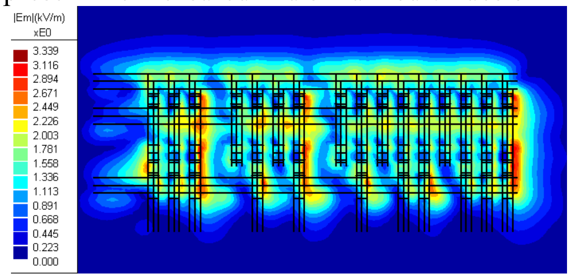

Figure 18. The electric field intensity distribution of the 220kV switch-yard. (From the ground 1.5m)

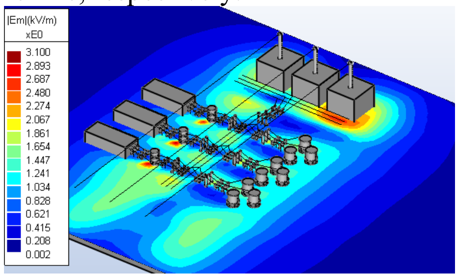

Figure 19. The electric field intensity distribution of the 35kV switch-yard. (From the ground 1.5m)

It can be seen from Figure 20 that the simulation results of this paper are consistent with the actual measured distribution curves. The simulation results show that the simulation results are more smooth in the range of 1~1.5kV/m. Based on the complex equipment structure and environment of the substation, this paper has achieved the ideal simulation results from the point of studying the electromagnetic environment distribution in the substation. Therefore, the simulation model can analyze the distribution of power frequency electromagnetic field in the substation, and the model simplification method is effective.

6. Conclusions

Comprehensive substation full-scale electric field intensity distribution, the proportion of the electromagnetic environment exceeding the standard is shown in table 3.

Combined with the table above and the substation’s electric field distribution diagram, we can see：

- The electric field distribution inside the whole outdoor substation is mainly affected by the voltage level and height of the busbar. The electric field intensity around the 500kV switch-yard is apparently more significant than those around 220kV switch-yard and 35kV switch-yard. Among them, the partial area within 500kV switch-yard has to exceed the limit.

- By the excellent electric field shielding effect and the high inlet wire above, the electric field intensity around the main transformer is relatively lower, within 4kV/m, without exceeding the limit.
- In the switch-yard, the field intensity below the middle phase of each line is small. The larger field intensity is mainly concentrated in the vicinity of the equipment (circuit breaker, disconnector), caused by a common effect, including the discontinuity of electric field in the normal direction of energized conductor, as well as the line's ground height, wire structure, the distance between electric field point and the ground and other factors.
- As the arrangement of the switch-yard bus couple equipment bunch is different from that of the other line equipment, if its surrounding electric field has overlap and distortion phenomena with other equipment, it is most likely to appear the maximum point of electric field intensity.

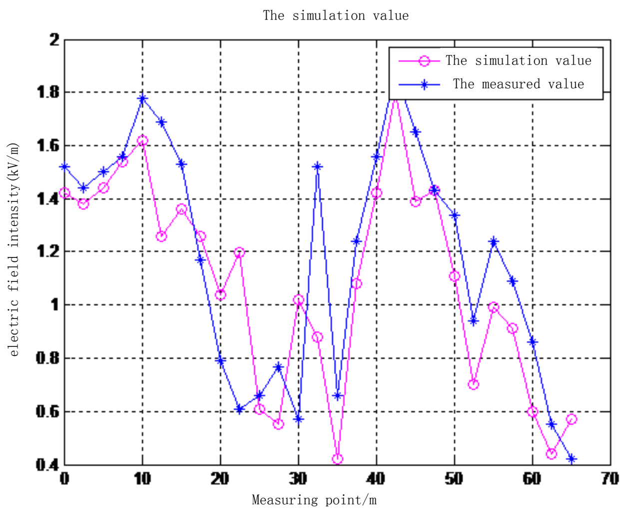

Figure 20. The electric field intensity distribution of the 35kV switch-yard. (From the ground 1.5m)

Table 3. The electric field intensity distribution of the 500kV substation.

Element	Electric field intensity
500kV switch-yard	15%
220kV switch-yard	0
35kV switch-yard	0

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