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Simplification Study of FE Model for 1000kV AC Transmission Line Insulator String Voltage and Grading Ring Surface Electric Field Distribution Calculation

Guoli Wang[1], Zheng Zheng[2], Daochun Huang*[2], Zhengfang Huang[2], Jiangjun Ruan[2], Yifan Liao[1]
[1] National Engineering Laboratory for Ultra High Voltage Engineering Technology (Kunming, Guangzhou), Guangzhou, China
[2] School of Electrical Engineering, Wuhan University, Wuhan, China
*Corresponding author, e-mail: wanggl@csg.cn, huangdc99@163.com

Abstract

The finite element model of the 1000kV Ultra High Voltage (UHV) AC transmission line porcelain insulator string voltage distribution and grading ring surface electric field distribution calculation has the characteristics of large size, complicated structure and various mediums. To insure the accuracy, related influencing factors should be considered to simplify the model reasonably for improving computational efficiency. A whole model and a simplified 3D finite element model of UHV AC transmission line porcelain insulator string were built. The influencing factors including tower, phase conductors, hardware fittings, yoke plate and phase interaction were considered in the analysis. And finally, the rationality of the simplified model was validated. The results comparison show that building a simplified model of three-phase bundled conductors within a certain length, simplifying the tower reasonably, omitting the hardware fittings and yoke plate and containing only single-phase insulator string model is feasible. The simplified model could replace the whole model to analyze the voltage distribution along the porcelain insulator string and the electric field distribution on the grading ring surface, and it can reduce the calculation scale, improve optimization efficiency of insulators string and grading ring parameters.

Keywords: *electric field distribution, finite element (FE), grading ring, voltage distribution, ultra high voltage (UHV)*

1. Introduction

Improving transmission capacity and increasing power transmission distance are needed urgently because of the imbalance distribution of energy resources and power loads in China. In order to meet the rapid load growth and save line corridors, construction of UHV backbone transmission network projects was proposed by SGCC and CSG [1].

Insulators are of great importance for electrical insulation and mechanical support for transmission lines, their reliable operation directly affects the reliability of high voltage power grid [2, 3]. Compared with composite insulator, porcelain insulator is more stable under the long-term effects of atmospheric environment, the acid and alkali pollution, and has better heat resistance and aging resistance. Hence, porcelain insulators are widely used in 1000kV UHV AC transmission lines and substations in China [4].

Under the high voltage effect of UHV AC transmission line, potential distribution is non-uniform along insulator strings because of the different conductor and tower stray capacitances of each insulator. The withstand voltage of the insulator at line end is the highest, and the electric field stress is also the highest. This can possibly cause strong corona and degradation of the insulation. Installation of grading ring has great effect to improve the potential distribution along insulator string [5, 6]. The problems of insulator string non-uniform potential distribution and corona characteristics are more serious under the 1000kV voltage level [7].

Large size, complicated structure and various mediums of the finite element model usually lead to difficulties for the electric field analysis of the UHV AC transmission line insulator and grading ring. Finite element method can be used to calculate porcelain insulator string potential distribution and grading ring surface electric field distribution [7, 8]. The results can be

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used to improve the insulator string voltage distribution, improve the corona and degradation caused by non-uniform voltage distribution and unsuitable parameters of grading ring, and ensure that audible noise and grading ring corona characteristics can satisfy the engineering requirements of UHV AC transmission line.

IEEE Working Group calculated the typical grading ring’s surface field strength and analyzed AC transmission line composite insulators electric field distribution influencing factors [9]. Jing Li built a 3D finite element model, analyzed 1000 kV UHV AC substation porcelain insulators’ potential distribution and grading rings’ electric field distribution and determined the typical parameters of grading rings through simulation and testing [10]. T. Doshi calculated the 1200kV electric field distribution of composite insulator and grading ring, considered the ring parameter, bundled conductor, insulator string and surface state, and optimized grading ring parameters [11]. Suat Ilhan optimized 380kV glass insulator V-string grading ring parameters through the simulation and experiment [12], and studied the effect of grading ring parameters on insulator string [13]. D. Cruz Dominguez analyzed two stress grading options for 115kV non-ceramic suspension insulators by means of 2D and 3D simulations [14].

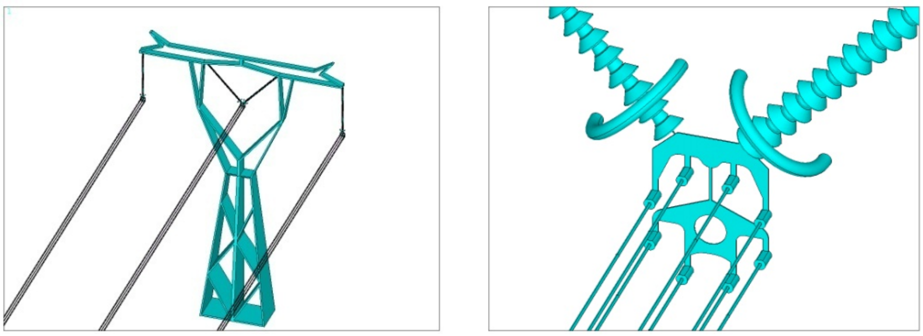
With the computer technology improving, insulator string potential and grading ring surface electrical field distribution of power transmission lines can be calculated according to the line parameters and tower configuration. Some related researches with whole model analysis had been carried out [10, 15, 16], but whole 3D models need higher computer memory and take much computation time. While 2D models also widely used in some researches, sometimes ignored the effects of earth, tower, conductors and yoke plate [17], or just building single phase insulator string, could not guarantee the accuracy.

In summary, existing researches built the whole model or excessive simplified model. In order to improve insulator string reasonable configuration and grading ring parameters optimization efficiency, the FE model simplification study has a very important theoretical and practical meaning. A whole and some simplified 3D finite element model of UHV AC transmission line porcelain insulator string are built in this paper. Related influencing factors including tower, phase conductors, hardware fittings, yoke plate and phase interaction are considered to simplify the model reasonably for improving computational efficiency. Study results show that using a simplified model instead of the whole model calculation can significantly reduce the computational scale, improve computational efficiency, and has an important reference for UHV AC transmission lines insulator string configuration and grading ring parameters optimization design.

2. Whole Model Building and Caclulation

2.1. Calculation Model

The 1/2 whole FE model considered tower, insulator string, grading ring, 8 bundled conductors, hardware fittings, yoke plate according to the UHV AC test and demonstration project in China, shown in Figure 1. The air truncation boundary is a half column with 160m radius, and the length of the column is built as the same as the width of tower (14m), and it will be extended to 100m after the model is meshed.



(a) whole model (b) local model

Figure 1. 1/2 Calculation Model (insulator sheds are simplified)

Caring for grading ring surface field and porcelain insulator string voltage distribution, those area is meshed carefully to improve calculation accuracy, and the number of element is about 16.3 millions. The grading rings, conductors, yoke plate and other hardware fittings of the middle phase are loaded with the maximum operation phase voltage of 1000kV AC power system $U_m=1100\sqrt{2}/\sqrt{3}=898.1462$ kV, the other two phases are loaded with $-U_m/2$. The tower, hardware fittings at ground end and external boundaries are loaded with 0.

2.2. Calculation Results and Analysis

Figure 2 and Figure 3 show the middle phase V porcelain insulator string and the grading ring surface electric field distribution. The red part is high field strength area. when the middle phase are loaded with high potential, the maximum electric field distribution both of middle phase grading ring appears at the bottom of their outside, the maximum surface electric field strength of the middle phase is 19.58kV/cm, which are all below the electric field strength limitation value of 26kV/cm for 1km and below altitude regions in China [18].

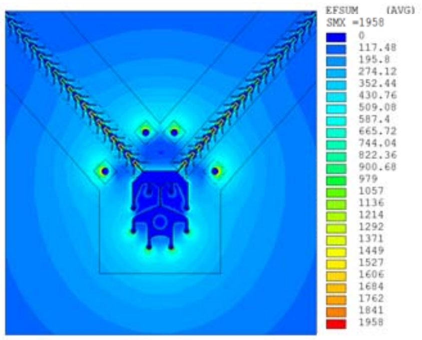


Figure 2. Electric Field Distribution of Insulator String and Grading Rings (kV/m)

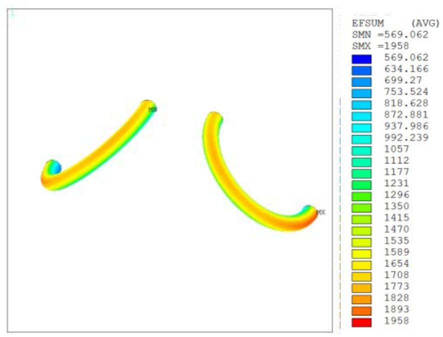


Figure 3. Electric Field Distribution on the Middle Phase Grading Rings' Surface (kV/m)

Figure 4 shows the curve of voltage distribution along middle phase porcelain insulator string. The line side insulators obviously withstand high voltage, and in turn reduce when far from the line. The highest voltage is 47.37kV on the fifth insulator, which is 5.27% of the total voltage. The top 10 insulators (from line side) withstand about 45.59% of the total voltage.

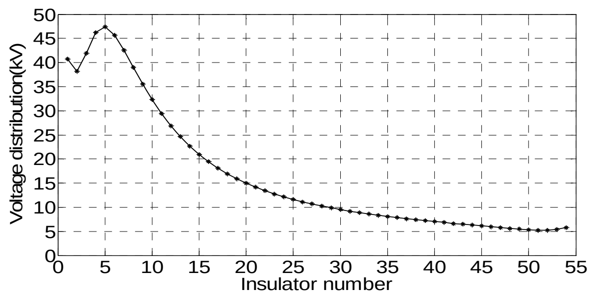


Figure 4. Voltage Distribution along Porcelain Insulator String

The finite element mesh of the whole model maybe is not fine enough for the characteristics of large size, complicated structure and various mediums of UHV transmission line, and the calculation accuracy is not guaranteed but still time consuming as 5 hours with 64GB memory computer. In order to reduce the calculation scale, improve optimization efficiency of insulators string and grading ring parameters, building a reasonable simplified model is necessary. FE Model simplification is necessary to consider conductor, tower, hardware, and three phases interaction on grading ring surface electric field distribution and the voltage distribution of the porcelain insulator string. Unreasonable simplification model will lead to large deviation, influence the accuracy of the calculation results. Reasonable simplified model can effectively reduce the computation scale, improve insulator string and grading ring parameters optimization allocation efficiency.

3. Discussion of the Influencing Factors

FE Model simplification is necessary to consider the influencing factors of conductor, tower, hardware fittings, and three phases interaction on grading ring surface electric field distribution and the voltage distribution along the porcelain insulator string.

3.1. Phase Conductor

It will waste element and reduce computational efficiency when the conductors and air entities are too large in a model. Considering the conductors length of 0m, 14m (tower width), 100m respectively, the maximum electric field strength on the grading ring surface E_m is given in Table 1.

Table 1. Comparison of the E_m with Different Conductor Length

Model	0 m	14 m	100 m
E_m (kV/cm)	35.30	19.74	19.58
Difference with whole model (%)	80.29	0.82	0

When the length of the conductors is reduced from 100m to 14m (width of the tower), the E_m on the grading ring surface is 0.82% increased, that is small enough to be ignored. Length of the conductors changes within a certain range (>14m), the influence on the result of the calculation is small. However, if the length of the conductors is reduced to 0 m, the E_m changed from 19.58kV/cm to 35.30kV/cm, that is 80.29% increased. Hence, three phase conductors must be built in the FE model.

Comparing three different conductor length, Figure 5 shows voltage distribution along the axis of middle phase porcelain insulator string. 100m conductor and 14m conductor curves of voltage distribution along porcelain insulator string are almost the same, and the maximum voltage of porcelain insulator is within 50kV. When without conductors, the porcelain insulator string voltage distribution is more non-uniform, the top 10 discs of insulator near the conductor in the whole insulator string withstand most of the total voltage, the maximum voltage of single insulator withstanding is close to 70kV, which may damage the insulation and lead to flashover.

In conclusion, when the length of conductor changes within a certain range (>14m), the influence on the result of the calculation is small. The length can be reduced to 14m and can reduce the calculation scale.

3.2. Tower

Establishing and analyzing without tower model and simplified tower model respectively, and Figure 6 shows the complete tower model and simplified tower model.

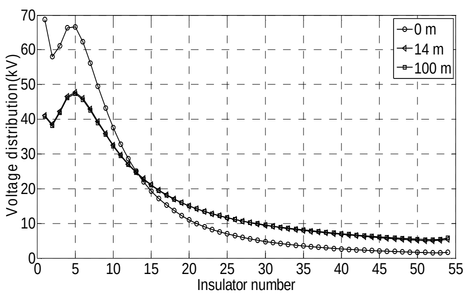
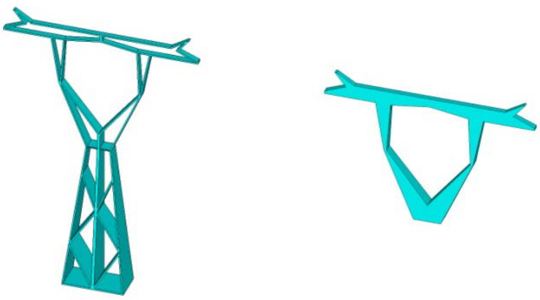


Figure 5. Comparison of Voltage Distribution along Porcelain Insulator String with Different Conductor Length



(a) whole (b) tower

Figure 6. Tower Model

The $\boldsymbol{E}_m$ on the grading ring surface is shown in Table 2, and insulator string voltage distribution curve is shown in Figure 7.

Table 2. Comparison of the $\boldsymbol{E}_m$ with Different Tower Models

Model	Whole model	Without tower	Simplified tower
$\boldsymbol{E}_m$ (kV/cm)	19.58	16.62	19.59
Difference with whole model (%)	0	15.12	0.05

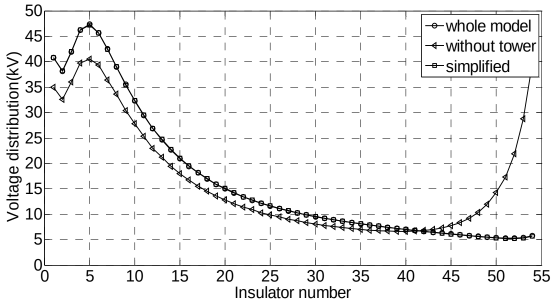


Figure 7. Comparison of Voltage Distribution along Porcelain Insulator String with Different Tower Models

Table 2 shows that the $\boldsymbol{E}_m$ is 15.12% lower than that of the whole model, if the tower is not built in the model. Hence, the tower is necessary to be built but can be simplified appropriately. Using internal hollow simplified tower window as simplified tower in the model, the $\boldsymbol{E}_m$ is almost the same as that of the complete tower model.

Figure 7 shows that when without tower, the top 10 porcelain insulator withstand voltage is smaller than that of with tower. The maximum voltage of insulator withstanding is about 40kV, but there would be a sharp increase of voltage withstanding of the insulators near the ground end. The porcelain insulator string voltage distribution curve of simplified tower and the whole model are basically identical.

In conclusion, internal hollow simplified tower model is efficient instead of the whole model in the calculation of porcelain insulator string voltage and grading ring surface electric field distribution.

3.3. Yoke Plate and End Hardware Fittings

The mesh generation is difficult because of the large dimensional difference with the hardware fittings, yoke plate and tower. The influence of hardware fittings and yoke plate to the $\boldsymbol{E}_m$ is shown in Table 3, and the insulator string voltage distribution curves are almost the same.

Table 3. Comparison of the $\boldsymbol{E}_m$ without Yoke Plate and End Hardware Fittings

Model	Whole model	Without yoke plate	Without hardware fittings
$\boldsymbol{E}_m$ (kV/cm)	19.58	19.84	19.58
Difference with whole model (%)	0	1.33	0

As shown in Table 3, when the yoke plate and end hardware fittings are not built in the model, the $\boldsymbol{E}_m$ on the grading ring surface changes a little. Hence, the yoke plate and end hardware fittings can be omitted in the simplified model.

3.4. Phase Interaction

The whole model of UHV AC transmission line includes middle phase insulator V-string and side phase insulator I-string. When the grading ring and insulator string are as the main research objects, field region near grading ring and insulator string should be meshed in detailed for accuracy. The calculation scale of the whole model including three phases is huge. The insulator string influence of phase to phase should be small as considering the shielding effect of the tower window. If the errors are within the allowable range, a simplified model only including the middle phase or one side phase, and other phases just build conductors is reasonable, that can reduce elements, save calculation time and computer resources greatly.

Table 4 shows the $\boldsymbol{E}_{\mathrm{m}}$ of the V-string grading ring. The insulator string voltage distribution curves of whole model and only with middle phase V-string model are the same.

Table 4. Comparison of the $\boldsymbol{E}_{\mathrm{m}}$ with One Phase Insulator String Models

Model	Whole model	Middle phase V-string
$\boldsymbol{E}_{\mathrm{m}}$ (kV/cm)	19.58	19.58
Difference with whole model (%)	0	0

As shown in Table 4, the $\boldsymbol{E}_{\mathrm{m}}$ are same with whole model when side phase insulator strings are not built. Hence, when one phase insulator and grading ring are under focused, the insulator strings of other two phases can be omitted in the simplified model.

4. Verification of the Simplified Model

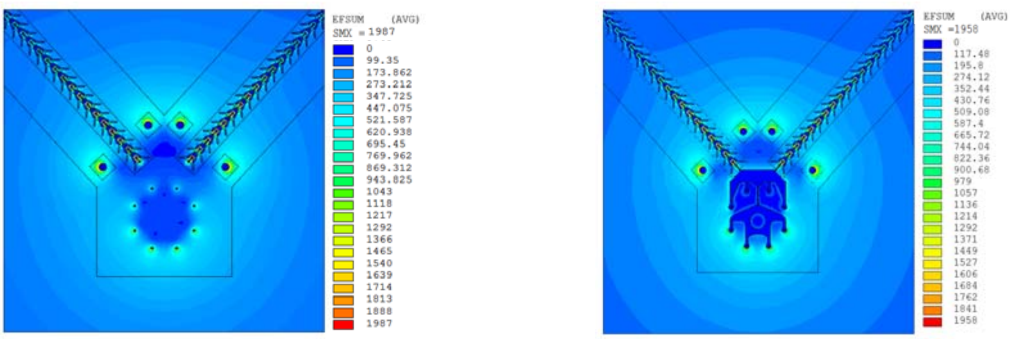
Summarizing above suggestions, a simplified model of three-phase bundled conductors within a certain length, simplifying the tower reasonably, omitting the end hardware fittings and yoke plate and containing only single-phase insulator string is built. The $\boldsymbol{E}_{\mathrm{m}}$ of the whole and simplified model are given in Table 5.

Table 5. Comparison of the $\boldsymbol{E}_{\mathrm{m}}$ with Whole and Simplified Models

Model	V-string		I-string	
	Whole	Simplified	Whole	Simplified
$\boldsymbol{E}_{\mathrm{m}}$ (kV/cm)	19.58	19.87	17.83	18.25
Difference with whole model (%)	0	1.5	0	2.4

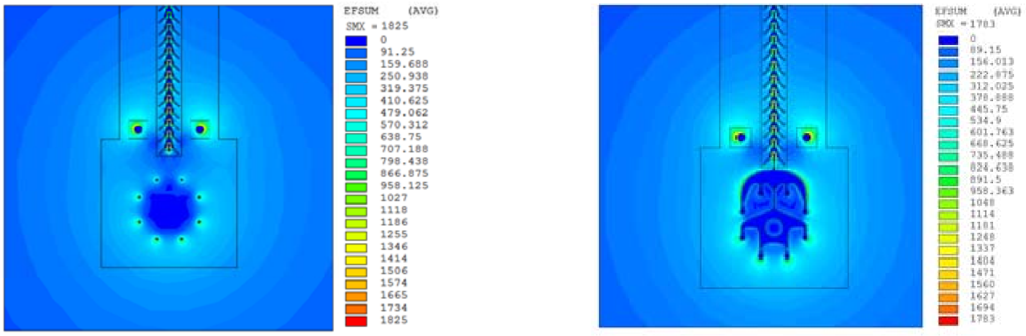
As shown in Table 5, the $\boldsymbol{E}_{\mathrm{m}}$ increases 1.5% in simplified V-string than that of the whole model, and is 2.4% for simplified I-string. Hence, the simulation relative errors can be controlled within 2.4%.

Comparison of simplified V-string and I-string model with whole model, shown in Figure 8 to Figure 11.



(a) simplified model V string (b) whole model V string

Figure 8. Comparison of the Electric Field Distribution of Simplified V-string and Whole Model(kV/m)



(a) simplified model I-string (b) whole model I-string

Figure 9. Comparison of Electric Field Distribution of Simplified I-string and Whole Model (kV/m)

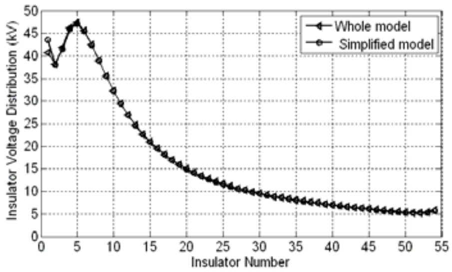


Figure 10. Comparison of the Voltage Distribution along Porcelain Insulator String of Simplified V-string and Whole Model

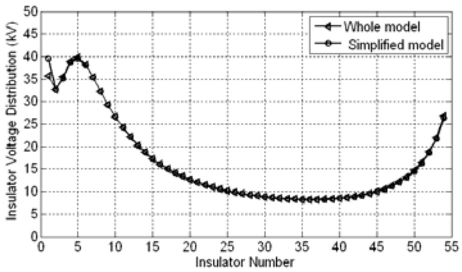


Figure 11. Comparison of the Voltage Distribution along Porcelain Insulator String of Simplified I-string and Whole Model

It can be seen from Figure 10 and Figure 11, the voltage distribution curves along porcelain insulators V-string and I-string of the simplified model and the whole model are almost the same, especially the maximum withstand voltage.

Ignored and simplified parts of the model has little impact to analyze the voltage distribution along the porcelain insulator string and the electric field distribution on the grading ring surface.

The time consumption of the simplified model is reduced to about 2 hours in the premise of high accuracy. Using the simplified model to replace whole model for porcelain insulator string of voltage distribution and grading ring surface electric field distribution analysis is reasonable, and can significantly reduce the calculation scale, improve calculation efficiency.

5. Conclusion

In order to overcome the difficulties in the analysis of the UHV AC transmission line porcelain insulator string voltage distribution and grading ring surface electric field distribution, influencing factors including tower, phase conductors, end hardware fittings, yoke plate and phase interaction are discussed and compared with the whole model in the paper. Conclusions can be drawn as follows:

1) Three-phase conductors and tower should not be neglected when modeling, and simplified model of conductor length can be controlled within a certain range (> 14 m); using a simplified model instead of a complete tower is reasonable; the yoke plate and end hardware fittings can be omitted in the simplified model.

2) In the simplified model, insulator can be built only of the middle phase V-string, or the side phase I-string for high potential phase insulator string voltage distribution and grading ring surface electric field distribution analysis.

3) The simplified model can replace the whole model to analyze the voltage distribution along the porcelain insulator string and the electric field distribution on the grading

ring surface, and it can reduce the calculation scale, improve optimization efficiency of insulators string and grading ring parameters.

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