Modified Minimum Approach Distance Formula for Five Working Used for 500kV Insulated Aerial Vehicles with Double Circuits on the Same Tower

Chen Chao¹a, Ma Zhenyu²b, Ge Leijiao³c, Wen Binbin⁴d, Xu Yipin⁵e, Zhou Jinhui⁶f

¹ Electric Power Research Institute State Grid Zhejiang Power Company Ltd
Hangzhou, China

² Electric Power Research Institute State Grid Zhejiang Power Company Ltd
Hangzhou, Wuhan

³ Key Laboratory of Smart Grid of Ministry of Education Tianjin University Tianjin, China

⁴ Wuhan Lide Electric Power Technology Co.Ltd Wuhan, Wuhan

⁵ Electric Power Research Institute State Grid Zhejiang Power Company Ltd
Hangzhou, China

⁶ Electric Power Research Institute State Grid Zhejiang Power Company Ltd
Hangzhou, China

a Email: 40251647@qq.com, b Email: ma_zhenyu@sgcc.com.cn,
  c Email: legendglj99@tju.edu.cn, d Email: 276453143@qq.com,
  e Email: 466267856@qq.com, f Email: zhoujinhui_hz@163.com

Abstract. 500kV double circuits on the same tower can effectively improve the natural transmission power and reduce the width of the line corridor, but the electromagnetic environment under the conductor is deteriorated. In order to ensure the safety of the workers in the insulated aerial vehicles and equipment during the live working, this paper firstly calculates the electric field distribution on the operating surface of the 500kV double-circuits truck with the actual line parameters, and then defines the distance coefficient. The existing minimum safe distance formula is modified, and a reference calculation method of the distance coefficient is given in combination with the data in the paper. Finally, the simulation data is used to verify.

1. Introduction
Since the insulated aerial vehicles can provide a safe and convenient working platform for live operators, it has been widely used in the transmission and distribution lines with different voltage levels such as 66kV in [1] and 220kV in [2]. Many scholars have studied the safety distance when it is used in 500kV and other ultra-high voltage lines in [3]. With the increase of voltage demand in China, a large number of UHV/EHV digital power projects have been completed and put into operation. In order to save the line, the same tower multiple circuits have emerged. Insulated buck-arm truck used in live operation of 35 kV and below power distribution lines has been widely used in China, but there is no
relevant experience in the use of insulated buck-arm truck used in live operation of 500 kV power transmission lines in [4-10].

On the one hand, 500kV double circuits compact transmission line with the same tower can greatly improve the natural transmission power and reduce the cost of the line. On the other hand, because the interphase distance of 500kV double circuits compact transmission line with the same tower is significantly reduced, the electromagnetic environment below the line is deteriorated. In order to realize live operation in line detection, overhaul and transformation, it is necessary to consider the characteristics of 500kV double circuits compact transmission line with the same tower, study the safe distance of insulated aerial vehicles operation, and then develop effective protective measures to ensure the safety of live operator and equipment.

At present, some studies have been done on the effect of conductive suspension on the discharge of composite gap. Canadian scholar Rizk et al. studied the influence of spherical or rod-shaped electrodes on the discharge characteristics of such gaps as rod − plate, conductor − plate and conductor − tower, and derived empirical formulas for breakdown voltage and position and length of metal conductor [11]. Baldo, an Italian scholar, studied the discharge characteristics of insulator strings containing metal conductors and analyzed the influencing factors and mechanism of discharge [12]. Hutzler, a French scholar, studied the air gap discharge characteristics of the rod − plate containing spherical conductive suspension and analyzed the influence factors of spherical conductive suspension on the combined gap discharge [13]. Relevant researches of domestic scholars mainly focus on the discharge test of human body on the phase-earth gap, and no study has been conducted on the influence of large suspended conductor on the discharge characteristics of combined gap operation [14-15].

In this paper, the three-dimensional finite element simulation of COMSOL Multiphysics is used to calculate the distribution of the field intensity at the working position of the insulated aerial vehicle of 500kV double circuits on the same tower, and then modified with the existing safety distance formula to guide the field operation.

2. Electromagnetic environment of 500 KV compact transmission line with double circuits on the same tower

Theoretically, the electric potential and electric field intensity in the electromagnetic field can be measured by analog charge method and moment method. In this paper, the analog charge method is used for analysis. The potential equations and boundary conditions are shown in equations (1) and (2), respectively.

\[
\begin{align*}
    \nabla^2 \phi &= \frac{P}{\varepsilon} \\
    \nabla^2 \phi &= 0 \\
    \phi |_L &= f_1(P)
\end{align*}
\]

Further, boundary conditions (3) should be satisfied at the interface of different media. If the potential coefficient matrix, line charge density matrix and potential matrix are P, Q and φ, respectively, the equivalent substitution and superposition principle can be combined to establish a matching point potential equations (4).

\[
\begin{align*}
    \phi_1 &= \phi_2 \\
    \varepsilon_1 \frac{\partial \phi_1}{\partial n} - \varepsilon_2 \frac{\partial \phi_2}{\partial n} &= 0 \\
    P \cdot Q &= \phi
\end{align*}
\]

According to equation (4), the potential and electric field intensity of any point in the field can be solved. In this paper, a 500kV double-circuit compact transmission line with the same tower is taken as an example. The three-phase conductors are arranged in an equilateral triangle on the tower. The
Conductor parameters are listed in Table 1. The distribution of the lines on the tower and the diagram of the tower are shown in figure 1 and figure 2, respectively.

![Figure 1. Distribution of line phase](image1)

![Figure 2. Present of tower](image2)

| Wire model    | External diameter | DC resistance | Splitting distance | Number of split wires |
|---------------|-------------------|---------------|--------------------|-----------------------|
| 6XJL/G1A-300/40 | 2.394 cm          | 0.09614 Ωkm⁻¹| 37.5 cm            | 6                     |
| OPGW-17-150-3  | 1.660 cm          | 0.33000 Ωkm⁻¹| 0.0 cm             | 0                     |
| JLB40-150      | 1.575 cm          | 0.29500 Ωkm⁻¹| 0.0 cm             | 0                     |

It is known from literature [17] that the electric field around the working bucket of the insulated aerial vehicles is very little affected by its body and the insulating arm, so only the influence of the working bucket on the operating clearance can be considered. Suppose that the arrangement of insulation bucket and simulators in the middle and side phases is shown in figure 3 (a) and (b), respectively [16].
In this paper, the three-dimensional finite element method is adopted to simulate the electric field distribution of 500kV line under the power frequency electric field, without considering the influence of insulator string on the electric field, and the potential of infinite distance, ground and tower surface is set as zero. The distribution of electric field at the plane 1.5m above the ground below the line is shown in figure 4, where figure 4 (a) is the single circuit and figure 4 (b) is the double circuits. It is known from figure 4 (a) that the maximum field intensity at 1.5m below the single-line is 11.2kV/m, and the double-circuit is increased to 13.1kV/m, which indicates that the field strength under the double circuits of the same tower is significantly larger than that at the same position under the single circuit. Therefore, the safety distance of live operation designed according to single circuit should be modified.
Further, this paper calculated the electric field intensity of insulated aerial vehicle at 1m below the line during live operation, as shown in figure 5. It can be seen that the maximum field intensity in the double circuits on the same tower is 103 kV/m, and the increase is about 7 kV/m compared with that in the single circuit.
3. Modified minimum approach distance formula

According to the literature[18], when a slow wave-front over voltage is applied to an air gap, the relation between the 50% of gap operated impulse discharge voltage $U_{50}$, the corresponding voltage waveform, the gap distance under the rod - plate gap operation impact 50% discharge voltage $U_{50RP}$ and the air gap distance $D$ can be described in equation (5).

$$U_{50} = KU_{50RP}$$

$$U_{50RP} = 500d^{0.6}$$

According to the literature [19], the gap discharge voltage $RP$ in Fig. 3 first decreases and then increases with the increase of gap $S1$ and the minimum discharge voltage is about 25% of the total gap length that occurs at $S1=1.0m$. On the other hand, the 50% of gap operated impulse discharge voltage of insulating bucket on tower body increases with the increase of clearance distance $S2$. Therefore, considering the characteristics of the double circuits on the same tower, the gap discharge voltage $U50$ should be increased to ensure the safety of live operators. According to equation (5), $U50$ can be increased by increasing gap coefficient $K$ or changing gap distance $d$.

The danger rate of live operation is the air gap between the operator and the live body. The probability of discharge under the action of system overvoltage is called the danger rate of live operation, and its formula is:

$$R_0(U) = \frac{1}{2} \int_0^\infty P_0(U)P_d(U)du$$

where, probability density function $P_0(U)$ of operating overvoltage amplitude is obtained from literature [14]. Suppose the $\sigma_d$ is the standard deviation of discharge voltage, then the probability distribution function of air gap breakdown under operating overvoltage of amplitude $U$ is:

$$P_d(U) = \int_0^\infty \frac{1}{\sigma_d \sqrt{2\pi}} \exp\left(-\frac{1}{2} \left(\frac{U-U_{50}}{\sigma_d}\right)^2\right)du$$

According to the above mathematical model, the risk rate of live operation can be calculated. It is a necessary link for workers to calculate the danger rate of electrification operation.

According to literature [20], the gap coefficient represents the discharge characteristics of different types of gaps, and its value is the value of 50% discharge voltage in the air gap divided by the $U_{50}$ of the rod - plate gap for other structural types. Under the action of the positive impact voltage, the gap coefficient basically does not change with the gap distance [21]. Therefore, the gap distance $d$ should be appropriately increased to increase the 50% discharge voltage of the air gap, but the convenience of live
operator operation should be considered. The required minimum clearance distance can be obtained from equation (7) and modified as equation (8).

\[ d = \lambda \left[ \frac{U_{500}}{500K} \right]^{0.6} \quad (8) \]

where \( \lambda \) is the distance coefficient considering the electromagnetic effect of the double circuits on the same tower, and \( \lambda > 1 \). In this paper, the value of \( \lambda \) is defined as the ratio of the maximum field intensity in the double circuits on the same tower and that in single circuit in Fig. 5, which is 1.07. According to Fig. 5, the field intensity is about 88.7 kV/m when the line is 1 m away from the horizontal direction in the double circuits on the same tower, which is lower than that in the single circuit. The maximum field intensity at 1 m below the line is 97 kV/m. Therefore, the validity of the revision (8) proposed in this paper can be verified.

4. Conclusion
Taking 500kV compact double circuits on the same tower as an example, this paper calculated the electric field distribution at 1m below the line. It is found that the electric field of double circuits on the same tower is significantly enhanced compared with that of single circuit line on the same tower, which has an impact on live operators and equipment. In order to ensure the safety of the staff and equipment in the insulated aerial vehicles when working in the double circuits on the same tower, this paper introduces the distance coefficient, corrects the formula of the minimum safe distance of the insulated bucket, and verifies the validity with the simulation data in this paper.

Acknowledgments
This paper is supported by “State Grid Zhejiang Electric Power Company Science and Technology Project of China: Research and application of integrated non-blackout operation device based on insulated rod operation method and bypass operation method of bucket arm truck (Ref. 5211DS18002N)”. The corresponding author is Leijiao Ge (legendglj99@tju.edu.cn).

References
[1] H. M. Deng, W. Cai, X. Yu, R. Ke, M. H. Liu, and C. M. Li, “Methods and Safety Protection of Live Working on 66 kV Transmission Lines by Aerial Device with Insulating Boom,” High Voltage Engineering, pp.3091-3096, 2015.
[2] L. Zhao, G. H. An, and J. J. Zhang, “Research on state maintenance of trans-mission line of Tangshan power grid,” Insulators and Surge Arresters, 2011.
[3] T. Liu, P. Tang, B. L. Zhou, and K. Liu, “Experiment research of minimum approach distance for live working used of 500kV insulated aerial vehicles,” High Voltage Engineering, pp. 2315-2321, Jul. 2016.
[4] L. Barbieri, R. Malgesini, A. Villa, G. De Donà, C. D. Milanello and A. Zanotti, “Insulated aerial vehicles and high voltage live working in Italy: tests and studies to assess the safety aspects,” in Proceedings of the 11th International Conference on Live Maintenance (ICOLIM), Budapest, pp. 1-5, 2014.
[5] C. L. Jiang, D. H. Zou, J. L. Li, Z. L. Zhang, and D. J, “ Mei. Research on electric field distribution of UHVDC transmission lines and body surface during live working,” 2017.
[6] X. Q. Liu, W. Li, C. L. Jiang, D. H. Zou, J. Niu, and C. F. Liu, “Transient Characteristics of Potential Transfer of Live Working on ±1 100 kV UHVDC Transmission Line,” Gaodianya Jishu/High Voltage Engineering, vol.43, no.10, pp. 3149-3153, Oct. 2017.
[7] X. F. Yang, H. Z. Liu, H. L. Meng, K. Liu, B. Xiao, and W. J. Ma, “Experimental Research on Safety Protection for Live-wire Operation on ±660 kV DC Power Transmission Line,” Electric power construction. vol. 33, no. 3, Mar. 2012.
[8] X. Han, W. Sima, M. Yang, L. Li, T. Yuan and Y. Si, “Transient Characteristics Under Ground and Short-Circuit Faults in a ±500kV MMC-Based HVDC System With Hybrid DC Circuit Breakers,” IEEE Transactions on Power Delivery, vol. 33, no. 3, pp. 1378-1387, Jun. 2018.
[9] S. Ji , L. Marko, X. X. Huang, J. J. Sun, W. Giewont, F. Wang, and L. M. Tolbert, “Short-Circuit Characterization and Protection of 10-kV SiC mosfet,” IEEE Transactions on Power Electronics, vol. 34, no. 2, pp. 1755-1764, Feb. 2019.

[10] F. Hinz and D. Möst, “Techno-Economic Evaluation of 110 kV Grid Reactive Power Support for the Transmission Grid,” IEEE Transactions on Power Systems, vol. 33, no. 5, pp. 4809-4818, Sep. 2018.

[11] A. Farouk, M. Rizk, “Effect of floating conducting objects on critical switching impulse breakdown of air insulation,” IEEE Transactions on Power Delivery, pp.1360-1370, Jul. 1995.

[12] G. Baldo, and G. Pesavento, “Floating potential bodies an their interaction with discharge development,” in Proceedings of the Sixth International Symposium on High Voltage Engineering. New Orleans, USA, 1989.

[13] B Hutaler, “Switching impulse strength of air gaps containing a metallicbody at floating potential,” in Proceedings of the Fifth International Symposium on High Voltage Engineering. Braunschweig, German, 1987.

[14] L. N. Wang, Y. Hu, G. W. Shao, K. Liu, C. G. Zheng, Y. Xu, J. X. Hu, and T. Liu, “Research on minimum approach distance for live working on 1 000 kV AC transmission line,” High Voltage Engineering, vol. 32. no . 12, pp.78-82, Dec. 2006.

[15] Y. Hu, K. Liu, and T. Liu, “ Live working on EHV/UH transmission lines,” High Voltage Engineering, pp. 1808-1819, 2012.

[16] Q. D. Wang, X. Chu, and F. Yang, “Analysis on transmission capability of 500 kV double circuits on the same tower compact transmission lines,” Power System Technology, pp. 114-117, 2011.

[17] B. L. Zhou, P. Tang, P. Bai, B. Zhang, D. Z. Xu, L. Zhou, and X. R. Li, “Influencing factors analysis on personnel body-surface electric field in an insulated boom-type aerial car based on finite element method,” Shanxi Electric Power, vol. 43. No. 1, pp. 55-59, 2015.

[18] Insulation co-ordination - Part 2: Application guide, IEC 60071-2-1996.

[19] Y. Du, Y. Peng, T. Liu, T. Liu, K. Liu, T. Y. Xu, and M. Tu, “ Experimental research for safe gap distance of helicopter live working with platform method on UHV transmission line,” High Voltage Engineering, vol.41, no.4, pp. 1292-1298, Apr. 2015.

[20] L. Paris, “Influence of air gap characteristics on line-to-ground switching surge strength,” IEEE Transactions on Power Apparatus and Systems, pp.936-947, 1967.

[21] Y. Z. An, M. Dai, Z. J. Li, “Research on Typical Long Air Gaps With Negative Switching Impulses(II)-Gap Factor,” Proceedings of the CSEE, vol.34, no.24, pp. 4145-4151, Aug. 2014.