Factors Affecting the Discharge Characteristics of Rod-Rod Long Air Gaps at Different Altitudes

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Abstract. The impulsive discharge characteristics of the air gap is one of the main bases for the design of the external insulation of high-voltage electrical equipment; meanwhile, air gap discharge characteristics at different altitudes have been of concern for a long time. In this paper, the impact discharge tests of rod-rod gaps at different altitudes were carried out to study the influences of elements such as electrode shape, voltage polarity, altitude and temperature. It can be found that, with the increase of the gap distance, the 50% impulse voltage of the switching impulse tends to be saturated, and the discharge characteristic curve can be fitted by exponential function. The 50% impulse voltage of the lightning impact and the gap distance shows a good linear relationship which can be fitted by the linear function. This is no direct relationship with temperature and altitude. The saturation tendency of switching impulse's 50% discharge voltage decreased with the decrease of temperature. With the increase of the altitude and the decrease of the 50% impulse discharge voltage, the polar effect of the air gap between the rod-rod and the rod-plate decreases. The results are of great reference value for Insulation configuration of electrical equipment in high altitude.

1. Introduction

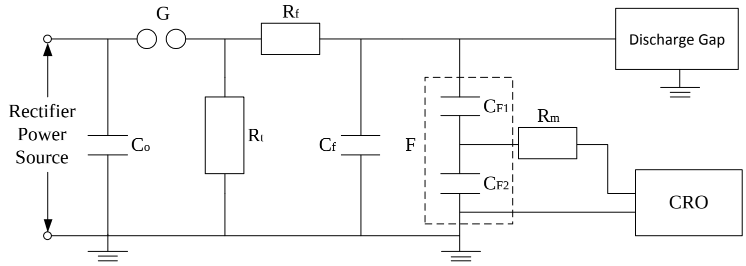
Reasonable insulation coordination is the basic guarantee for the safe and reliable operation of the power system[1]. China is a large country with a large altitude difference especially in the east and west regions where the altitude is between 3000 and 5300 meters in Qinghai-Tibet region; therefore, in the construction of high-voltage transmission projects in high altitude areas, we must solve the problems of outer insulation, corona and electromagnetic as required[2~6]. In engineering practice, most of the electric fields encountered are inhomogeneous electric fields. Since the rod-rod air gap electric field gets perfect symmetry in all kinds of extremely inhomogeneous electric field air gaps, its breakdown characteristics can be used as reference for other types of inhomogeneous electric fields[7,8].

In this paper, the impact discharge tests were conducted in two regions: a place in the coast area of China (altitude of 50m) with the temperature range of 5~5°C and 15~25°C in the discharge tests fields while the second located somewhere in Qinghai-Tibet region (altitude of 4300m) with the temperature in the range of 15~25°C. The impulsive discharge tests include switching impulse and lightning impact tests. Those tests are conducted to analyze air gap impulse discharge characteristics based on test results, such as the polarity effect of impulse voltage, saturation phenomenon, and dispersion.

2. Impact test principle

Impulse voltage generator use multi-stage capacitor to charge in parallel and discharge in series to generate the required voltage, while its waveform can be adjusted by changing the resistance of R_f and R_t.

Air gap impact test principle of wiring is shown in Figure 1. The test of wiring mainly consists of the impact of voltage generators, capacitive voltage divider, digital recorder, and other discharge gap components.



Co:Main Capacitor of Impulse Voltage Generator; G:Isolation Gap;
Rf:Wavefront Resistance; Rt:Stroke Resistance; Cf:Wavefront Capacitor;
F:Shock Capacitor Divider; Rm:Protective Resistance; CRO:Oscilloscope

Figure 1. Air Gap Impact Test Principle of Wiring

Using the lifting method, the voltage's rise and drop magnitude is estimated to be about 3~5% in the impact flashover voltage test where the interval between each impact is about 3~5min. Atmospheric pressure, humidity, temperature and other meteorological parameters were measured every time before and after each test, and the average is taken as the experimental data of the atmospheric parameters[9,10].

50% discharge voltage U_{50} is calculated as:

$$U_{50} = \frac{\sum(n_i \times U_i)}{n} \tag{1}$$

In the equation above: U_i stands for Impact voltage value, kV; n_i is the number of valid tests at the same surge voltage (U_i); n equals the number of valid tests.

Generally speaking in each data point, the number of operational impact pressure is 40 times and the effective number of lightning impulse is 30 times. If the impulse voltage series is less than four (i<4), the impact test operation can be carried out 30 times, while the lightning impulse test can be carried out 20 times. Standard deviation of operational impact does not exceed 5%, and the standard deviation of lightning impulse does not exceed 3%. For the test whose standard deviation does not meet the standard data points, test is re-runned.

The minimum of 50% impulse discharge voltage in each test is taken as the reference value, and the 50% impulse discharge voltage in the test is taken as the per unit value. Per unit value for the 50% of the percussive discharge voltage (U_{50*}) is as below:

$$U_{50*} = \frac{U_{50}}{U_{50B}} \tag{2}$$

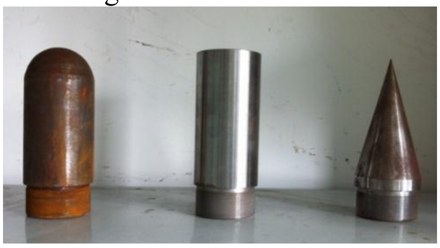
In the equation above: U_{50} is the actual value of the 50%discharge voltage, kV; U_{50B} is the reference value of 50% discharge voltage, taking the minimum of 50% impact discharge voltage in each set of tests, kV.

The dispersion of the data of the test data can be showed by the coefficient of variation. The coefficient of variation is calculated as follows:

$$z = \frac{\sigma}{U_{50}} \times 100\% \tag{3}$$

In the equation above: U_{50} is the 50% discharge voltage, kV; σ is the standard deviation.

The diameter of the rod electrode used in the experiment was 60 mm. There are three shapes at the ends, hemispherical, flat, and conical, respectively. The cone angle of the conical rod electrode was 30°. The shape of each end is shown in Figure 2.



(a) Hemispherical rod electrode (b) Flat rod electrode (c) Conical rod electrode

Figure 2. Rod electrodes

Positive polarity impact discharge tests were performed on the above three end-shape rod-rod electrodes' air gap.

Fitting the test results to get the relationship between the U_{50*} of the rod-rod electrode and the gap distanced of the three end shapes, as is shown in the curve in Figure 3.

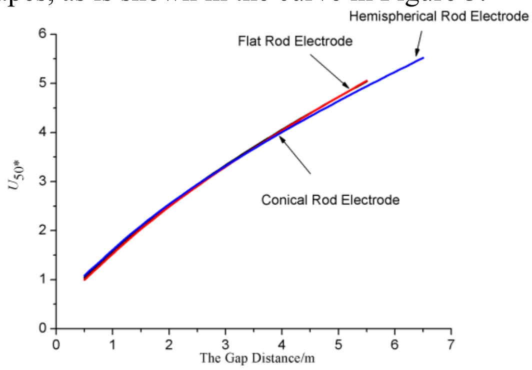


Figure 3. The relationship between the switching impulses of the electrode of different shapes U_{50*} and the gap distance d

As can be seen from Fig.3, the impact discharge curves of three different end-shape rod-rod electrodes are basically coincident, with little difference between the three test results. It can be seen that when the long air gap is more than 1 meter (d>1m), the shape of the end of the rod electrode is not the main factor affecting the discharge voltage. As the hemispherical rod electrode is the most typical form used in the power system, the semi-spherical rod electrode is chosen as the follow-up test rod electrode.

3. Factors affecting the discharge characteristics of the air gap

Air gap discharge test was carried out in different environments to analyze the influencing factors of rod-rod air gap. The environmental parameters of the test are shown in table 1.

Table 1. The Environmental Parameters of the Test

	Place A in the coast area	Place B in the coast area	somewhere in Qinghai-Tibet region
Altitude	50m	50m	4300m
Impact type	Switching impulse/ Lightning impact	Switching impulse/ Lightning impact	Switching impulse/ Lightning impact
Voltage Polarity	+ /-	+ /-	+ /-
Temperature Range	-5~5℃	15~25℃	15~25℃
Average Temperature	-1℃	21℃	18℃

IOP Conf. Series: Materials Science and Engineering **366** (2018) 012061 doi:10.1088/1757-899X/366/1/012061

Absolute Humidity range	2~5 g/m3	4~11 g/m3	3~7 g/m^3
Average Absolute Humidity	4.1 g/m3	6.0 g/m3	5.3 g/m^3

3.1. Effect of Temperature on Air Gap Discharge Characteristics

It is generally believed that when the temperature raises, the average kinetic energy of air molecules increases, and the molecular activity increases, so the discharge voltage of the air gap decreases. In order to investigate the effect of temperature on the discharge characteristics of air gap, we compared the experimental data of low temperature (-5~5℃) and high temperature (15~25℃) both conducted in coastal area to analyze the influence of temperature on the discharge characteristics of air gap. The curves of rod-rod electrode impact discharge U_{50*} changing with the gap distance are as following.

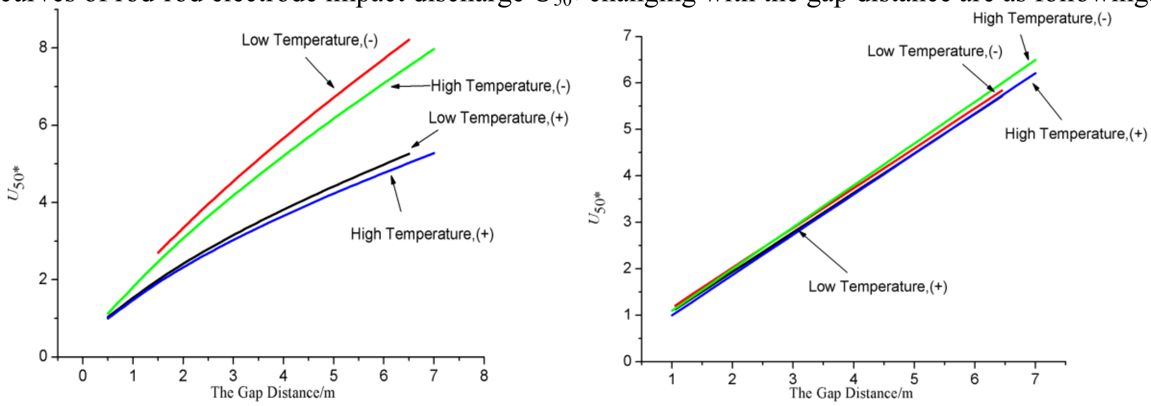


Figure 4. The relationship between switching impulse U_{50*} and the gap distance d as well as the relationship between lightning impact U_{50*} and the gap distance d in different temperature.

Table 2. Coefficient of Variation of Rod-rod Air Gap Impact U_{50}

Impact Type	Coefficient of Variation（z）
switching impulse（low temperature）	3.6%~4.8%
switching impulse（high temperature）	2.9%~4.8%
lightning impact（low temperature）	1.8%~2.9%
lightning impact（high temperature）	1.8%~3.0%

As can be drawn from Figure 4 and Table 2:

(1) As the temperature decreases, the breakdown voltage of the rod-rod air gap increases. The effect of temperature on the impact polarity of the rod-rod air gap is great: when the air gap distance is in the range of 2m-6m, the switching impulse of rod-air gap at low temperature$U_{50\,(-)}$ increases by about 6% ~ 9% comparing to it at high temperature $U_{50(-)}$. The switching impulse $U_{50\,(+)}$ of the rod-rod air gap at low temperature increased about 1%~4% compared with the $U_{50\,(+)}$ at high temperature. The greater the gap distance, the greater the difference between them. The effect of temperature on the polarity effects of the lightning impulses of the rod-rod air gap is less significant: at both temperature levels, the positive and negative U_{50} can be considered equal.

(2) When the temperature rises, the saturation tendency of the switching impulse voltage of the rod-rod air gap increases, and the effect of temperature on the saturation trend of the switching impulse $U_{50\,(-)}$ is greater than that of the $U_{50\,(+)}$.

(3) As the temperature decreases, the rod-rod air gap's switching impulse dispersibility of the U_{50} increases; while the temperature has less effect on the dispersibility of the lightning impact U_{50}.

3.2. Influence of Altitude on Air Gap Discharge Characteristics

With the increase of altitude, the density of air decreases, and the mean free path of free electrons in air increases, hence the ionization process of gas increases, while the discharge voltage of air gap

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decreases. In this part, we compare the experimental data at low altitudes (50m, 15~25℃) and the one at high altitude (4300m, 15~25℃) somewhere in the Qinghai-Tibet region to analyze the influence of altitude on the air gap discharge characteristics. The curves of rod - rod electrode impact discharge U_{50*} changing with the gap distance are as following.

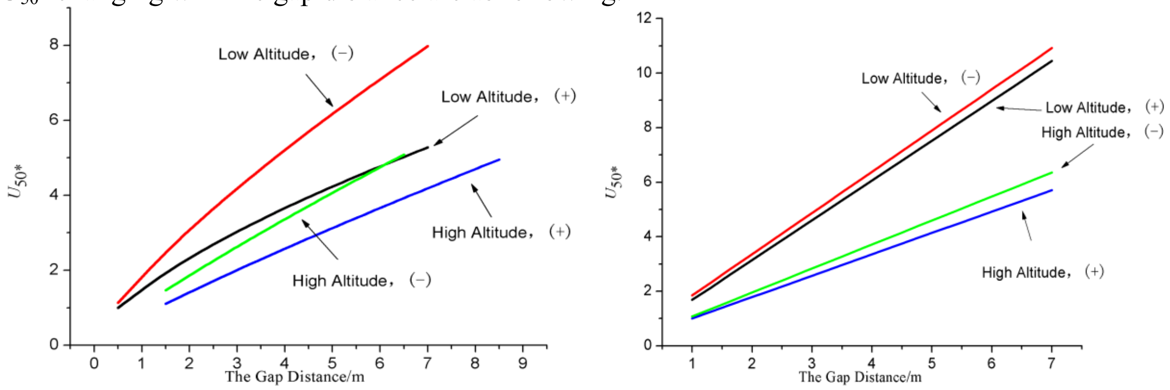

Figure 5. the relationship between switching impulseU_{50*} and the gap distance d as well as the relationship between lightning impact U_{50*} and the gap distance d in different altitude

Table 3. Coefficient of variation of rod- rod air gap impact U_{50}

Impact Type	Coefficient of Variation（z）
Switching Impulse（50m）	2.9%~4.8%
Switching Impulse（4300m）	2.6%~4.8%
Lightning Impact（50m）	1.8%~3.0%
Lightning Impact（4300m）	1.4%~3.0%

As can be drawn from Figure 5 and Table 3:

(1) As altitude increases, the U_{50} of the rod-rod air gap decreases; the saturation trend of switching impulse U_{50} drops. Altitude has a large effect on the impact discharge characteristics of the rod-rod air gap: U_{50} at an altitude of 4300 m is about 60% to 80% of it at an altitude of 50 m for a positive-polarity switching impulse; for a negative-polarity switching impulse at an altitude of 4300 m U_{50} is about 60%-70% of it at the sea level of 50m. For a lightning impact, the U_{50} at an altitude of 4300m is about 55% of the U_{50} at an altitude of 50m; therefore, the effect of altitude on positive and negative polarity lightning impulse voltage is basically the same.

(2) As the altitude increases, the polar effect of the rod-rod air gap decreases.

(3) According to the test data dispersion analysis, it is found that the dispersion of the impact discharge U_{50} of the rod- rod air gap in the high altitude area is generally lower than that in the low altitude area. The difference between the two is so tiny that it can be taken as there is no difference at all.

4. Conclusions

In this paper, the impact-discharge tests of air gap between rod and rod at a temperature range of -5 ~5℃ and 15~25℃ in a certain place along the coast and those at the altitude of 4300min the Qinghai-Tibet region are conducted. The characteristics of impingement discharge of air gap are analyzed from several aspects, such as polarity effect, saturation phenomenon, and dispersibility. When the other environmental conditions are close to each other, temperature and altitude are chosen as two parameters for studying the influence of single environmental factor on the air-gap discharge voltage. The main conclusions of this thesis are as follows:

(1) For a long air gap, the end shapes of the electrode have no effect on the air gap impulse discharge characteristics when the rod electrode diameter is 60 mm.

(2) When the gap distance is longer, there is a polar effect on the impact discharge of the rod-rod air gap under different experimental conditions. Usually the 50% impulse discharge voltage of the negative polarity is greater than it of the positive polarity. With the increase of the gap distance, the 50% impulse voltage of the switching impulse tends to be saturated, and the discharge characteristic curve can be fitted by exponential function. The 50% impulse voltage of the lightning impact and the gap distance shows a good linear relationship which can be fitted by the linear function. The breakdown voltage data dispersion of the switching impulse is greater than the lightning impact's; while the voltage polarity has less effect on the data dispersion of the 50% impulse discharge voltage.

(3) The saturation tendency of switching impulse's 50% discharge voltage decreased with the decrease of temperature. The increase of discharge voltage is large in the rod-rod air gap's switching impulse. The temperature influence on rod-rod air gap of the lightning impact is relatively small. When the temperature decreases, the depressiveness of 50% discharge voltage of the rod-rod air gap's switching impulse increases; the temperature has little effect on the dispersion of the 50% discharge voltage of the lightning impact.

(4) With the increase of the altitude and the decrease of the 50% impulse discharge voltage, the polar effect of the air gap between the rod-rod and the rod-plate decreases. The saturation tendency of the 50% discharge voltage decreases with the switching impulse, and the increase range of 50% discharge voltage decreases. The dispersion of 50% impulse discharge voltage at high altitude is slightly less than it at low altitude.

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