Analysis of Electric Field Distribution on Composite Insulator of 500kV AC Typical Tower and Its Effect on Decay Fracture

Yu Fan\textsuperscript{1,4,a}, Yu Deng\textsuperscript{1,*}, Jun Zhou\textsuperscript{1}, Jian Wang\textsuperscript{2}, Longwu Lei\textsuperscript{3}, Jun Xu\textsuperscript{3} and Xiaojie Wang\textsuperscript{3}

\textsuperscript{1} China Electric Power Research Institute, Beijing, 100192, China
\textsuperscript{2} State Grid Corporation of China, Beijing, 100031, China
\textsuperscript{3} State Grid Fujian Electric Power Research Institute, Fuzhou, Fujian Province, 350003, China
\textsuperscript{4} State Key Laboratory of Electrical Insulation and Power Equipment, Xi’an Jiaotong University, Xi’an, Shaanxi Province, 710049, China
\textsuperscript{a} ee_fanyu@stu.xjtu.edu.cn
\textsuperscript{*} Corresponding author’s e-mail: dengyu8391@sina.com

Abstract. A new type of composite insulator mechanical failure named decay-like fracture happens rather often in UHV AC transmission lines. However, the cause from the point view of electric field is not clear. To investigate the effect of electric field on the occurrence and development mechanism of decay-like fracture, the 3D tower-conductor-insulator models for ZB2-type and CZ34-type transmission tangent towers are established and analysed based on the finite element simulation. The conclusion can be drawn that the tower type has a significant effect on the electric field distribution along the axial direction of the insulator string, and the degradation is more likely to occur in high-voltage side of the B-phase string, which is consistent with the fracture failure investigation. Simulation results also show that the withstand electric field strength is 297kV/m. The distribution of surface potential and electric field under the actual operating voltage provide a new idea for the condition monitoring of the decay-like fracture of UHV AC composite insulators in transmission lines, as well as a reference for further research in the field of decay-like fracture failure.

1. Introduction

As the core component in high voltage transmission lines, the composite insulator has a decisive influence on supporting and insulation, which is widely utilized in power systems. However, a new type of composite insulator mechanical failure in high voltage transmission lines, which is different from normal fracture and brittle fracture, named Decay-like Fracture, appeared in China and Korea \cite{1-3}. Based on the statistical analysis to the accidents about decay-like fracture insulators, it is found that the decay-like fracture insulators mostly occurred in the UHV AC 500kV compact transmission towers and cup-type tower.

Yuan \textit{et al}. \cite{4} put forward the theory about the decay-like fracture failure mechanism of the GRP rod, which divided into four stages: deterioration of end fitting, hydrolysis and ionic exchange, oxidation of the epoxy resin, and rapid development. Lu \textit{et al}. \cite{5} proposed that the defects formed during the partial discharge caused by the internal defects during manufacturing were primary causes...
of temperature rise and the degradation of the GRP rod. Liang et al. [1-3] and Lutz et al. [6] proposed that the failure of the sheath-core interface was the primary cause and water was a necessary factor. Overall, all these speculations are based on the experimental analysis and the cause from the point view of the electric field is not clear. In other words, the occurrence and development mechanism are far from resolved.

In response to this situation, the 3D tower-conductor-insulator models for ZB2-type and CZ34-type transmission tangent towers are established with finite element software COMSOL. The surface potential and electric field distribution along composite insulators and the effect of related structure parameters are obtained by analysis of computation results.

The electric-field intensity, as a non-contact electrical parameter [7], can reflect the operating conditions of the composite insulators. All of these provide exact data for on-line monitoring [8] and remote data transmission of UHV AC composite insulators, which has important scientific and engineering value in the field of decay-like fracture failure to improve the operational reliability of composite insulators.

2. Simulation models and settles

2.1. Tower models

The structure of ZB2-type and CZ34-type transmission tangent towers are shown in Figure 1.

![Figure 1. Structure of the transmission line tower.](image)

2.2. Composite insulator model

The FXBW-500/210-2 type suspension composite insulator is selected as the simulation object. The parameters are shown in Table 1. The structure is shown in Figure 2, and the simplified structure to be modelled is shown in Figure 3.

| Structural parameters                                      | Value     |
|------------------------------------------------------------|-----------|
| structure height/mm                                        | 4450±50   |
| minimum dry arc distance/mm                                | 4070      |
| minimum creepage distance/mm                               | 14000     |
| diameter of FRP rod/mm                                     | 24        |
| sheath thickness/mm                                        | 5         |
| diameter of disc/mm                                        | 135/170   |
| inclined angle of the sheds/°                              | 10        |
| spacing between big sheds/mm                               | 88        |
| spacing between big shed and small shed/mm                 | 41        |
2.3. Model configuration

The model is a low-frequency AC system, for the voltage frequency of the three-phase AC transmission line is 50Hz during normal operation, which means the wavelength is much larger than the geographical size of the research domain \(^9\). Therefore, we can treat it as an electrostatic field problem.

The voltage value of the conductors is set to 449kV (the maximum operation phase voltage amplitude: \(500 \times \sqrt{2} \times 1.1 = 449kV\)), while the voltage value of the tower, air boundary and end fittings are set to zero potential. The volume conductivity effect of the air surrounding the insulators is considered, and the range of the air domain is set to 70m \(\times\) 70m \(\times\) 90m.

3. Simulation

The finite element mesh dissecting is established, and each model has more than 600,000 units respectively. The mesh drawings are shown in Figure 4.

In addition, the cross-arms, corona rings and connecting fittings are also considered.
Figure 5. The finite element mesh dissecting of the insulator and corona ring.

The measurement path is set at a distance of 0.1m from the axis of the insulator, and the electric field strength along the measurement line is extracted as the axial electric field distribution at the edge of the sheds.

4. Results and analysis

4.1. Potential distribution

The potential distribution is shown respectively in Figure 6.

(a) ZB2-type tower model  
(b) CZ34-type tower model

Figure 6. The potential distribution of the models.

The high potential of the CZ34-type tower system is concentrated in the tower window, while the ZB2-type tower system is more uniform.

4.2. Electric field distribution

The electric field intensity distribution is shown respectively in Figure 7.

(a) ZB2-type tower model  
(b) CZ34-type tower model

Figure 7. The potential and electric field mode distribution of the models.
The surface electric field distribution of the composite insulator is shown in the enlarged images:

(a) A-phase string of ZB2-type tower  
(b) B-phase string of ZB2-type tower  
(c) A-phase string of CZ34-type tower  
(d) B-phase string of CZ34-type tower

Figure 8. The enlarged images of the electric field distribution.

Because of the symmetrical structure of the A-phase and C-phase insulator string, their electric field distribution are the same. Hence, we only consider the A-phase for simplicity.

As seen in Figure 8(a)~8(d), the equipotential lines of the B-phase insulators are denser than that of the A-phase and C-phase for ZB2-type tower, as well as CZ34-type tower. The equipotential lines near the high-voltage side are denser than the grounding end side. In other words, the equipotential lines of the high-potential side of the B-phase string insulators are the densest.

In addition, it can be concluded that the electric field strength on the surface of the composite insulator is mainly along the axial direction, for the equipotential lines are perpendicular to the axis of the insulator approximately.

(a) ZB2-type tower model  
(b) CZ34-type tower model

Figure 9. Electric field distribution of the insulators along the axial direction.
It can be demonstrated from Figure 9 that the electric field of the insulators along the axial direction features an approximate U-shaped distribution. Compared with the grounding end side, the distortion of the electric field near high-voltage side is more serious, which is consistent with the electromagnetic theory. What’s more, calculating the integral of the area under the curves, and the values are approximately equal to the potential on the conductors which are set before. Thus, the feasibility of the simulation results has been verified.

For ZB2-type tower, the electric field strength of the high-voltage side of the B-phase insulator (308kV/m) is higher than that of the A-phase insulator (259kV/m), while the electric field strength of the grounding end side of the B-phase insulator (141kV/m) is lower than that of the A-phase insulator (221kV/m). The maximum field intensity of the whole model appears at the B-phase high voltage corona ring, while the minimum one appears at the middle part of the A-phase insulators.

For CZ34-type tower, the maximum field strength appears at the high voltage side of the B-phase string (386kV/m), while the minimum one appears at the middle part of the B-phase string (36kV/m). And in terms of A-phase, the field distribution of the left string is different from the right one. The average field strength of the high-voltage side of the left string is 251kV/m, which is larger than the right one (165kV/m). The average field strength of the grounding end side of the left string is 157kV/m, which is smaller than the right one (216kV/m). The average field strength at the middle part of the left string and the right string is similar, being 62kV/m and 60kV/m, respectively.

The conclusion can be drawn that the tower type has a significant effect on the electric field distribution of the insulator along the axial direction.

4.3. Comparison with actual decay fracture
The investigation and analysis showed that, the fractures usually appear within 300mm from the high-voltage end of B-phase string (as in Figure 10). Since the failure occurred site is close to the position of the highest electric field, which is consistent with the simulation results in this paper, it can be inferred that there may exist a strong relationship between electric intensity and decay fracture. In summary, this study confirms the effect of electric field strength on decay-like fracture insulators. And the relationship between them will be further studied.

![Figure 10](image1.png)  ![Figure 10](image2.png)

(a)  
(b)  

Figure 10. Images from the decay-like fractured failure site.

5. Conclusion
On the basis of the finite element simulation software COMSOL Multiphysics 5.4, the tower-conductor-insulator simulation models of ZB2-type tower and CZ34-type tower are established and analysed, and the potential and numerical electric field distribution along the axis are investigated. Comprehensive analysis shows that:

- The electric field along the axial direction of the composite insulator mainly distributes in asymmetrical U-shape, and the field strength at the high-voltage end is significantly higher than other parts of the insulator.
The maximum field strength of the system appears in the outer side of the high-voltage corona ring, and the nearby sheds are exposed to high electric field strength. The field distortion near the bonding position is so serious that would cause bonding degradation and interface problem.

The results comparison shows that tower structure has a significant effect on the field distribution of the composite insulator in the axial direction. The maximum field strength of the composite insulator strings appears in the CZ34-type tower. Due to the shielding effect of the ZB2-type tower body on the field distribution of each phase is more significant, for the conductors of each phase are arranged horizontally and the electric field in nearby region is more uniform. On the contrary, the three phase conductors are arranged in inverted-delta mode within the same tower window for CZ34-type tower.

The field strength is concentrated within the 500mm from the high-voltage end, and the maximum field strength reaches 386kV/m. Through the investigation and statistical analysis of the accident data, the fractures usually appear within 300mm from the high-voltage end, and the field strength is over 297kV/m. Through analysis, there are two reasons: ① The separation gap between the sheath and the core rod is at this position; ② The corona ring makes the electric field distribution more uniform and decelerates the bonding degradation near high-voltage side. Within a distance of 1000mm from the high-voltage side, about 65% of the field strength is concentrated. Although the electric field strength is lower in the middle part of the insulator, bonding failure still appears sometimes, indicating that the sheath and core rod peeling will gradually develop from the high-voltage side to the middle part.

Acknowledgments
The authors are grateful for the financial and technical support of Science and Technology Project of SGCC: Research on the chalking characteristics and performance evaluation of composite insulators in long-term operation in saline and coastal climate areas (Project No. 52130418000F) and State Grid Corporation of China.

References
[1] X. Liang, W. Bao, Y. Gao, “Decay-like Fracture Mechanism of Silicone Rubber Composite Insulator,” IEEE Trans. Dielect. Electr. Insul., vol. 25, no. 1, pp. 110–119, 2018.
[2] X. Liang, Y. Gao, “Study on Decay-Like Fracture of Composite Insulator: Part I- the Principal Character, Definition and Criterion of Decay-Like Fracture,” P. CSEE, vol. 36, no. 17, pp. 4778–4785, 2016.
[3] J. Wang, X. Liang, Y. Gao, “Failure Analysis of Decay-like Fracture of Composite Insulator,” IEEE Trans. Dielect. Electr. Insul., vol. 21, no. 6, pp. 2503–2511, 2014.
[4] Z. Yuan, Y. Tu, Y. Zhao, H. Jiang and C. Wang, "Degradation behavior and aging mechanism of decay-like fractured GRP rod in composite insulator," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 26, no. 3, pp. 1027-1034, June 2019, doi: 10.1109/TDEI.2019.007788.
[5] M. Lu, Z. Zhang, L. Li, Z. Liu, K. Hua, X. Yang, “Reason Analysis of Decay-Like Aging for Composite Insulator,” Power Syst. Technol., vol. 42, no. 4, pp. 1335–1341, 2018.
[6] B. Lutz, L. Cheng, Z. Guan, L. Wang, F. Zhang, “Analysis of a Fractured 500 kV Composite Insulator–Identification of Aging Mechanisms and their Causes,” IEEE Trans. Dielect. Electr. Insul., vol. 19, no. 5, pp. 1723–1731, 2012.
[7] M. F. Al Hamdani, R. Azis Prasojo, Suwarno and A. Abu-Siada, "Power Transformer Degradation Condition and Insulation Index Estimation Based on Historical Oil Dat," 2019 2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS), Denpasar, Bali, Indonesia, 2019, pp. 1-5, doi: 10.1109/ICHVEPS47643.2019.9011135.
[8] I. A. D. Giriantari, "Monitoring the insulator condition by on-line voltage distribution measurement," 2008 International Conference on Condition Monitoring and Diagnosis, Beijing, 2008, pp. 392-394, doi: 10.1109/CMD.2008.4580309.
[9] D. Huang, Z. Zheng, Z. Huang, X. Xie, J. Ruan and F. Huo, "Study on parameters design and corona characteristics test equivalent of grading rings for 1000kV UHV AC compact transmission line," 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Shenzhen, 2013, pp. 638-642, doi: 10.1109/CEIDP.2013.6748236.