Qing Yang, Rui Wang, Wenxia Sima, Tao Yuan and Lei Liao
Chongqing University

Improvement of the Electric Field Distribution around the Ends of Composite Insulator with Series Connection of Glass Insulator

***Abstract**. This paper proposes a new compound mode composed of a composite insulator in series with glass insulators, designed to improve its electric field distribution based on its own capacitive electric field distribution characteristics. A three-dimensional electric field calculation model of a composite insulator in a transmission line was designed and employed to study the improved situation of the surface potential and the electric field distribution of a composite insulator, with a glass insulator installed in its high-voltage side at 110 kV.*

***Streszczenie.** W artykule zaproponowano system połączenia izolatorów kompozytowych i szklanych. Obliczono numerycznie pole elektryczne modelu izolatora zainstalowanego w sieci 110 kV. (**Poprawa rozkładu pola elektrycznego na końcach izolatorów kompozytowych połączonych z izolatorami szklanymi**)*

Keywords: composite insulator; glass insulator; electric field distribution; finite element.
Słowa kluczowe: izolatory kompozytowe, izolatory szklane.

Introduction

Similar with porcelain insulator strings, the axial potential distribution of composite insulator strings is non-uniform. Based on the characteristics of capacitive electric field distribution of composite insulators, this paper presents a new measure to improve electric field distribution based on previous studies conducted at the Chongqing University [1]. The main concept of the proposed method is to present a new compound mode composed of a composite insulator in series with glass insulators, designed to improve the electric field distribution of composite insulator. In order to verify the electric field optimization, the electrical circuit analysis and the 3D electric field calculation are carried out for the clean insulation system, which is the usual electric field optimization method for the insulation system. Moreover, one of the main reasons for the application of composite insulator is that composite insulators have the better anti-contamination-flashover performance compared with the glass and ceramic insulators. Therefore, in order to find whether the compound mode has the effect on the contamination flashover performance of composite insulators, the artificial pollution flashover tests are carried out. Finally, this compound mode has been put into the reality application and shows a good service performance.

Characteristics of capacitive electric field distribution of composite insulators

HV and EHV composite insulators are used under extremely uneven electric fields. As a result of its structure and size characteristics, a vertical capacitor is smaller and its axial electric field distribution is more uneven. The electric field distribution optimization of composite insulator is usually carried out for the clean and dry insulators, as shown in the reference [2-4]. In a dry and clean state, the voltage distribution of a composite insulator string is characterized by a capacitive distribution. According to Kirchhoff's law, if a composite insulator circuit is placed in a series with capacitors, resistors, or inductors, the voltage of the composite insulator can be assumed to be significantly improved.

Inasmuch as any device installed in series must have an insulation property, performing this using glass or porcelain insulators, which are inherently capacitive, is feasible. The equivalent longitudinal capacitance of a glass insulator is large. To analyze qualitatively the changes in the electric field distribution when a composite insulator is in series with a glass insulator at the conductor side, the equivalent circuit diagram of the composite insulator in series with a glass insulator is illustrated, as shown in Figure 1. In the equivalent circuit, the capacitance between the connection of composite insulators and glass insulator strings and the ground is represented as C_g. The capacitance between the connection of composite insulators and glass insulator strings and conductor is C_c. C_1 and C_2 are the self-capacitances of composite and glass insulators, respectively. $C_{g'}$ is the stray capacitance between the conductor and the ground.

In Figure 1, assuming that the voltage of a line is U_g, then the voltage applied to the entire insulator strings is U_g. According to Ohm's law, the voltage ΔU applied to the capacitance C_2 is

(1) $$\Delta U = \frac{\dfrac{1}{j\omega(C_2 + C_c)}}{\dfrac{1}{j\omega(C_1 + C_g)} + \dfrac{1}{j\omega(C_2 + C_c)}} U_g$$

Simplify equation (1), the following is obtained:

(2) $$\Delta U = \frac{C_1 + C_g}{C_1 + C_2 + C_c + C_g} U_g$$

The self-capacitances of glass insulator is about 30~50*pF*, the stray capacitance between the conductor and the ground is about 4~5*pF* and the capacitance between the conductor and transmission line is about 0.5~1*pF* [5]. The self-capacitances of 110kV composite insulator is about 10~20*pF* [6]. Therefore, when the values of the capacitors C_1 = 15*pF*, C_2 = 50*pF*, C_g = 4*pF*, C_c = 0.7*pF* are replaced into equation (2):

(3) $$\Delta U = 27.25\% U_g$$

Therefore, it can be found that when a composite insulator is in series with a glass insulator at the conductor side, the glass insulator sustains 27.25% of the voltage drop across the line, so the corresponding voltage drop on composite insulator is 72.75%. Thus, the potential distribution of a composite insulator is improved effectively.

Based on the above results, a composite insulator in series with glass insulator strings can effectively reduce the voltage that the composite insulator withstands, as well as adjust the axial potential distribution. For specific application guidelines of composite insulators in series with glass insulators at different voltage levels, a more detailed analysis of a three-dimensional model of the electric field must be made.

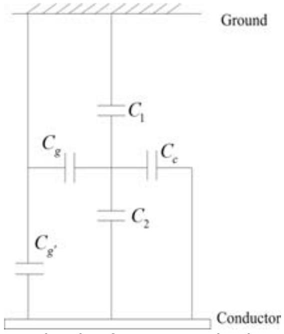

Fig.1. The equivalent circuit of a composite insulator in series with a glass insulator

Field analysis of composite insulator in series with glass insulators

Foundation of the electric field model

The general solution for the low frequency electromagnetic fields in insulating systems can be obtained by solving Maxwell's equation. Because the power frequency is a very low frequency field, and the conductivity of dielectrics is very small, the coupling effect between the electric field and the magnetic field can be omitted. Therefore, the quasi-static field calculation method is applied in the electric field calculation model. In the present study, based on the quasi-electrostatics field model [7-8] of the finite element software COMSOL Multiphysics 3.4 AC/DC Module, the three-dimensional electric field calculation models of 110 kV tower-conductor-insulators is set up [2,9].

The three-dimensional electric field calculation model of a composite insulator in series with glass insulators is composed of insulators, towers connecting with insulators, conductors, and hardware fittings, shown in Figure 2. The parameters are the practical sizes of equipments in Figure 2. The type of tower is 110kV Z-type cup-tower. The height of the tower is 16 m, and the length of crossarm is 13m. The type of the conductor is LGJ-300. The type of the ground wire is GJ-50, and the types of insulators are $FXBW_3$-110/70 and FC-100/146. In the model, insulators are in a dry and clean state. This study considers the towers to be made of synthesis steel, which is of good conductive property. Synthesis steel reticulation has good shielding performance. In the calculations, the towers of complex network structures are considered as equipotential pyramids. Inasmuch as the towers are connected to the ground and the ground wire, their electrical potential is set as zero.The number of elements reaches about three hundred thousand units. The computation time in relation with the characteristics of the PC reaches tens of minutes and the relative tolerance is set as 0.001.

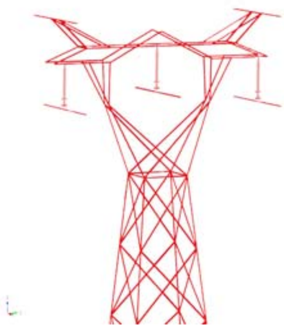
Fig.2. The three-dimensional computing model of the 110kV transmission line

Based on this electric field calculation model, the three situations of the composite insulators in series with glass insulators are as follows. The first is composed of a standard composite insulator and a standard composite insulator in series with a glass insulator at the conductor side. The second is composed of a standard composite insulator and a composite insulator in series with a glass insulator, whose total length is equivalent to that of the former. The last is composed of a standard composite insulator and a composite insulator installed with a corona ring in series with a glass insulator, whose total length is equivalent to that of the former. All of these are shown in Figure 3. Figure 3(a) presents the construction of a new transmission line, and Figures 3(b) and (c) illustrate the transformation for old transmission lines.

The structure parameters of 110kV composite insulator, glass insulator and corona ring are shown in Table1:

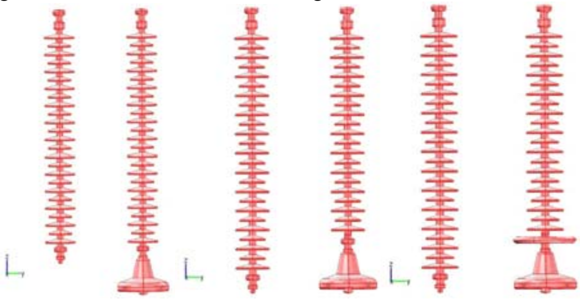
(a) (b) (c)
Fig.3. Standard composite insulator and its several improvements

Table 1. (a) The main parameters of composite insulator (mm)

Product model	umbrella group number	Diameter big/small
$FXBW_3$-110/70	13big 12small	150/115
structure height	insulation distance	creepage distance
1190	1040	3200

(b) Parameters of corona rings

Voltage level	D(mm)	d(mm)	h(mm)
110kV	195	30	35

(c) The main parameters of glass insulator

Product model	Diameter	structure height	creepage distance
FC-100/146	255	146	320

By establishing the three-dimensional electric field model, the electric field calculation method can be used to study a composite insulator in series with glass insulators at the 110 kV voltage level. Compared with the electric field distribution of standard composite insulators, the simulation results are used to analyze improvements in the electric field distribution. In calculating at 220 kV and 500 kV voltage levels, the composite insulator in series with glass insulators can also be used as reference.

Electric field analysis of standard composite insulator in series with glass insulators

Electric field of a standard composite insulator in series with glass insulators is simulated, illustrated as Figure 3(a). The simulation results of axial potential distribution for standard composite insulators, standard composite insulators in series with *n* units of glass insulators are shown in Figure 4 and 5.

Figure 4 illustrates the electric field distribution as equip-potential lines when standard composite insulators are in series with *n* (*n* =0, 1, 2) units of glass insulators. From this figure, it can be found with the increase of the unit of glass insulators, the equip-potential lines around the high voltage end of the composite insulator start to be dispersed, which means the electric field around the high voltage end starts to decrease. Figure 5 and Table 2 show that when the corona ring of a composite insulator is removed, the uniformity of the potential distribution is improved by the composite insulator in series with glass insulators. As the number of glass insulators in series with composite insulator increases, the high voltage end potential of the composite insulator declines. When the composite insulator is in series with a glass insulator, the high voltage end potential of the composite insulator is 65.33 kV, which shows a 27.25% decrease than that of a standard composite insulator. The potential difference of 20% dry arc distance from the high voltage end of the composite insulator is reduced from 58.24% to 48.26%. The maximum surface electrical field strength is 0.54 kV/mm. When the composite insulator is in series with two glass insulators, the high voltage end potential of the composite insulator is at 52.83 kV and the 20% dry arc distance from the high voltage end of the composite insulator withstands 41.69% of the total voltage. The maximum surface electrical field strength is 0.34 kV/mm. The two glass insulators of the whole insulator string have a withstand voltage of 36.16 kV. The maximum surface space electrical field strength is 0.32 kV/mm, which is smaller than the surface discharge field of glass insulators in the air.

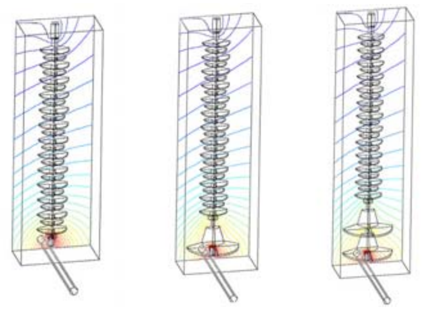

Fig.4. Equipotential lines of 110kV standard composite insulator in series with glass insulators.

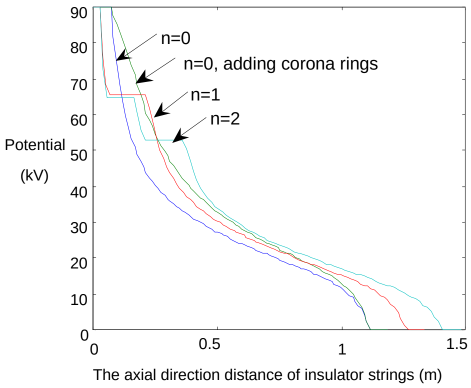

Fig.5. Potential distribution of 110kV standard composite insulator in series with glass insulators

Table 2. The field strength computation of 110kV standard composite insulator in series with glass insulators

n	0	0(corona rings)	1	2
Potential difference which composite insulator withstands, %	100	100	72.75	58.83
The maximum surface electrical field strength (kV/mm)	1.2	0.39	0.54	0.34
The potential difference of 20% dry arc distance from the high voltage end of the composite insulator, %	58.24	45.78	48.26	41.69

Therefore, at the 110 kV voltage level, when a composite insulator is in series with glass insulators, the potential difference, which the composite insulator withstands, declines because of the sharing role of glass insulator strings. This shows that the high end of the composite insulator is far away from a high electric field area. As a result of the voltage-sharing role of glass insulator strings, the surface electric field strength of composite insulators is improved significantly as the number of glass insulators in series increases. When a standard composite insulator is in series with two glass insulators, the surface potential distribution and the electrical field strength of the composite insulator can be controlled efficiently.

Electric field analysis of equivalent structure height insulator strings

Simulation results from the previous section show that a composite insulator in series with glass insulators at the high voltage end can achieve desirable effects in improving surface potential distribution and electrical field strength of composite insulators.

The simulation model of an equivalent structure height of a composite insulator in series with glass insulator strings is built and calculated to study the electric field and its potential distribution, as shown in Figure 3(b). The so-called equivalent structure height is made by reducing the length of the standard composite insulator core rod, making the transformed strings' height of composite insulator in series with glass insulators similar to the height of a standard composite insulator. This layout can maintain the insulation level between the transmission line and the ground.

Figure 6 illustrates the electric field distribution as equip-potential lines when equivalent structure height insulator strings are in series with *n* (*n* =0, 1, 2) units of glass insulators. The axial potential distribution of the 110 kV equivalent structure height of a composite insulator in series with glass insulator strings changes with string length, as shown in Figure 7.

The trend in Figure 6 and 7 is similar to that of a standard composite insulator in series with glass insulators. In the case of the same number of glass insulators in series with a composite insulator, because of the decrease in the length of the core rod, the voltage-sharing role of the glass insulator strings falls, thus increasing the potential difference of the composite insulator.

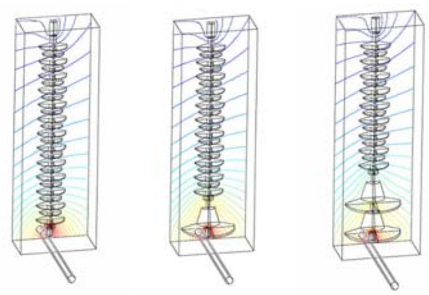

Fig.6. Equipotential lines of 110kV equivalent structure height composite insulator in series with glass insulators.

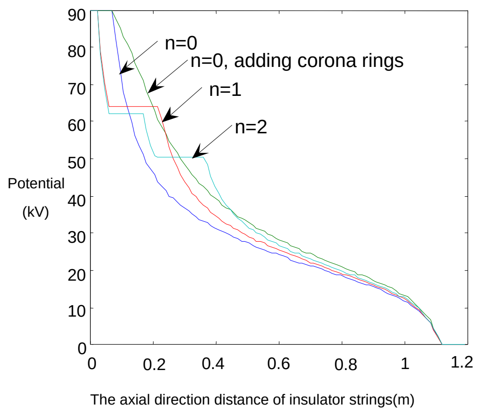

Fig.7. Potential distribution of 110kV equivalent structure height insulator strings

Table 3. The field strength computation of 110kV equivalent structure height composite insulator

n	0	0(corona rings)	1	2
Potential difference which composite insulator withstands, %	100	100	71.34	56
The maximum surface electrical field strength (kV/mm)	1.2	0.39	0.54	0.34
The potential difference of 20% dry arc distance from the high voltage end of the composite insulator, %	58.24	45.78	39.95	43.67

Comparison with installing corona ring

A corona ring has the distinct role of reducing the maximum electric field strength of a composite insulator surface. Local and foreign studies on corona ring have shown that it improves the electric field distribution around the high voltage end of a composite insulator while limiting the total potential distribution of insulators.

Figure 8 illustrates the electric field distribution as equip-potential lines when the corona ring and glass insulators are installed simultaneously at the high voltage end of the composite insulator. When a glass insulator is in series with the high voltage end of a composite insulator with a corona ring, the equip-potential lines at the high voltage end are well-distributed.

This is mainly because of the partial pressure role of glass insulator strings in adjusting the potential distribution and in reducing the uneven distribution of its potential. Meanwhile, because of the voltage-sharing role of a corona ring and glass insulators, the surface electric field of composite insulators, which is far below the surface initiative corona discharge field, is controlled efficiently, and a large margin is also observed.

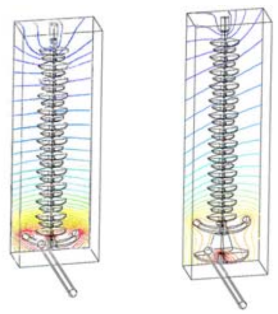

Fig.8. Equipotential lines of 110kV equivalent structure height composite insulator adding corona rings in series with glass insulators.

Table 4. The field strength computation of 110kV composite insulator adding corona rings

n	0	1
The maximum surface electrical field strength (kV/mm)	0.39	0.229
The potential difference of 20% dry arc distance from the high voltage end of the composite insulator, %	45.78	38.51

In summary, comparing the three compound modes proposed in Figure 3(a), (b) and (c), the best compound mode is the one in Figure 3(c), namely a composite insulator installed with a corona ring and a glass insulator at the high voltage end. Under this condition, the surface electrical field strength and the potential difference of 20% dry arc distance from the high voltage end of the composite insulator are both the smallest. Moreover, this compound mode will not reduce the insulation level of the transmission line.

Contamination flashover characteristics in the experimental research of composite insulators in series with glass insulators for different ESDD and NSDD

Simulation results from the previous section show that the composite insulator in series with glass insulators at the conductor side can achieve desirable effects, thereby improving surface potential distribution and electrical field strength of composite insulators. The contamination flashover performance is investigated to find whether the contamination flashover performance is reduced or changed by means of this compound mode. Artificial contamination tests were then carried out to provide data support for the simulation results and to act as reference for use of this new insulator compound mode.

Using the 110 kV voltage level as an example, the contamination flashover characteristics of a composite insulator in series with glass insulators for different contamination levels are studied from two aspects as: increasing ratio of flashover voltage and the average flashover gradient. Composite insulators at the 220 kV and the 500 kV voltage levels can also use this as reference.

Test equipment and test methods

The test samples are FXBW3-110/70 and FC-100/146. Their structure parameters are shown in Table 1. The test was carried out in a multi-functional artificial fog room, which can simulate rain, fog, and other weather conditions, at the State Key Laboratory of Power Transmission Equipment and System Security and New Technology of the Chongqing University. Test power was measured using a 500 kV/2000 kVA AC test transformer, whose short circuit current is 75A, to meet the requirements of IEC507 and GB/T4585 (2004) tests for contamination test power.

IEC60815 (2004) was used as the test standard to simulate contamination in a composite insulator in series with glass insulators. The contamination of samples refers to the solid coating method recommended by IEC 60507 (1987) and GB/T4585 (2004). Conductive materials are simulated using NaCl, while insoluble materials are simulated using diatomite. Different contamination degrees of salt density were selected as 0.12, 0.15, 0.2, 0.25, and 0.3 mg/cm^2. The ratio between salt density and non-soluble deposit density was 1:6. Samples were moistened by steam fog and exerted by uniform ascending pressure method. Each insulator string flashover test was done four to five times every 3–5 minutes. The average of all points, whose error is no more than 10% of the average, is considered as U_f.

Test results and analysis

Table 5. The creepage distance under different conditions

n	Creepage distance(mm)
0	3200
1	3520
2	3840

Table 6. Test results about the relation between U_f vs. ρ_{ESDD} and ρ_{NSDD}

		u_f /kV		
ρ_{ESDD} /(mg/cm^2)	ρ_{NSDD} /(mg/cm^2)	*n*=1	*n*=2	*n*=3
0.05	0.3	179.2	200.8	221.9
0.15	0.9	136.5	153.8	172.8
0.2	1.2	127.2	143.3	159.6
0.25	1.5	120.1	136.9	152.6
0.3	1.8	115.3	129.4	143.9

As the pieces of glass insulators in series with a composite insulator at the conductor side increase, the total height and the creepage distance also increase. Flashover voltage also rises correspondingly. Therefore, considering the effectiveness of creepage distance and its effects on polluted flashover voltage is necessary. As a result of the increases in creepage distance when composite insulator is in series with glass insulators, studying flashover gradient changes comparatively is necessary.

The flashover voltage gradient along the leakage distance indicates that, under different contamination degrees, the creepage distance per unit length can withstand the maximum voltage as a direct reflection of the utilization efficiency for the insulator creepage distance. Flashover gradient can be expressed as

(4) $$E_C = U_f / L$$

where E_C is the flashover gradient of insulator string, kV/mm; L is the creepage distance of insulator string, mm.

Table 7. The relation between E_C vs. ρ_{ESDD} and ρ_{NSDD}

		Flashover gradient (kV/mm)		
ρ_{ESDD} /(mg/cm^2)	ρ_{NSDD} /(mg/cm^2)	n=1	n=2	n=3
0.05	0.3	0.056	0.057	0.058
0.15	0.9	0.043	0.044	0.045
0.2	1.2	0.04	0.041	0.042
0.25	1.5	0.038	0.039	0.04
0.3	1.8	0.036	0.037	0.038

In Tables 6 and 7, for 110 kV composite insulators under different contamination degrees, with the pieces of glass insulators in series with composite insulator increasing, flashover voltage increases correspondingly because of the upsurge in creepage distance. When the composite insulator is in series with one or two glass insulators at the conductor side, there is little effect on the flashover gradient.

Application of reality

The research results above indicate that the compound mode of Figure 3(c) is the optimum. Therefore, this compound mode of Figure 3(c) is put into use in reality. According to the findings and the recommendations of the Henan Electric Power Research Institute, the 110 kV Shabao line adopts the scheme of a composite insulator in series with one glass insulator at the conductor side. The new compound mode of one glass insulator in series with the composite insulator with a corona ring is adopted when technical reform was completed in 2008.

The 110 kV Shabao line, with a total length of 14.115 km, and composed of 48 towers, was put into operation in August 2002. The Shabao line's wire type is LGJ-300, its ground wire type is GJ-50, and its insulator types are FXWP-70 and FXBW-110/100.

Fig.9. 110kV Shabao line: composite insulator in series with one glass insulator at conductor side

From 2006 to 2008, aging of the composite insulator and the tripping incidents occurred frequently on this transmission line because of lightning strikes. Examination reveals that there is a clear vestige on the fault point of insulators. Results indicate that there is a direct relation between lightning strike accidents, the weather, and the landscape, aside from the factor of low lightning withstand level. Obvious aging of the composite insulators occur and the surfaces appear to have much electric traces and electric erosions. To improve the surface electric field of insulators, the new compound mode of one glass insulator in series with the composite insulator with a corona ring was adopted. From the three years observation, this method improved the electric field distribution of the composite insulator and the lightning withstanding level of transmission lines.

Conclusion

In this paper, a new compound mode composed of a composite insulator in series with glass insulators at the conductor side is proposed in order to improve the electrical field distribution of composite insulators. The three compound modes of the composite insulator in series with the glass insulator at the conductor side are applied to the electric field calculation and analysis. The artificial contamination flashover tests results indicate that the anti-contamination-flashover performance remains barely unchanged. The reality application shows a good service performance of such electric field optimization method.

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***Authors**: prof. Qing Yang, Wenxia Sima and Tao Yuan. State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing of China, E-mail: yangqing@cqu.edu.cn, cqsmwx@cqu.edu.cn, and yuantao_cq@cqu.edu.cn; Master candidates Rui Wang and Lei Liao, E-mail: wangruicqu@cqu.edu.cn, liaolei@cqu.edu.cn.*

The correspondence address is:
e-mail: yangqing@cqu.edu.cn.