Breakdown Characteristics of Long Air Gap at Different Frequency Based on Series Resonance

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Abstract. In today's rapid economic development, with the development of science and technology, higher requirements have been put forward in the economic operation of the system. This requires various departments to make more reasonable use of existing energy and equipment, and to ensure quality. Meet all aspects of supply with more energy-saving and more economical operation methods. Therefore, more and more attention has been paid to the research on the method of predicting the breakdown voltage of the air gap. Although domestic and foreign scholars have used power frequency test transformers to carry out a large number of long air gap experimental researches, the research on the breakdown voltage of long air gaps based on the principle of vector machines is still blank. In this paper, a vector machine test device is used to study the breakdown discharge characteristics of a long air gap at two frequencies of 229Hz and 68Hz. Comparing the test phenomena at different frequencies, it is found that the initial discharge voltage of the streamer corona is lower when the frequency is 229Hz, and the discharge phenomenon before breakdown is more intense, and the quality factor will be significantly reduced due to the violent discharge. At the same time, under the same test conditions, the breakdown voltage at 229Hz is lower than that at 68Hz, and as the air gap increases, the difference between the two is greater. The experimental results show that the breakdown voltage of the long air gap based on the vector machine is different when the frequency is different, and the safety distance of the field withstand voltage test should be evaluated according to the experimental data under the vector machine condition to ensure the safety of the test.

Key words: Switchgear, Series Resonance, Long Gap, Breakdown Characteristics

1. Introduction
The AC withstand voltage test of high-voltage switchgear is an important means to assess the main insulation of the equipment to ensure that the equipment will not fail due to insulation problems after it is put into operation. Therefore, the best test method is to use the power frequency test transformer to generate a high voltage of 50Hz to assess the equipment insulation ability. However, due to the large size of test transformers with voltage levels of 500kV and above, it is inconvenient to transport. Therefore, the AC withstand voltage test carried out on site usually uses the variable frequency vector
machine test device. According to the standard, the AC voltage of 10Hz~30Hz can be used in the withstand voltage test of the switchgear.

Before carrying out a high-voltage test on site, it is usually necessary to evaluate the test safety distance based on the test voltage and the electrical withstand characteristics of the air gap. Although scholars at home and abroad have carried out a large number of typical air gap discharge experimental studies, Zhao L obtained the discharge characteristics under different gap scales, different voltage waveforms and different electrode shapes [1]. However, the current research on the long-gap breakdown discharge is generally not enough. Some of them have only made some actual measurements to determine the phenomena, parameters, influencing factors, and change laws of things, and the phenomena, processes, and The causes of the law have not yet been fully explained. At the same time, the research work of previous experts and scholars was basically carried out by using power frequency test transformers, while the variable frequency vector machine device was generally used in field tests. At present, domestic and foreign has not seen the use of variable frequency vector machine devices to carry out experimental research on the breakdown of long air gaps at different frequencies.

In this paper, a vector machine test device is used to study the breakdown discharge characteristics of a long air gap at different frequencies. The test phenomena at different frequencies are compared, and the breakdown discharge voltage curve under the condition of the vector machine is obtained. The breakdown voltage and the The relationship between the Q value can provide a useful reference for the field test of the switchgear and the evaluation of the test safety distance.

2. Test Method

2.1. The Definition and Basic Principles of Support Vector Machines

(1) Support vector machine is a two-classification model. The basic model is to find the linear classifier with the largest interval in the feature space. The perceptron model only needs to find the separation hyperplane, and the SVM not only needs to separate the samples, but also meet the maximum interval. When the training samples are linearly separable, a linearly separable SVM is obtained by maximizing the hard interval. If the training samples are only close to linearly separable, a slack variable needs to be introduced, and a linear SVM is obtained by maximizing the soft interval. When the training samples are linearly inseparable, it is necessary to introduce a kernel technique to map the feature space from low-dimensional to high-dimensional, so that the samples are close to separable, and the soft interval is maximized to learn to obtain a nonlinear support vector machine.

(2) The basic principle of the support vector machine is how to find an optimal classification line, that is, how to correctly separate the two types of training samples, and to maximize the classification interval to meet the requirements of the classification line and ensure that the training error reaches zero. Introducing the classification line into the high-dimensional space is called the classification surface.

2.2. Construction of test model

The support vector machine test device uses the principle of a vector machine, uses an excitation transformer to excite the vector machine loop, adjusts the output frequency of the inverter, and makes the loop inductance F and the tested product E vector machine. The resonance voltage is the voltage applied to the tested product. [2-3]. The test device is composed of a frequency conversion cabinet, an excitation transformer, a reactor, a capacitive voltage divider and a compensation capacitor; and a long bar-plate gap is set between the high-voltage end and the ground, as shown in Figure 1.

The current of the series circuit is:

$$I_p = U_p / [R^2 + (\omega L - 1 / \omega C)^2]^{1/2}$$

(1)

In the formula, is the current on the high voltage side of the excitation transformer, is the voltage on the high voltage side of the excitation transformer, R is the loop resistance; \( \omega \) is the angular frequency; L is the loop inductance; C is the loop capacitance.
When $\omega_L = 1/\omega_C$, the loop is completely in resonance.

Let $Q = \omega_L/R$, then the high-voltage side voltage of the tested product $U_C = Q^* U_b$, and $Q$ is called the quality factor of the resonant circuit.

This article adjusts the resonant frequency by paralleling a compensation capacitor. When there is no compensation capacitor, the frequency is 229Hz; when a 25nF capacitor is connected in parallel, the resonant frequency is 68Hz.

**Figure 1.** Wiring diagram of series resonance test system

One of the characteristics of long air gap discharge is the existence of a pilot discharge process. When the air gap is long (such as the rod-plate gap distance is greater than 1 meter), during the discharge development process, the stream often cannot penetrate the entire air gap at one time. There is a progressively advanced pilot discharge phenomenon [4-5]. In view of the 500kV voltage level switchgear's withstand voltage value is usually 740kV, the length of the air gap studied in this paper is set at 1.5 meters to 4 meters. According to the traditional rod-plate model size, a 6-meter long rod electrode and a 6-meter x 6-meter plate electrode are set.

The high-voltage lead between the vector machine equipment uses a 500mm outer diameter snake skin tube to avoid corona from affecting the Q value in the test; the rod electrode is suspended from high altitude, the total length is about 6 meters, and the upper part of the rod is a 500mm outer diameter snake skin tube. The lower part is reduced to a snakeskin tube with an outer diameter of 200mm, and the end electrode is a smooth pressure equalizing ball with a radius of curvature of 100mm; a 6m x 6m metal plate is set on the ground as a plate electrode, and the electrode is connected to the grounding grid through a grounding wire, as shown in Figure 2. Shown.
2.3. Test Process
Use the above model to carry out discharge test research and record the breakdown discharge voltage. First, do the test without connecting the compensation capacitor, and the resonance frequency is 229Hz; adjust the length of the discharge gap, and conduct the test at 1.5m, 2.0m, 2.5m, 3.0m, 3.5m and 4.0m in sequence. Before each test, use a thermohygrometer, barometer, etc. to record the test atmospheric conditions. The test is repeated three times for each gap, with an interval of 5 minutes between each test. In order to avoid over-pressurizing to affect the breakdown voltage value, after reaching 70% of the expected breakdown voltage, the boosting speed is not higher than 1kV per second. During the test, observe and record the test phenomenon and breakdown voltage [6-7].

After the above test is completed, connect the compensation capacitor to test again, the resonance frequency is 68Hz, and repeat the above test process.

The test equipment, nearby equipment layout, and rod-board model are kept consistent under the two frequency conditions. The atmospheric test conditions are slightly different. The test environment temperature is between 23.8°C~25.1°C, the relative humidity is between 64.7%~75.0%, and the atmospheric pressure is between 100.3~100.5kPa, which meets the general requirements of high voltage test [8].

In order to improve the validity of the test data, the test voltage value shall be corrected for atmospheric conditions in accordance with Clause 4.3 of GB/T 16927.1-2011 "High Voltage Test Technology Part 1 General Definitions and Test Requirements".

3. Experimental Phenomenon

3.1. Streaming Corona Onset Voltage
When the voltage rises to a certain value, a corona discharge will appear, showing repetitive current pulses; when the voltage continues to rise to a certain value, there will be an irregular streamer corona.
current pulse with a much larger amplitude [9-10]. The experiment found that the onset voltage of streamer corona at different frequencies is slightly different. In order to eliminate the impact of human hearing differences, an oscilloscope is used to capture the discharge current to determine the initial voltage [11]. Set the ground current trigger level to 20mV, and the voltage corresponding to the moment when the ground current signal is captured is the obvious corona initiation voltage.

The corona initiation voltage at the resonant frequency of 229 Hz is lower than when the resonant frequency is 68 Hz, and as the gap increases, the difference between the two is larger, as shown in Table 1. Since the migration rate of positive ions is low, about 1 m/ms, after the occurrence of a positive corona, there will be a dense positive space charge area near the pole; when the next negative voltage comes, the space charge will still be It has an impact on the electric field of the rod. At higher frequencies (229Hz), the positive space charge is closer to the rod, and the field strength is higher under the superposition of the electric field, so it is easier to produce a streamer corona discharge with a larger amplitude [12].

**Table 1.** Streaming initiation voltage at different frequencies

| Clearance (m) | Resonance frequency 229Hz | Resonance frequency 68Hz | Voltage amplitude difference |
|---------------|---------------------------|--------------------------|----------------------------|
| 1.5m          | 270kV                     | 280kV                    | 3.7%                       |
| 2.0m          | 280kV                     | 290kV                    | 3.6%                       |
| 2.5m          | 295kV                     | 315kV                    | 6.8%                       |
| 3.0m          | 300kV                     | 325kV                    | 8.3%                       |
| 3.5m          | 305kV                     | 330kV                    | 8.2%                       |
| 4.0m          | 310kV                     | 340kV                    | 9.7%                       |

3.2. Discharge Phenomenon

After the streamer corona discharge occurs, as the voltage increases, there will be a filamentous brush-like discharge, and the discharge is still streamer discharge at this time. As the voltage continues to rise, more streamers appear, the discharge current increases, and the streamers converge to form a brighter channel-like discharge, forming a pilot discharge.

Experiments have found that the discharge phenomenon is more severe at 229Hz, and the discharge frequency and discharge current are significantly higher than at 68Hz. Intercept the discharge phenomena at 5 different moments before the breakdown, as shown in Figure 3. It can be seen from the figure that the length of the brush discharge is longer at 229 Hz, and the discharge channel is brighter.

**Figure 3.** Comparison of discharge phenomena at different frequencies in the long gap of the rod-plate model
The difference of the discharge intensity at different frequencies can be manifested by the reduction degree of the quality factor $Q$ of the resonant tank; the greater the discharge intensity, the lower the $Q$ value, as shown in Figure 4.

![Figure 4. Q value at lower voltage and before gap breakdown](image)

Under the resonant frequency of 229Hz, the $Q$ value is greater than 95 at 100kV and 200kV without corona; however, the $Q$ value drops very severely before the breakdown of each gap, and the $Q$ value drops to 69.1 before the breakdown of the 1.5m gap, a decrease of 28.8%. The 4m gap is reduced to 48.5 before breakdown, and the drop rate is 50.0%.

Under the condition of the resonance frequency of 68 Hz, the $Q$ value is greater than 123 at 100kV and 200kV without corona; the $Q$ value drops slightly before the breakdown of each gap, and the $Q$ value before the breakdown of the 1.5m gap is 121.5, a drop of 2.9%. The $Q$ value before the breakdown of the 4-meter gap was 106.1, a decrease of 15.2%.

The discharge of the rod electrode is not continuous, and the discharge intensity does not vary uniformly; if the discharge intensity is high in a certain period, the quality factor $Q$ will decrease, and the high-voltage side voltage will decrease accordingly. The waveform at the time of breakdown at a frequency of 229 Hz and a gap of 2 meters has a large discharge current and violent discharge within 5 cycles before breakdown, so the corresponding primary peak voltage decreases. It should be noted that when the discharge is severe, the high-frequency oscillation signal generated by the discharge will also be transmitted to the digital display meter through the voltage divider, and the digital display will record the peak value of the high-frequency component as the waveform peak value, thereby affecting the peak voltage and the calculation of effective values.

Therefore, although the standard DL/T 474.4-2018 "Guidelines for the Implementation of Field Insulation Tests and AC Withstand Voltage Test" stipulates that the test voltage reading is peak value/$\sqrt{2}$, when the discharge is strong and the meter reading jumps up and down, read the effective value more reasonable.

4. Breakdown Voltage and Analysis

Under vector machine conditions, all breakdown voltages occur in positive polarity, which is the same as the power frequency test result.

Experiments have found that there is often a brush discharge within 5us~31us before breakdown. In 36 tests, 33 times there is a small discharge before breakdown, and the probability reaches 91.7%. This phenomenon shows that the previous amplitude is larger. The small voltage oscillation and space charge generated by the small discharge are favorable factors to promote the breakdown of the long gap.

The breakdown voltage of each gap after correction is shown in Table 2. It can be seen from the
table that the breakdown voltage of the air gap under the vector machine has little dispersion, and the coefficient of variation $z$ is kept at a small value, which is equivalent to the coefficient of variation of 2%~3% under the power frequency voltage. Under the same gap conditions, the breakdown voltage of 229Hz is lower than the breakdown voltage of 68Hz; as the air gap increases, the difference between the two is larger, and the difference reaches about 20% at a 4-meter gap.

**Table 2.** Experimental data of breakdown voltage at different frequencies and gaps

| Air gap (m) | Breakdown voltage at resonance frequency 229Hz (effective value kV) | Breakdown voltage at resonance frequency 68Hz (effective value kV) | Frequency difference breakdown voltage (%) |
|------------|---------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------------|
| 1.5 m      | The first time: 350.6 360.5 365.4 358.8 1.7% 395.2 392.2 379.9 389 1.7% 8.4% | The second time: 482.1 517.8 493.0 498 3.0% 8.8% |                                           |
| 2.0 m      | The first time: 467.2 445.3 460.8 457.7 2.0% 482.1 517.8 493.0 498 3.0% 8.8% | The second time: 579.3 636.3 590.2 602 4.1% 15.2% |                                           |
| 2.5 m      | The first time: 519.4 522.4 525.3 522.4 0.5% 679.4 680.2 713.6 691 2.3% 17.5% | The second time: 588.2 583.2 588.2 1.3% 679.4 680.2 713.6 691 2.3% 17.5% |                                           |
| 3.0 m      | The first time: 599.2 582.2 583.2 588.2 1.3% 679.4 680.2 713.6 691 2.3% 17.5% | The second time: 641.2 645.8 641.2 0.5% 756.8 767.1 780.6 768 1.3% 19.8% |                                           |
| 3.5 m      | The first time: 639.8 637.8 645.8 641.2 0.5% 756.8 767.1 780.6 768 1.3% 19.8% | The second time: 686.5 683.8 686.5 1.3% 845.4 821.6 835.9 834 1.2% 21.5% |                                           |
| 4.0 m      | The first time: 676.8 698.7 683.8 686.5 1.3% 845.4 821.6 835.9 834 1.2% 21.5% | The second time:                                               |                                           |

Analysis believes that the difference in discharge voltage at different frequencies is mainly affected by space charges. During each period of time at high potential before breakdown, a large-amplitude streamer and lead discharge are generated near the rod electrode. Although the electron velocity of the electron collapses is about 150 m/ms, the velocity of positive or negative ions is relatively high. Slow, about 1 meter/ms. Under long gap conditions, the positive ions produced by the previous discharge are not completely diffused, and a large amount of charges are still distributed in the gap; charged ions and applied voltage will affect the spatial electric field distribution at the same time, and the ionization rate of air molecules has a greater influence on the electric field distribution. Therefore, when the 229Hz resonant discharge intensity is greater, there are more ions distributed in the gap; and the time between the two voltage peaks is shorter, and the ions are very close to the rod; once a pilot discharge occurs at the tip of the rod, then The positive ions in the discharge path will promote the development of the streamer, which makes the gap breakdown discharge more likely to occur.

Appendix F of the national standard GB/T 311.2-2013 "Insulation Coordination Part 2: Guidelines for Use" expresses the 50% breakdown voltage formula of the rod-plate model:

$$U_{50RP} = 750\sqrt{2}\ln(1 + 0.55d)(KV, \text{peak value, meters})$$

Where $U_{50RP}$ is the 50% breakdown voltage value (peak value) of the rod-plate model.

The comparison shows that the experimental value of the breakdown voltage under the vector machine condition is lower than the recommended value in GB/T 311.2, as shown in Figure 5.
Figure 5. Breakdown voltage at different frequencies of the long gap of the rod-plate model

The analysis believes that because the series resonance 68Hz is closer to the power frequency 50Hz, the difference caused by the different frequencies is small. The main reason for the difference between the series resonance 68Hz experimental data and the standard recommended value is the different experimental conditions, such as the influence of the surrounding equipment on the electric field. The influence of the grounding body, etc.

At present, in the newly expanded power transmission and transformation project, the variable frequency vector machine test device is usually used to conduct handover test of switchgear; therefore, the withstand voltage test is carried out on site, especially in the limited space, the safety distance should be based on the vector. The breakdown discharge curve under mechanical conditions is evaluated, and if necessary, insulation enhancement measures are adopted.

5. Conclusions

The thesis first introduces the basic concepts of breakdown voltage prediction methods and the significance of breakdown voltage prediction methods. Through the research on the application status of air gap breakdown voltage prediction methods, a method based on support vector machines is proposed. Then the statistical theoretical basis of support vector machine is introduced in detail, and the algorithm of support vector regression machine is extracted. By analyzing the characteristics of the breakdown voltage of the air gap and using support vector machines as the training algorithm, this paper has achieved the following results:

1) On the basis of analyzing and summarizing the breakdown voltage characteristics of the air gap, a similar month selection based on the grey relational analysis theory is proposed. The principle of this method is clear, the amount of calculation is small, and the calculation speed is improved.

2) Aiming at the missing data and abnormal data in the breakdown voltage sequence, a data preprocessing method suitable for breakdown voltage is proposed.

3) The method proposed in the thesis was verified by examples. The prediction results proved the correctness and effectiveness of the method proposed in the thesis, and compared with traditional calculation methods, it can achieve better prediction accuracy.

Acknowledgments

This work was supported by the Science and Technology Project of the State Grid Corporation of China (Project Number: B30940200002)
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