Study on Multi-influence Factors of Dry Ice Cleaning Effect Based on Orthogonal Test Method

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Abstract. In order to apply dry ice to the insulator cleaning in power systems, it is necessary to obtain the optimal parameter range of each of the influencing factors. In this paper, a six-factor, five-level orthogonal test method is used to obtain a representative test plan. The influence level of air pressure, dry ice flow rate, cleaning distance, cleaning time, nozzle rotation speed and cleaning time on the cleaning effect were obtained. Results revealed that the optimal range for each cleaning parameter is: air pressure 0.7MPa~0.8MPa, dry ice flow rate 2.5kg/min~3.0kg/min, cleaning distance 10cm~15cm, cleaning angle 10°~20°, nozzle rotation speed 5~15r/min, cleaning time 30s~36s.

1. Introduction

In long-term operation of the external insulation in the power distribution room, a certain degree of pollution will be accumulated on the surface, often resulting in pollution flashover in humid climate conditions [1, 2, 3]. At present, the commonly used anti-pollution flashover measures in China include: regular manual cleaning, strengthening insulation configuration, adding auxiliary umbrella skirt, adjusting the external insulation creepage distance, and coating the surface of the insulator with anti-pollution flashover organic coating [4]. Among them, removing dirt on the surface of insulators is the main anti-pollution flashover measure, which can effectively prevent the insulator from flashing accidents and ensure the safe and stable operation of power systems [5].

Cleaning of the external insulation in power systems is mainly divided into power-off cleaning and in-service cleaning. Power-off cleaning is mainly carried out manually, and in-service cleaning includes water cleaning, electrochemical cleaning and mechanical cleaning. Dry ice cleaning technology is to make liquid carbon dioxide into dry ice granules and spray them with dry air onto the surface of the object to be cleaned using a dry ice spraying machine. By the impact force generated by high-speed movement of dry ice granules, combined with the low temperature characteristics of dry ice itself and the thermal expansion caused by sublimation, the dirt, oil stains and residual impurities on the surface are quickly removed, and the object to be cleaned is not damaged. Dry ice cleaning is a new type of in-service cleaning technology, which has obvious advantages compared with other charged cleaning technology, and it has broad application prospects [6].
The main factors affecting the cleaning effect of dry ice include air pressure, dry ice flow rate, cleaning distance, cleaning angle, nozzle rotation speed and cleaning time [7]. Theoretical analysis shows that the factors are not independent, but are related to each other and affect the cleaning effect simultaneously. In the single variable test of air pressure, if the selected dry ice flow rate is too small, no matter how to increase the air pressure, the cleaning effect is still not satisfactory; if the air pressure is too small, no matter how to increase the dry ice flow rate, dry ice granules cannot get enough kinetic energy, and the cleaning effect is still not good. Changes in cleaning distance and cleaning angle both affect the dry ice scattering area, which in turn affect the cleaning effect. In this paper, we studied the influence level of each factor on the cleaning effect and obtained the best cleaning parameter range by orthogonal test method.

2. Orthogonal test plan
Orthogonal test is a mathematical statistical method that uses a set of off-the-shelf standardized orthogonal tables to scientifically arrange tests and analyze test results. The main advantage of this method is that it can select some representative points for testing in a comprehensive range of tests. By analyzing the results of these few tests, we can identify the optimal (or better) solution and get more information about each factor. This method is a scientific method for efficiently dealing with multi-factor optimization problems [8].

Taking the insulator as the test object, the orthogonal test was carried out to study the cleaning effect under the influence of a combination of multi-parameters. The test selected six factors including air pressure, dry ice flow rate, cleaning distance, cleaning time, nozzle rotation speed and cleaning time. Five values were selected for each influencing factor. The values of compressed air pressure (A) are 0.4MPa (A1), 0.5MPa (A2), 0.6MPa (A3), 0.7MPa (A4) and 0.8MPa (A5). The values of dry ice flow rate (B) are 1.0kg/min (B1), 1.5kg/min (B2), 2.0kg/min (B3), 2.5kg/min (B4) are 3.0kg/min (B5). The Cleaning distances (C) are 5cm (C1), 10cm (C2), 15cm (C3), 20cm (C4) and 25cm (C5). The cleaning angles (D) are 5° (D1), 10° (D2), 15° (D3), 20° (D4) and 25° (D5). The values of nozzle rotation speed (E) are 5r/min (E1), 10r/min (E2), 15 r/min (E3), 20r/min (E4) and 25r/min (E5). The values of cleaning time (F) are 12s (F1), 18s (F2), 24s (F3), 30s (F4), 36s (F5). A 6-factor, 5-level orthogonal test table was constructed, as shown in Table 1.

Table 1. 6-factor, 5-level orthogonal test table.

| Number | A (air pressure)/MPa | B (dry ice flow rate)/kg/min | C (cleaning distance)/cm | D (cleaning angle)° | E (nozzle rotation speed)/r/min |
|--------|----------------------|-----------------------------|--------------------------|-------------------|-------------------------------|
| 1      | A1 (0.4)             | B1 (1.0)                    | C1 (5)                   | D1 (10)           | E1 (5)                        |
| 2      | A1 (0.4)             | B2 (1.5)                    | C2 (10)                  | D2 (15)           | E2 (10)                       |
| 3      | A2 (0.5)             | B3 (2.0)                    | C3 (15)                  | D3 (25)           | E3 (20)                       |
| 4      | A2 (0.5)             | B4 (2.5)                    | C4 (20)                  | D4 (25)           | E4 (20)                       |
| 5      | A3 (0.6)             | B3 (2.0)                    | C5 (25)                  | D5 (20)           | E5 (20)                       |
| 6      | A3 (0.6)             | B4 (2.5)                    | D1 (10)                  | E6 (10)           |                               |
| 7      | A3 (0.6)             | B1 (1.0)                    | C2 (10)                  | D2 (15)           | E7 (10)                       |
| 8      | A4 (0.7)             | B3 (2.0)                    | C3 (15)                  | D3 (25)           | E8 (15)                       |
| 9      | A4 (0.7)             | B4 (2.5)                    | C4 (20)                  | D4 (20)           | E9 (15)                       |
| 10     | A5 (0.8)             | B1 (1.0)                    | C5 (25)                  | D5 (10)           | E10 (10)                      |
| 11     | A5 (0.8)             | B2 (1.5)                    | C1 (10)                  | D6 (10)           | E11 (15)                      |
| 12     | A5 (0.8)             | B3 (2.0)                    | C2 (10)                  | D2 (15)           | E12 (15)                      |
| 13     | A5 (0.8)             | B4 (2.5)                    | C3 (15)                  | D3 (25)           | E13 (15)                      |
| 14     | A5 (0.8)             | B5 (3.0)                    | C4 (20)                  | D4 (20)           | E14 (15)                      |
| 15     | A5 (0.8)             | B1 (1.0)                    | C5 (25)                  | D5 (20)           | E15 (15)                      |
| 16     | A5 (0.8)             | B2 (1.5)                    | C1 (10)                  | D6 (10)           | E16 (15)                      |
| 17     | A5 (0.8)             | B3 (2.0)                    | C2 (10)                  | D2 (15)           | E17 (15)                      |
| 18     | A5 (0.8)             | B4 (2.5)                    | C3 (15)                  | D3 (25)           | E18 (15)                      |
| 19     | A5 (0.8)             | B5 (3.0)                    | C4 (20)                  | D4 (20)           | E19 (15)                      |
| 20     | A5 (0.8)             | B1 (1.0)                    | C5 (25)                  | D5 (20)           | E20 (15)                      |
| 21     | A5 (0.8)             | B2 (1.5)                    | C1 (10)                  | D6 (10)           | E21 (15)                      |
| 22     | A5 (0.8)             | B3 (2.0)                    | C2 (10)                  | D2 (15)           | E22 (15)                      |
| 23     | A5 (0.8)             | B4 (2.5)                    | C3 (15)                  | D3 (25)           | E23 (15)                      |
| 24     | A5 (0.8)             | B5 (3.0)                    | C4 (20)                  | D4 (20)           | E24 (15)                      |
| 25     | A5 (0.8)             | B1 (1.0)                    | C5 (25)                  | D5 (20)           | E25 (15)                      |
3. Analysis of test results

The dry ice cleaning tests were carried out according to the orthogonal test table. The test results are shown in Table 2, where the residual degree is the average of the ESDD (equivalent salt deposit density) and NSDD (non-soluble deposit density).

Table 2. Orthogonal test results.

| Number | Air pressure (MPa) | Dry ice flow rate (kg/min) | Cleaning distance (cm) | Cleaning angle (°) | Nozzle rotation speed (r/min) | Residual degree (%) |
|--------|-------------------|---------------------------|------------------------|-------------------|-----------------------------|--------------------|
| 1      | 0.4               | 1.0                       | 5                      | 10                | 5                           | 63.2               |
| 2      | 0.4               | 1.5                       | 10                     | 15                | 10                          | 49.1               |
| 3      | 0.4               | 2.0                       | 15                     | 20                | 15                          | 36.3               |
| 4      | 0.4               | 2.5                       | 20                     | 25                | 20                          | 37.4               |
| 5      | 0.4               | 3.0                       | 25                     | 20                | 25                          | 53.5               |
| 6      | 0.5               | 1.0                       | 10                     | 25                | 20                          | 46.2               |
| 7      | 0.5               | 1.5                       | 15                     | 10                | 25                          | 58.6               |
| 8      | 0.5               | 2.0                       | 20                     | 15                | 5                           | 39.3               |
| 9      | 0.5               | 2.5                       | 25                     | 25                | 10                          | 42.1               |
| 10     | 0.5               | 3.0                       | 20                     | 25                | 15                          | 24.0               |
| 11     | 0.6               | 1.0                       | 15                     | 15                | 10                          | 44.4               |
| 12     | 0.6               | 1.5                       | 20                     | 10                | 15                          | 38.0               |
| 13     | 0.6               | 2.0                       | 25                     | 15                | 20                          | 52.7               |
| 14     | 0.6               | 2.5                       | 20                     | 10                | 25                          | 45.3               |
| 15     | 0.6               | 3.0                       | 5                      | 10                | 5                           | 23.2               |
| 16     | 0.7               | 1.0                       | 20                     | 20                | 25                          | 57.4               |
| 17     | 0.7               | 1.5                       | 25                     | 10                | 5                           | 44.1               |
| 18     | 0.7               | 2.0                       | 5                      | 15                | 10                          | 29.2               |
| 19     | 0.7               | 2.5                       | 10                     | 25                | 15                          | 37.3               |
| 20     | 0.7               | 3.0                       | 15                     | 20                | 20                          | 26.4               |
| 21     | 0.8               | 1.0                       | 25                     | 15                | 15                          | 54.8               |
| 22     | 0.8               | 1.5                       | 5                      | 10                | 20                          | 38.6               |
| 23     | 0.8               | 2.0                       | 10                     | 15                | 25                          | 34.5               |
| 24     | 0.8               | 2.5                       | 15                     | 10                | 5                           | 20.5               |
| 25     | 0.8               | 3.0                       | 20                     | 25                | 10                          | 24.0               |

The method of orthogonal analysis was used to analyze the test results. The results are shown in Table 3 below:

Table 3. Analysis of orthogonal test results.

| Air pressure (A) | Dry ice flow rate (B) | Cleaning distance (C) | Cleaning angle (D) | Nozzle rotation speed (E) | Cleaning time (F) |
|-----------------|-----------------------|-----------------------|--------------------|---------------------------|-------------------|
| k1/\%           | 47.9                  | 53.2                  | 40.06              | 40.84                     | 38.06             | 47.16             |
| k2/\%           | 42.04                 | 45.68                 | 38.06              | 40.74                     | 37.76             | 42.98             |
| k3/\%           | 40.72                 | 38.4                  | 37.24              | 39.18                     | 38.08             | 39.52             |
| k4/\%           | 38.88                 | 36.52                 | 39.22              | 40.64                     | 40.26             | 36.88             |
| k5/\%           | 34.48                 | 30.22                 | 49.44              | 42.62                     | 49.86             | 37.48             |
| R               | 13.42                 | 22.98                 | 12.22              | 3.44                      | 12.1              | 10.28             |

In Table 3, R (range) is the difference between the maximum and minimum of the integrated level for each factor, reflecting the influence degree of six factors on the cleaning effect. From the above table, it can be concluded that R_B>R_A>R_C>R_E>R_F>R_D, which means that the order of influence degree is: dry ice flow rate>air pressure>cleaning distance>nozzle rotation speed>cleaning time>cleaning
angle. In Table 3, $k_{i1}$, $k_{i2}$, $k_{i3}$, $k_{i4}$, $k_{i5}$ ($i=A, B, C, D, E$) respectively indicate the relationship between the six parameters at each level and the cleaning residual degree, which can reflect the cleaning effectiveness of six factors at different level. Using the values in the above table, the relationship between each factor and the residual degree is plotted. The optimal range for each cleaning parameter factor can be obtained and the verification test was carried out.

As can be seen in Figure 1, in the range of values taken in the test, as the air pressure increases, the residual degree decreases, and the cleaning effect becomes better. This is because increasing the air pressure can speed up the dry ice jet speed and enhance the striking force.

![Figure 1. Relationship between air pressure and residual degree.](image)

It can be seen in Figure 2 that the residual degree decreases and the cleaning effect becomes better as the dry ice flow rate increases. This is because increasing the dry ice flow rate can increase the number of dry ice granules that are sprayed, thereby enhancing the striking force and the micro-blasting effect during the sublimation process.

![Figure 2. Relationship between dry ice flow rate and residual degree.](image)
Figure 3. Relationship between cleaning distance and residual degree.

It can be seen from Figure 3 that the cleaning effect first becomes better and then deteriorates as the cleaning distance increases, and the residual degree first decreases before it rises. When the cleaning distance is less than 15cm, the level of kinetic energy of the dry ice granules is high when reaching the contamination layer, and the striking force on the contamination layer is large. As the cleaning distance increases, the cleaning rate increases, and the residual degree decreases. After the cleaning distance exceeds 15cm, there is a large loss of kinetic energy when the dry ice granules reach the contamination layer, and the striking force acting on the contamination layer decreases. The cleaning rate decreases, and the residual degree increases.

Figure 4. Relationship between cleaning angle and residual degree.

Figure 4 reveals that the residual degree first decreases and then rises as the cleaning angle increases, and the cleaning effect first becomes better before deteriorating. When the cleaning angle of the nozzle is less than 15°, the vertical striking component of the dry ice granules acting on the contamination layer is small, and the cleaning rate is low. As the cleaning angle increases, the vertical striking component gradually increases, and the residual degree gradually increases. However, when the cleaning angle exceeds 15°, the cleaning area becomes smaller due to the shielding effect of the edge of the insulator sheds, and the cleaning rate remarkably decreases.
Figure 5. Relationship between nozzle rotation speed and residual degree.

It can be seen from Figure 5 that the residual degree first decreases and then rises as the nozzle rotation speed increases, and the cleaning effect first becomes better before deteriorating. When the nozzle rotation speed is small, the micro-blasting effect of the dry ice granules at the striking point will reduce the kinetic energy of the subsequent dry ice, resulting in lower cleaning efficiency. As the nozzle rotation speed increases, the cleaning rate increases and the residual degree decreases. When the nozzle rotation speed is too fast, the time for dry ice granules to act on the contamination layer is reduced, and the residual degree increases.

Figure 6. Relationship between cleaning time and residual degree.

It can be seen from Figure 6 that the residual degree decreases and the cleaning effect becomes better as the cleaning time increases. Increasing the cleaning time can increase the continuous striking time of the dry ice granules and improve the cleaning effect. When the cleaning time exceeds 30s, the time of the dry ice granules striking on the contamination layer will be sufficient, and the residual degree does not decrease significantly as the cleaning time increases.

The above orthogonal test results are consistent with the results of the previous single factor tests [9, 10]. According to the orthogonal test results, the optimal range for each parameter of dry ice cleaning is determined as follows: air pressure 0.7MPa~0.8MPa, dry ice flow rate 2.5kg/min~3.0kg/min, cleaning distance 10cm~15cm, cleaning angle 10°~20°, nozzle rotation speed 5r/min~15r/min, cleaning time 30s~36s. The contamination residual degree can be below 20% under the combination
of parameters. Selecting the artificially smeared insulator, setting the air pressure 0.7MPa, dry ice flow rate 2.5kg/min, cleaning distance 15cm, cleaning angle 15°, nozzle rotation speed 10r/min and cleaning time 30s, the verification cleaning test was carried out in the optimal range of cleaning parameters. The insulator before cleaning is shown in Figure 7, and the single-piece shed of the insulator which has been cleaned is shown in Figure 8. The residual degree of shed is 14%, which shows the excellent cleaning effect.

Figure 7. Before cleaning.

Figure 8. After cleaning.

4. Conclusion
(1) The results of orthogonal tests show that $R_B > R_A > R_C > R_D > R_E > R_F$, which means that the influence degree order of six factors on dry ice cleaning effect is: dry ice flow rate $>$ air pressure $>$ cleaning distance $>$ head speed $>$ cleaning time $>$ cleaning angle.

(2) The orthogonal test results are consistent with the previous single factor test results. According to the orthogonal test results, the optimal range for each parameter of dry ice cleaning is determined as follows: air pressure 0.7MPa–0.8MPa, dry ice flow rate 2.5kg/min–3.0kg/min, cleaning distance 10cm–15cm, cleaning angle 10°–20°, nozzle rotation speed 5r/min–15r/min, cleaning time 30s–36s. The contamination residual degree can be below 20% under the combination of parameters, achieving a good cleaning effect.

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