Feasibility Analysis and Protection Measures of Live Working on the multi-circuit Transmission Lines on the Same Tower

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Abstract. Live line operation is the most direct and effective means for the maintenance of multi-circuit transmission lines on the same tower. It is also a special operation mode developed to improve the reliability of power supply and the safety of power grid. Therefore, it is necessary to analyze the feasibility of live line operation of multi-circuit transmission lines on the same tower. In this paper, 110 kV, 220 kV and 500 kV multi-circuit transmission lines on the same tower are taken as object, and the safety analysis of live working is carried out for typical working positions. According to the results of operation impact discharge test, the risk rate and safe working distance of live working are obtained; Finally, the minimum effective insulation length of load-bearing tools and operation tools is calculated.

1. Introduction
The increasing number of multiple overhead transmission lines on the same tower has greatly reduced the investment and increased the transmission capacity of the lines, but also brought new problems to the maintenance and repair of the lines, especially the live working in [1-2]. Compared with conventional single circuit AC transmission lines, multi-circuit transmission lines on the same tower generally have the characteristics of high tower height, diverse tower types, small cross arm distance and inter phase clearance distance, and relatively complex conductor layout in [3]. The maintenance of adjacent lines must be conducted under power failure in accordance with the operation requirements according to the maintenance of single circuit lines. This maintenance method is bound to cause more areas to force power rationing, which significantly affects the operation mode of power network and power supply, even may lead to different voltage load of lines and substations in [4] and increase the switching operation pressure of operators.

Live working is not limited by operation and equipment status through which running status of equipment could be detected at any time, equipment defects and hidden dangers could be found and eliminated in time, and uninterrupted power supply of power grid and reasonable power flow distribution of system could be ensured. It is immensely helpful in improving power supply reliability and equipment availability, ensuring maintenance planning, reducing equipment and personal accidents and power grid line loss, reducing equipment operation and conveniencing system scheduling and improving economic benefits.
At present, there are two main methods of live line maintenance which are widely used in power production at home and abroad: ground potential operation and equipotential operation. The safe live working must meet the following requirements. Firstly, after wearing the shielding clothing, the surface field strength of the body inside the shielding clothing shall not be greater than 15 kV/m, and the field strength of the exposed part shall not be greater than 240 kV/M; Secondly, the safety distance with the live body shall be kept to ensure that the risk rate is less than \(1 \times 10^{-5}\) [5]. The test in refs.[6-7] reveals that the discharge mechanism of combined gap and safety distance of UHV line live working, and determines the safety distance, combined gap and minimum safety distance of adjacent phase. In ref.[8], the electric field distribution simulation of insulated rod for 1000kV UHV transmission line live working under the typical operating conditions is performed. Aiming at the serious electric field distortion, the influence of the number of metal joints is discussed. An improved scheme of adding grading ring at the head metal joint is proposed. In ref.[9], through the calculation of risk rate, the minimum safety distance and minimum combined clearance distance for live working of 220 kV transmission line in the range of 3000-5500m above sea level are recommended. In ref.[10], a comparative method is provided to study on the three live working at the middle voltage level. In ref.[11],the equivalent charge method and the simulated charge method are used to obtain the distribution of power frequency electric field when the transmission lines cross each other. In ref.[12], based on the three-dimensional flux line method, the method of simulating charge is proposed to calculate the nominal electric field, and the method of Deutsch hypothesis is used to calculate the composite electric field distribution on the ground when ± 800 kV line crosses ± 500 kV line. In ref.[13], a three dimensional electric field model of crossing towers and lines is established to analyze the influence of the crossing angle, span height and offset distance on the overhaul space of the lower tower and the surface electric field of live-working systematically. 110kV ~ 500kV multi-circuit transmission lines on the same tower have a large demand for live working, but at present, there is still a lack of feasibility demonstration and research on live working of multi-circuit transmission lines on the typical tower.

In this paper, impact discharge test is carried out at the typical live working positions of 110kV~500kV multi-circuit transmission lines on the same tower, and the safety of live working is analyzed according to the safety judgment method of live working. Finally, the minimum effective insulation length of the operators for live line maintenance of 110kV~500kV towers through experiments is determined.

2. Insulation coordination in live working

The common methods of insulation coordination in live working are the conventional method and the simplified statistical method. The insulation of insulating tools, devices and equipment for live working can be generally divided into self-recovery insulation and non-self-recovery insulation [14].

2.1. Common usage of insulation coordination

The common usage is to make the minimum breakdown voltage value of electrical equipment insulation higher than the maximum over-voltage value that may occur in the system, and a little safety margin is given. The relationship among the maximum over-voltage of the system, insulation withstand voltage and safety margin is as follows:

\[
A = \frac{U_w}{U_{0\text{max}}} = \frac{U_w}{U_0 \sqrt{\frac{2}{3} K_r K_0}}
\]  

(1)

Where \(A\) is the safety margin; \(U_w\) is the insulation withstand voltage (kV); \(U_{0\text{max}}\) is the maximum overvoltage of system (kV); \(U_0\) is the rated voltage effective value of system (kV); \(K_r\) is the voltage rise coefficient; \(K_0\) is the overvoltage multiple of system.

However, the conventional judgment data obtained from too large margin coefficient is conservative. At the same time, the maximum over-voltage and the minimum withstand voltage are
random variables, and there are no strict rules to follow, so it is unable to accurately estimate its specific value. Therefore, the common usage is only applicable to the case of 220kV and below in self-recovery insulation.

In order to improve the accuracy of insulation coordination judgment data, the change of conventional usage may lead to a series of extreme situations and false safety situations [14]. Using the simplified statistical method recommended by IEC to measure the level of safety accurately, among them, the probability distribution of operation over-voltage and air gap breakdown are assumed to obey the normal distribution, and the probability of discharge is defined as the risk rate. Then the risk rate of live working can be calculated by the following formula [15-16]:

\[
R_0 = \frac{1}{2} \int_{0}^{U_m} P_0(U) \times P_d(U) \, dU
\]

\[
P_0(U) = \frac{1}{\sigma \sqrt{2\pi}} \times e^{-\frac{(U - U_m)^2}{2\sigma^2}}
\]

\[
P_d(U) = \frac{1}{\sigma^d \sqrt{2\pi}} \times e^{-\frac{(U - U_{50})^2}{2\sigma^d^2}} \, dU
\]

Where \( P_0(U) \) is the probability density function of operation over-voltage amplitude, and \( P_d(U) \) is the probability distribution function of air gap breakdown under operation over-voltage with the amplitude \( U \). \( U_m \) is the average value of operation overvoltage (kV); \( \sigma \) is the standard deviation of operation over-voltage (kV); \( U_{50} \) is 50% discharge voltage of air gap (kV); \( \sigma_d \) is the standard deviation of air gap discharge voltage (kV). Among them, \( U_m \) can be calculated by the following formula:

\[
U_m = \frac{U_{0.13\%}}{1+3[\sigma]}
\]

Where \( U_{0.13\%} \) is the maximum overvoltage, \( \sigma \) is the relative standard deviation of overvoltage, and [\( \sigma \)] = \( \frac{\sigma}{U_m} \).

The safety degree of live working is different in different operation modes on different tower types, so at the first step, \( U_{50} \) is calculated by test. Then the corresponding risk rate of live working is obtained one by one according to the above mathematical model. Finally, the safety of live working is analyzed and the safety distance of live working is determined. The simplified statistical method is suitable for the case of 330kV and above in UHV self-recovery insulation.

3. Analysis on the danger rate of live line operation of multiple circuits in the same tower

For live working of multiple circuits on the same tower, the specific component layout and conductor form structure of different tower types are different. However, several typical working positions of live working are basically the same, among which there are four typical positions 1-4 for linear tower and one typical working position 5 for tension tower, which is shown in Figure.1.
As shown in Figure 1, operator at position 1 stands upright on the tower body (ground potential) and works on the live wire through insulating operating pole; Operator at position 2 contacts the wire (equipotential) and works on the live wire; Operator at position 3 is on the wire (equipotential) and works on the live wire; Operator at position 4 is on the cross arm (ground potential) and directly below the live wire above; Operator at position 5 is located on the tension string of the tension tower and contacts the grading ring (equipotential) to operate the live wire.

3.1. Operation impact discharge test of typical operation position

The safe distance of live working on multi-circuit lines on the same tower is mainly determined by the characteristics of impulse discharge. In order to analyze and study the safety of live working, under the condition of standard atmospheric pressure, the operation impulse discharge test at the above typical working position is carried out by some devices, including 5400kV, 527kJ impulse voltage generator, 5400 kV low damping series resistance capacitance voltage divider, 64M peak voltmeter and Tek TDS 340 oscilloscope. The experimental results obtained are shown in Figure 2, and the experimental data of strain tower at the position 5 are shown in Table 1. According to the empirical formula in ref. [14] of over-voltage insulation characteristics of air gap buffer front, the relationship between 50% discharge voltage of operation impulse and gap distance during operation at each typical position is shown in Table 2.

![Discharge voltage curve under different gap distance](image)

**Table 1 Experimental data of strain tower at the position 5**

| Total insulator pieces | Simulated human position | Distance from tower leg to simulated human(m) | \(U_{50}\) (KV) | Z(%) |
|------------------------|--------------------------|---------------------------------------------|----------------|------|
| 16                     | 3 pieces                 | 2.02                                        | 879            | 4.2  |
| 19                     | 3 pieces                 | 2.42                                        | 992            | 4.1  |
| 22                     | 3 pieces                 | 2.96                                        | 1117           | 4.7  |
| 25                     | 3 pieces                 | 3.41                                        | 1204           | 3.1  |
| 28                     | 3 pieces                 | 3.88                                        | 1285           | 3.6  |
Table 2 Relationship between discharge voltage and gap distance at each typical position

| position | Simulated operation | Relationship between discharge voltage and gap distance | K (considering safety margin) |
|----------|---------------------|--------------------------------------------------------|------------------------------|
| 1        | People stand on the frame of the tower body and hold the insulating rod to contact the conductor horizontally. People wear a full set of shielding clothing, which is located on the conductor | $U_{50} = 600d^{0.6}$ | 1.2 |
| 2        | People wear a full set of shielding clothing, which is located on the conductor | $U_{50} = 555d^{0.6}$ | 1.11 |
| 3        | People wear a full set of shielding clothing, which is located on the conductor. People are wearing a full set of shielding clothes, which are located on the cross arm of the middle phase, and the human occupied space is considered to be 1.0m. | $U_{50} = 530d^{0.6}$ | 1.06 |
| 4        | People wear shielding clothes and squat in the joint of strain string and conductor grading ring in the way of "Across two insulators and short circuit three insulators ". Deducting human occupation and changing the distance between tower frame and simulated human. | $y = 622.65\ln(x) + 441.02$ | 1.26 |

3.2. Safety distance and risk rate of live working at certain position

For different 500kV multi-circuit lines on the same tower, the safety distance is different with different times of maximum over-voltage. When the maximum working voltage of the system is 550kV and the maximum over-voltage of the system is 2.18p.u., the minimum gap distance of live working can be obtained according to the operation impulse discharge characteristic curve, and the calculated value is 3.1m. When the safety margin and human occupation are considered, the value can be taken as 3.6m. In addition, the minimum safety distance between phases is calculated to be 5.0m by considering overvoltage 1.3~1.4 times of the phase to ground. The minimum gap distance and corresponding $U_{50}$ are obtained by properly rounding the acceptable minimum clearance distance. According to the calculation formula of risk rate, the danger rate is calculated and shown in Table 3. Here, the relative standard deviation of over-voltage is 12%, and the variation coefficient of discharge voltage is 6%. Similarly, the minimum safety distance of 220kV and 110kV multi-circuit lines on the same tower is obtained and also shown in Table 3.

Table 3 Minimum safety distance of live working for multi-circuit lines on the same tower

| Operating voltage (kV) | Maximum operating voltage (kV) | Maximum overvoltage (p.u) | Minimum clearance distance (m) | $U_{50}$ (kV) | Risk rate $/10^6$ |
|------------------------|---------------------------------|---------------------------|-------------------------------|---------------|------------------|
| 500                    | 121                             | 2.18                      | 3.1                           | 1183          | 8.58             |
| 220                    | 242                             | 3                         | 1.6                           | 702.7         | 18               |
| 110                    | 550                             | 3                         | 0.5                           | 366.2         | 3.57             |
4. Study on the combined gap

4.1. Combined gap of linear tower.
The operation mode of entering the equipotential of the linear tower usually translates from the tower body to the conductor by using the vehicle, and the lowest discharge position of combined gap is where the operator is at a distance of 0.4m from high potential.

The experiment is carried out between the conductor and the cross arm of the lower layer closest to the tower body. The simulated person rides on the insulated hanging chair and translates from the slide rail to the conductor. The human body is at a distance of 0.4m away from the high potential. The distance between the simulated person's back and the tower body is adjusted. Here, the human body occupation is considered to be 0.5m. The test results under various voltage levels are shown in Table.4, and the curve made from the test data is shown in Figure.3.

![Figure.3 Discharge characteristics of combined gap](image_url)

Table.4 The experimental data of combined gap

| voltage | combined gap S(m) | $U_{50}$ (kV) |
|---------|-------------------|--------------|
| 110kV   | 0.4/0.4           | 516          |
|         | 0.4/0.6           | 585          |
|         | 0.4/0.8           | 683          |
|         | 0.4/1.2           | 778          |
| 220 kV  | 0.4/1.4           | 850          |
|         | 0.4/1.6           | 901          |
|         | 0.4/2.8           | 1176         |
| 500 kV  | 0.4/3.0           | 1202         |
|         | 0.4/3.2           | 1251         |

According to the test data, the gap factor is 1.16 ~ 1.19, here the value of $K$ is 1.16. The formula of impulse discharge voltage is as follows:

$$U_{50} = 580d^{0.6}$$

(4)

4.2. Combined gap of tension tower.
According to the actual working condition of the routine operators entering the equipotential along the strain string, the total gap is 30 pieces of insulators. Keep the total gap and adjust the gap between the simulated man and grading ring (high potential) to 0 piece, 2 pieces, 3 pieces, 5 pieces and 7 pieces of insulators respectively, and the 50% operation impact discharge voltage is obtained through the test.
The test results are shown in Table.5. It can be seen from the results that the lowest discharge position of the strain string is at 2 pieces of insulators.

Table.5 The test results of the lowest discharge position of the strain string

| Total insulators (pieces) | The gap between the simulated man and grading ring (pieces) | $U_{50}$ (kV) | Z(%) |
|--------------------------|------------------------------------------------------------|----------------|------|
| 30                       | 0                                                          | 1621           | 4.7  |
| 30                       | 2                                                          | 1419           | 4.8  |
| 30                       | 3                                                          | 1463           | 4.4  |
| 30                       | 5                                                          | 1653           | 4.6  |
| 30                       | 7                                                          | 1723           | 5.1  |

Fix the simulator position at two insulators, and adjust the gap between the simulated tower leg and grading ring (high potential) to 25 pieces, 30 pieces, 35 pieces, 40 pieces and 45 pieces of insulators respectively. Then the operation impact discharge test is carried out, and the test results are listed in Table.6, and the corresponding discharge characteristic curve is shown in Figure.4.

![Figure 4](https://example.com/figure4.png)

Figure.4 Operation impact discharge characteristics of the strain string combined gap

According to the fitting curve, the relationship between 50% operation impact discharge voltage of the strain string combined gap and the string length (excluding human occupation) is as follows:

$$U_{50} = 722.06 \ln(d) + 388.76$$  \hspace{2cm} (5)

Table.6 Test results of operation impact discharge of the strain string combined gap

| Total insulators (pieces) | The distance between the tower body and grading ring (m) | The gap between the simulated man and grading ring (pieces) | The gap between the simulated man and tower leg (pieces) | $U_{50}$ (kV) | Z(%) |
|--------------------------|---------------------------------------------------------|----------------------------------------------------------|--------------------------------------------------------|---------------|------|
| 20                       | 2.07                                                    | 2                                                        | 15                                                     | 938           | 4.3  |
| 23                       | 2.61                                                    | 2                                                        | 18                                                     | 1078          | 4.8  |
| 26                       | 3.27                                                    | 2                                                        | 21                                                     | 1234          | 4.1  |
| 29                       | 3.82                                                    | 2                                                        | 24                                                     | 1354          | 4.9  |

5. Determination of the minimum effective insulation length of insulating tools

In live working, insulated pole and insulated rope are common tools for supporting, pulling and hoisting. When the insulator string is replaced with electricity, the insulating rod (pull rod, suspender, etc.) and the insulating rope are usually connected in parallel at both ends of the insulator string. In this typical working position, the discharge voltage of the insulated tool and insulator string in parallel will be lower than that of the isolated insulated tool or insulator string. In order to test the safety of tools and operation methods, two insulated suspenders and two insulated ropes are installed beside the
edge phase I-type insulator string of the tangent tower in combination with the actual typical working position in the test. The layout of test objects is shown in Figure.5. Change the insulation length of the insulating tool, and calculate $U_{50}$ and $Z$.

Figure.5 The layout of the minimum effective length experiment of the bearing tool

When the effective insulation length $S_0$ of the tool changes from 2.8m to 4.0m, the test results (with meteorological correction) are shown in Table.7, and the change curve and fitting formula of the discharge voltage with the insulation length are shown in Figure.6.

Figure.6 Discharge characteristics of insulating tools

In areas with an altitude of 1000m and below, when supporting, pulling and hoisting tools are used for live working of 500kV multi-circuit lines on the same tower, the maximum over-voltage of the system is considered as 2.18p.u., and the minimum effective insulation length of supporting, pulling and hoisting tools is shown in Table.7. The minimum effective insulation length of insulating tools for live working shall be determined by the insulation length meeting the discharge risk rate and considering the safety margin of 10% of the length.

| Altitude (m) | Maximum overvoltage (p.u.) | $U_{50}$ (kV) | Insulation length (m) | Risk rate /10^6 | Safety margin (m) | Minimum effective insulation length (m) |
|--------------|---------------------------|---------------|-----------------------|-----------------|------------------|----------------------------------------|
| 1000         | 2.18                      | 1202          | 3.4                   | 4.57            | 0.3              | 3.7                                    |

It can be seen from Table.7 that in areas with an altitude of 1000m and below, the minimum effective insulation length of 500kV multi-circuit line bearing tools and insulated ropes on the same tower is 3.7m.
For insulated tools of the same voltage level, the minimum effective insulation length of the operating tools is increased by 0.3m on the basis of the insulation length of the supporting, pulling and hoisting tools. Therefore, in areas with an altitude of 1000m and below, the minimum effective insulation length of 500kV multi-circuit line operation tools on the same tower is 4.0m; Through calculation, the minimum effective insulation length of 220kV multi-circuit line support, pulling and hoisting tools on the same tower is 1.8m, so the minimum effective insulation length of operation tools is 2.1m; while the minimum effective insulation length of 110kV multi-circuit line support, pulling and hoisting tools on the same tower is 2.1m, so the minimum effective insulation length of the operation tool is 1.3m.

6. Conclusion
In this paper, through the operation impact discharge test on the typical working position of the multi-circuit line on the same tower, the risk rate, safety distance and combined gap based on the test results are calculated and analyzed. The results show that the minimum safety distance of 110kV, 220kV and 500kV multi-circuit line on the same tower is 1.0m, 2.1m and 5.0m respectively. Through the study of the combined gap, it is concluded that the linear string is the lowest discharge position of the combined gap when the operator is 0.4m away from the high potential, and the lowest discharge position of the strain string is at two insulator pieces of the simulated man distance grading ring (high potential). The effective insulation length of 110kV, 220kV and 500kV insulation tools is obtained through the operation impact discharge test.

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