山 形 大 学 紀 要（工学） 第12巻　第1号　昭和47年1月
Bull. of Yamagata Univ. Eng., Vol. 12 No.1 Jan. 1972

Flashover Characteristics of Single-Wave Voltage of Commercial Frequency in Non-uniform Electric Fields

Katsuya SUGANO*, Shin'ichi SHODA* and Tomoteru SATO**

*Department of Electrical Engineering, The Technical College
**Department of Electrical Engineering, Faculty of Engineering

Abstract

The experiments on the flashover characteristics in non-uniform electric fields formed by the needle-plane gaps are performed and the Volt-time characteristics for positive polarity are observed to slope down to the left, which suggests V-type Volt-time characteristics. The flashover voltages of the single-wave voltage of positive and negative polarities and the alternating current voltage of commercial frequency (50 Hz) are compared with one another. Further, the effect of irradiating the gap spacings by ultraviolet rays is examined on them. Finally, the flashover mechanism of the left-down characteristics is considered.

1. Introduction

Due to frequent operations of high speed circuit breakers, the rated voltage of half a wave of commercial frequency is suddenly impressed in ultra-high-voltage (UHV) transmission systems. In fact, the switching surge shapes obtained during a study of 735-kV network system by means of a transient network analyzer(1) are similar to the wave shape of half a wave of AC voltage of commercial frequency. Usually, laborarory tests have been performed by utilizing switching impulses consisting of a double exponential form with smooth front, such impulses being considered as duplicating the actual switching surges on network systems. Therefore, in order to duplicate faithfully the actual switching surges, single-wave voltage of commercial frequency also should be considered in switching surge tests.

On this line, a generating circuit by using a step-up transformer suitably energized from the low-voltage side should be adopted in order to generate single-wave voltage of commercial frequency. Flashover characteristics in uniform electric fields were reported as fundamental data in the previous paper(2). This paper deals with flashover characteristics in non-uniform electric fields, in which most of insulation configurations in actual network systems are included.

2. Experimental Arrangement

The generating circuit shown in Fig. 1 was summarized in the previous paper.(2) A needle-plane gap was used for the tested sample. The needle as the high potential electrode was made of brass, which is shown in Fig. 2. The plane as the earth potential electrode was a brass disc of 300 mm in diameter and 1.8 mm in thickness.

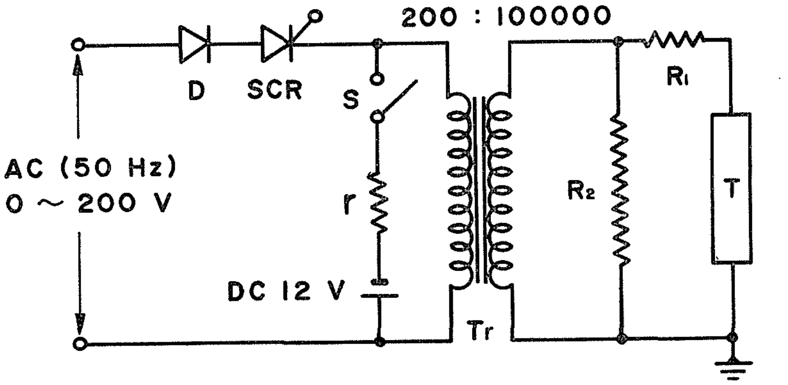


Fig. 1. Generating circuit of single-wave voltage of commercial frequency.
SCR : thyristor. **D** : protective diode. **r** : DC controlling resistor.
S : manual switch. **Tr** : testing transformer. **R**$_1$: discharge resistor.
R$_2$: load resistor. **T** : tested sample.

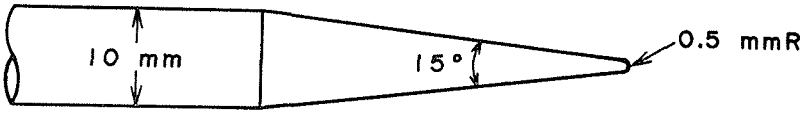


Fig. 2. The shape of a needle electrode.

V-t characteristics were measured in the range of gap spacings from 10 to 100 mm at 10 mm-intervals for positive polarity and from 10 to 50 mm at 10 mm-intervals for negative polarity. 50 % flashover voltage characteristics were measured in the range of gap spacings from 5 to 50 mm at 5 mm-intervals for both polarities. In order to examine the effect of irradiation by ultraviolet rays, the data with and without irradiations were obtained in all gap spacings. The mercury-arc lamp was used for the irradiation source. In the investigation of the distribution of flashover points on the plane, the sensitive paper for recopy was affixed on its surface and developed after the flashover. Flashover points appeared white on the violet ground-colour and could be easily counted.

Flashover voltage were divided by a potential divider of resistance type, and measured by a cathode ray oscilloscope. All the data were corrected for the relative air densities, but they were not corrected for the atmospheric humidity. The humidity condition in the measurement is written only in addition according to the recommendation of JEC-172 (1968).

3. Results and Discussions

"MINIMUM FLASHOVER VOLTAGE" was adopted in the expression of characteristics in uniform electric fields(2). In this paper, "50 % FLASHOVER VOLTAGE" was adopted. The reason is that even the single-wave voltage of commercial frequency with a super long wave-front flashovers in a little disorder in non-uniform electric fields. They are essentially identical. The results of experiments are discussed in the following subsections.

3. 1. 50 % flashover voltage characteristics

The humidity in the measurement was in the range from 12.4 to 20.7 g/m^3. 50 % flashover voltages of single-wave voltage of commercial frequency for positive and negative polarities are shown as a function of gap spacing in Fig. 3 and the flashover voltage of AC voltage of commercial frequency in Fig. 4. The effect of irradiation is not found. It is, however, observed in the test that the flashover voltages tend to be somewhat stable over the whole of gap spacings by irradiating. The effect of polarity is found to be remarkable. The negative flashover voltage is far higher than the positive one. These charcteristics are similar to those of DC voltage.

The flashover voltage of AC voltage does not perfectly agree with 50 % flashover voltage for positive polarity, but their whole inclinations can be considered to be identical with each other. In other words, it proves that AC voltage begins to flashover at positive half a wave in a needle-plane gap and that there is no difference between the impressing of repeated voltage and that of single voltage.

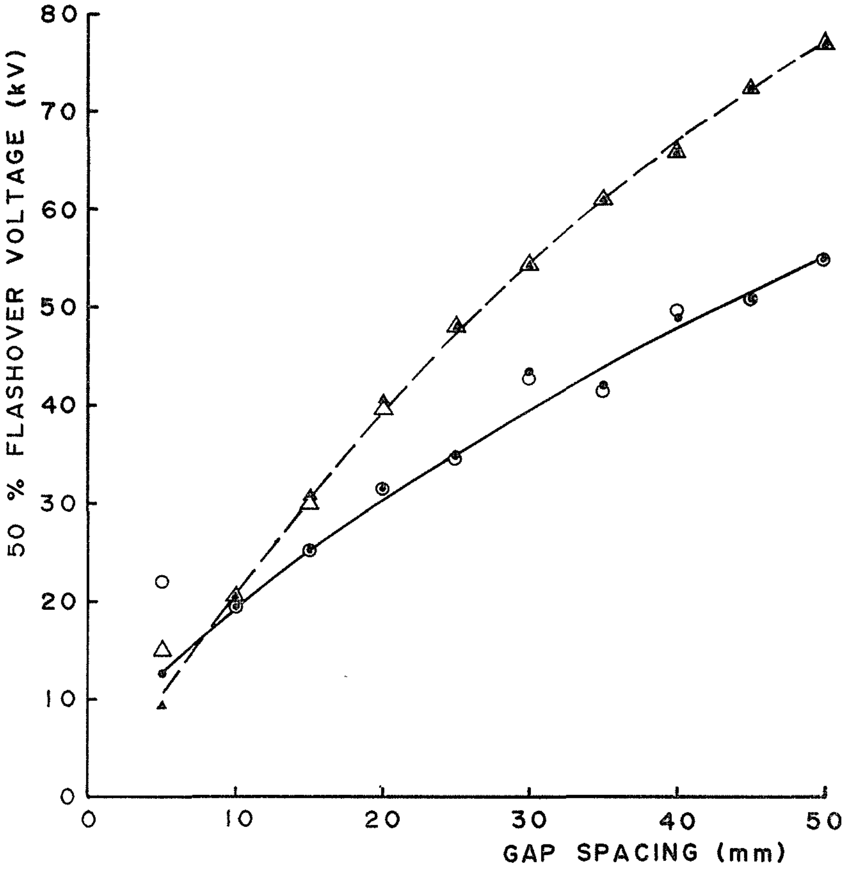


Fig. 3. 50 % flashover voltage as a function of gap spacing
(▲ : negative, irradiated, △ : nagative, not irradiated,
● : positive, irradiated, ○ : positive, not irradiated.)

3. 2. Volt-time characteristics

The humidity in the measurement was in the range from 4.8 to 8.5 g/m^3. The positive and negative characteristics with and without irradiations are shown in Figs. 5~8.

For positive polarity:

(a) The effect of irradiation is not clear as well as that of 50 % flashover voltage characteristics. Fig. 5 shows the characteristics with irradiation.

(b) The characteristics slope down to the left, which is clear in the gap spacings over 40 mm. Fig. 6 shows one of the detailed characteristics.

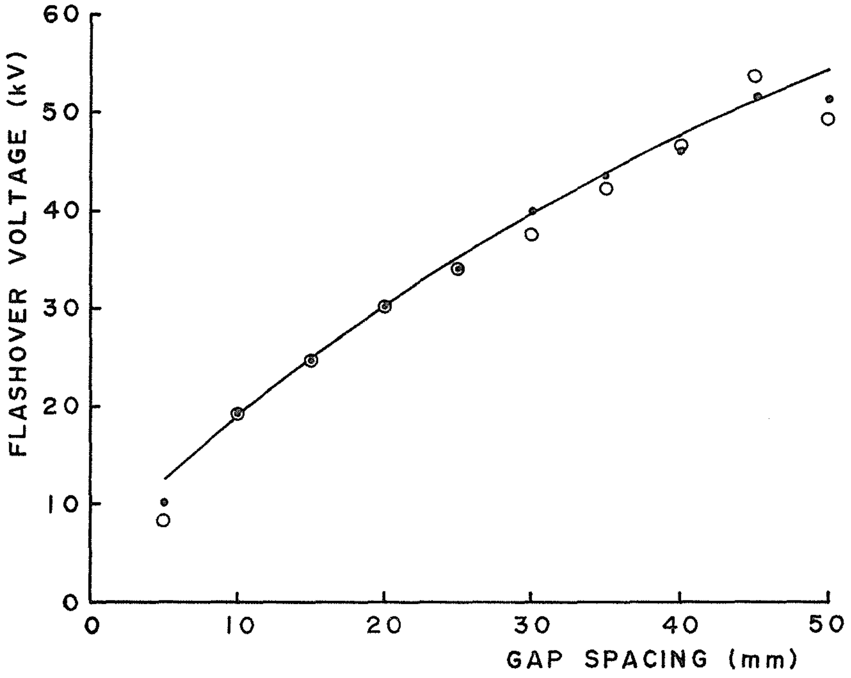


Fig. 4. The flashover voltage of AC voltage as a function of gap spacing.
(● : irradiated, ○ : not irradiated.)

(c) The slopes of the characteristic curves become steep as the gap spacing increases.

For negative polarity:

(a′) The effect of irradiation is not found at all. Fig. 7 shows the characteristics with irradiation.

(b′) The characteristics slope up to the left in all gap spacings, which means that the impressing of overvoltage brings conventionally the time lag of spark. Fig. 8 shows one of the detailed characteristics.

(c′) The slopes of the characteristic curves show the same tendency as for positive polarity.

(a) and (a′) are quite different from the V-t characteristics in a sphere-sphere gap, which form straight lines in irradiating the gap spacings, but which accompany distinct disorder in not irradiating them(2). The reason is

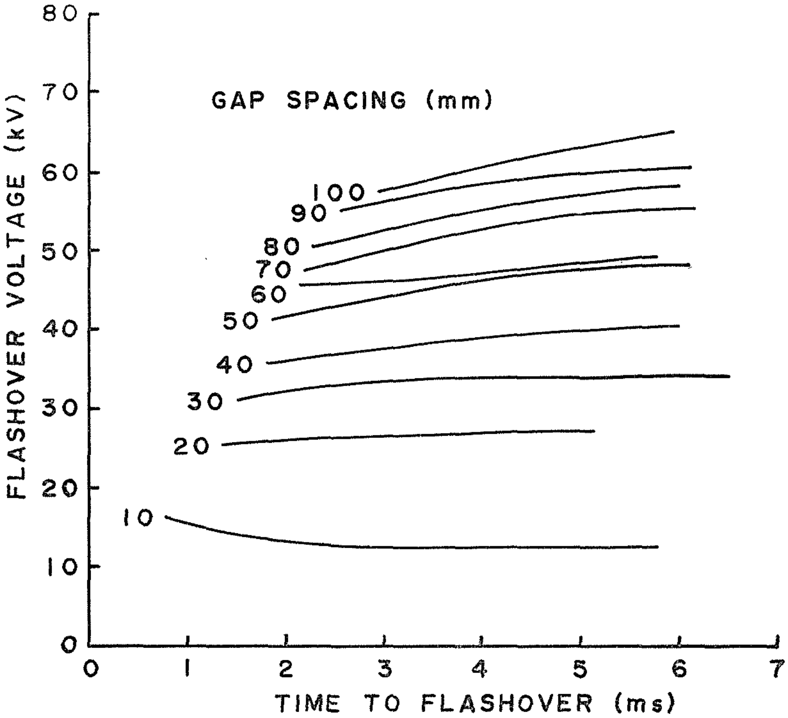


Fig. 5. Volt-time characteristics for positive polarity in irradiating the gap spacings.

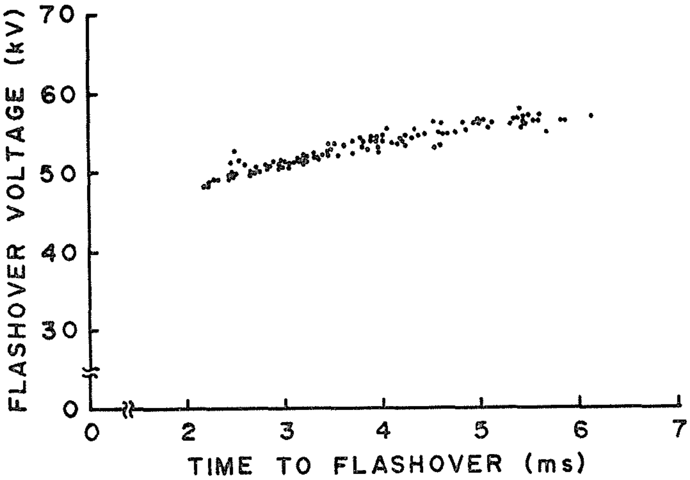


Fig. 6. The detailed Volt-time characteristic for positive polarity in the gap spacing of 70 mm.

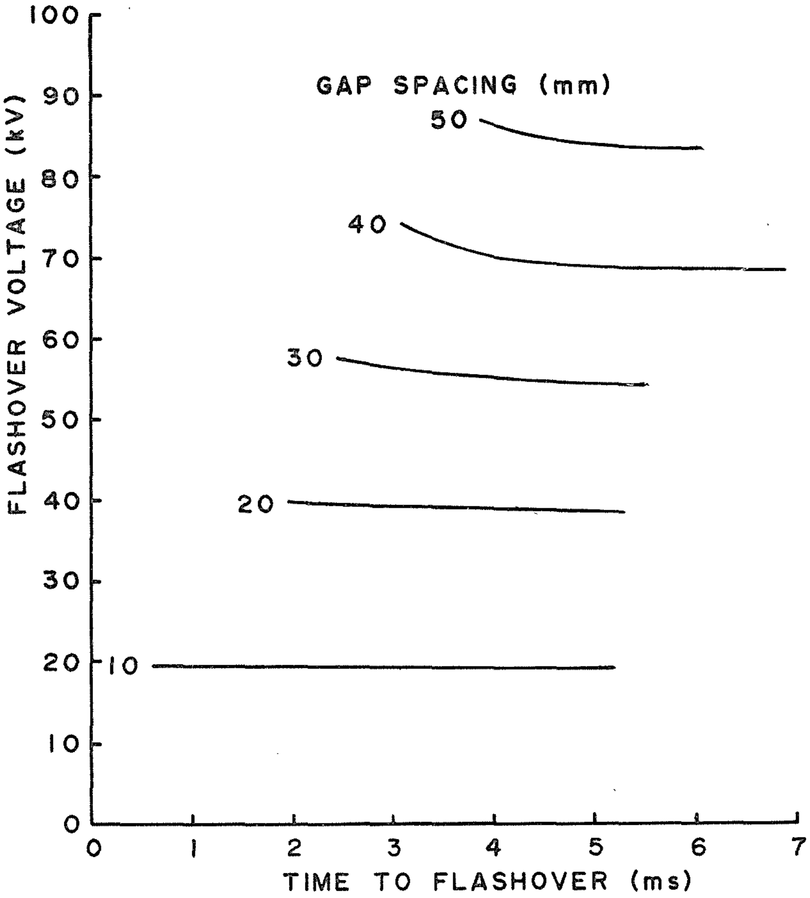


Fig. 7. Volt-time characteristics for negative polarity in irradiating the gap spacings.

that the corona provides ions and electrons sufficient for the flashover even if they are not provided from the outside. But it goes without saying that the flashover voltage in a sphere-sphere gap becomes stabler than that in a needle-plane gap once ions and electrons are provided. (b) suggests V-type V-t characteristics(3),(4). (c) and (c′) show that the increase of gap spacing makes the electric fields to be more non-uniform.

A test was made for the purpose of confirming whether the left-down characteristics only for positive polarity are caused by errors in the measurement or not. Voltage was impressed to parallel-connected needle-plane and sphere-sphere gaps. As shown in Fig. 9, the needle-plane gap has the V-t curve DBE sloping down to the left, and the sphere-sphere gap has the plain V-t curve

ABC. The sphere-sphere gap flashovered along the curve AB near the critical flashover voltage. As the impressed voltage became over, the flashover points removed from the curve AB to the curve BE, and then the needle-plane gap began to flashover. This result proves our results to be correct in the measurement.

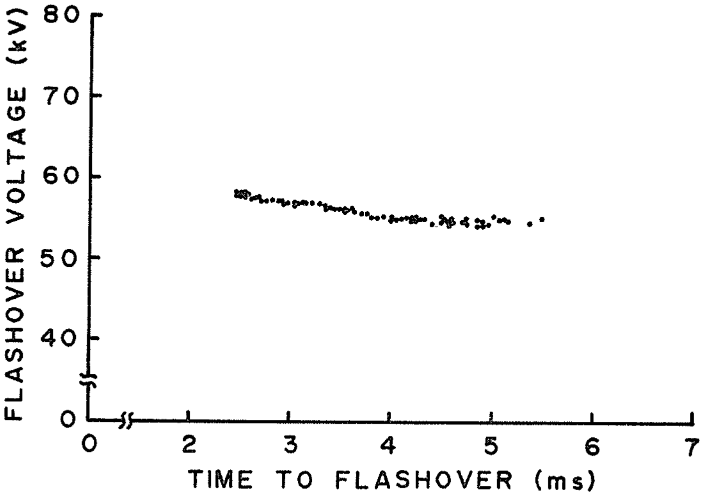


Fig. 8. The detailed Volt-time characteristic for nagative polarity in the gap spacing of 30 mm.

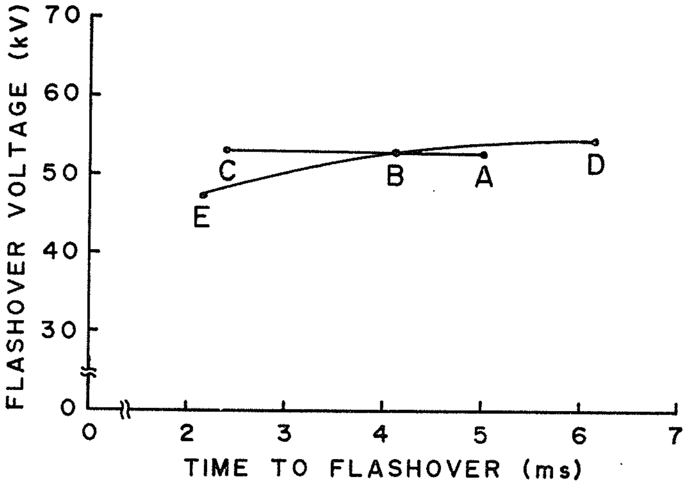


Fig. 9. Volt-time curves of parallel connected gaps (ABC : sphere-sphere, DBE : needle-plane)

3. 3. Flashover points on the plane and wave shapes of flashover voltage

The distribution of flashover points on the surface of plane electrode was investigated to examine the distribution of the electric field near the plane and to find out the cause of the remarkable effect of polarity. Voltage was changed in 7 levels and 100 shots were impressed for each voltage level. As a result, it was found that the distribution was not changed by the voltage of different levels at all. In Fig. 10, the average density of flashover points is shown as a function of the distance from the centre of plane. Since the slope of the curve is smooth, it is concluded that the electric field does not concentrate locally on the surface of plane⁽⁵⁾.

For positive polarity, the number of flashover points observed was equal to that of the multiple flashover caused by the impressing of overvoltage (Fig. 11-a). The first spark struck near the centre of the plane and the following ones gathered about the first without striking twice at the same place. This means that the partial oxidation of the surface where the spark struck reduced the electron emission there and thus made the place unfavorable for another spark⁽⁶⁾.

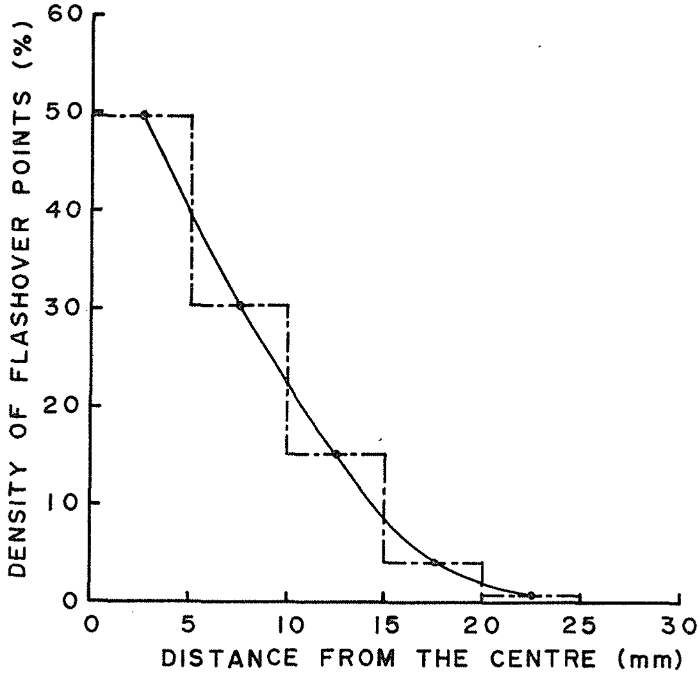
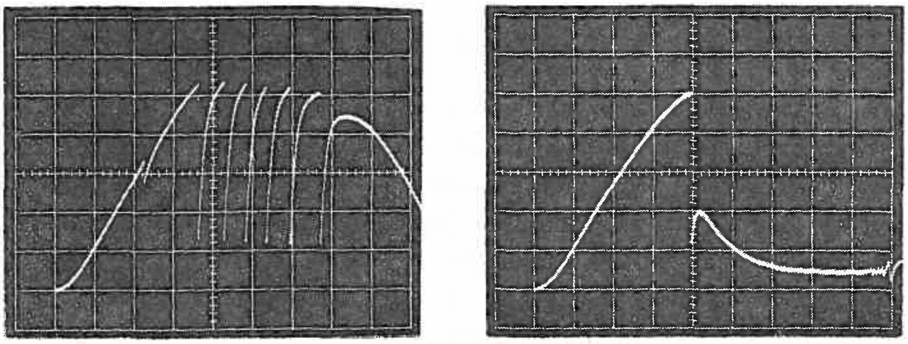


Fig. 10. The distribution of flashover points on the surface of the plane electrode for positive polarity in the gap spacing of 50 mm.



(**a**) positive (4.4 kV/div, 1 ms/div) (**b**) negative (8.8 kV/div, 1 ms/div)

Fig. 11. Wave shapes of flashover voltage.

For negative polarity, the number of flashover points observed was in the range from 4 to 20. Most of them overlapped at the same place. This means that the place where the spark struck once was favorable also for another spark because of the independence of the cathode oxidation. The distribution of flashover points is similar to that for positive polarity.

Fig. 11 shows the typical examples of positive and negative wave shapes of flashover voltage. The multiple flashover takes place in the positive voltage and its wave shape is distorted at the part of lower voltage before the flashover. The single flashover takes place in the negative voltage and its wave shape is not distorted. It is not difficult to suppose that this evident difference is concerned with the difference between the value of positive flashover voltage and that of negative one. The partial distortion of wave shape, however, disappears by irradiating or increasing the gap spacing. AC voltage also has the same phenomenon. The cause of wave distortion is that the voltage drop is partially caused depending upon the constant of the generating circuit since the enormous volume of pre-discharge pulse current flows. The negative wave shape is little affected by the voltage drop because of its higher flashover voltage.

The electron avalanche developing from casual electrons in the gap spacing induces the pre-discharge pulse current(7). But it disappers absorbed in the anode because impressed Voltage has not risen enough to flashover. When the gap spacing is irradiated, electrons and ions provided at random are balanced to a certain extent. Therefore, the local existence of space charges is impeded and the pre-discharge electron-avalanche is diffcult to develop.

The positive multiple-flashover can be interpreted as follows. The moment the streamer reaches the cathode and gives rise to the spark, a quantity of secondary electrons are emitted. These electrons neutralize the space charges near the plane and weaken the electric field; the self-maintaining condition of spark is broken. Since the disappearance of spark results in the impressing of steeply-building-up voltage, space charges are easily stored in the gap spacing (see subsection 3. 4.); the follwing flashover takes place at the lower voltge value. For negative polarity, the spark is stable because it is not the cathode that the streamer reaches finally.

3. 4. Consideration for the left-down V-t characteristics

The behavior of corona in the gap spacing was observed just before impressed voltages flashover according to their own V-t characteristics. For negative polarity, the glow corona was found to remain stable. For positive polarity, the filmy corona appearing at the beginning was found to develop into the streamer corona with the rising of the prospective peak value of impressed voltage. The more steeply impressed voltage built up, the more the streamer grew. From this result, the dominating factor of the left-down characteristics seems to be the behavior of space charges depending upon the building-up velocity of impressed voltage(8),(9) as described below.

The effect of polarity upon V-t characteristics can be connected with that upon DC corona; in comparison with the cathode corona ((−) corona), the anode one ((+) corona) is full of variety and it has complicated charcteristics(10). The electron source is secured by means of the γ-action on the surface of cathode. Therefore, (−) corona, which itself lies on the cathode, remains stable. The impressed voltage with steeply-building-up velocity yields the space charges depending upon the mobility difference between ions and electrons. These space charges weaken the electric field on the anode side crowded with ions, while they strengthen that in (−) corona on the cathode side. In other words, (−) corona increases its own stability.

On the contrary, (+) corona, which has the electron source on the opposite electrode (plane), remain instable. The space charges weaken the electric field in (+) corona, while they strengthen that ahead of (+) corona toward the plane. In other words, (+) corona increases its own instability. The more steeply impressed voltage builds up, the more easily space charges concentrate locally end affect (+) and (−) coronas. For negative polarity, the V-t characteristics slope up to the left due to the conventional lag time of spark. For positive polarity, the streamer grows easily and the V-t characteristics slope down to the left.

When the building-up velocity becomes still steeper, the lag time of spark becomes dominant. The V-t characteristics are expected to slope up to the left and to form V-type as a whole.

4. Conclusions

In this investigation, the results of flashover tests of single-wave voltage of commercial frequency are summarized as follows.

(1) 50 % flashover voltage is far higher for negative polarity than that for positive polarity. The effect of irradiatiation is not evident.

(2) 50 % flashover voltage for positive polarity agrees with AC flashover one.

(3) The wave shape of positive flashover voltage is distorted by the predischarge pulse current. The distortion disappears by irradiating or increasing the gap spacing.

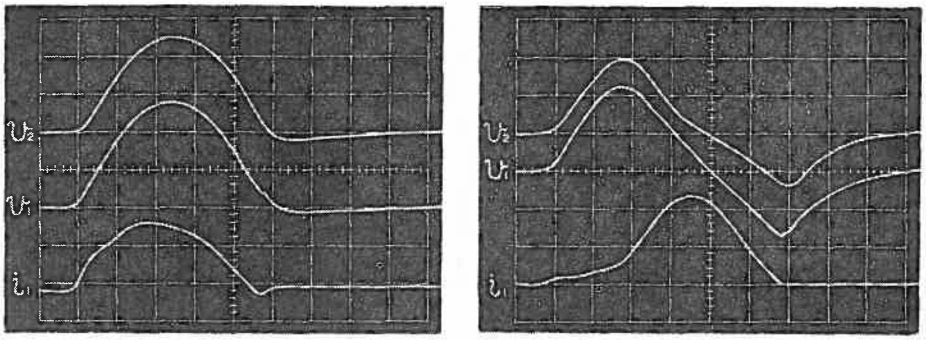
(4) Concerning V-t characteristcs, the negative characteristics conventionally slope up to the left, but the positive characteristics slope down to the left. The latter suggests V-type characteristics.

(5) Concerning the distribution of flashover points on the plane electrode, the positive flashover points do not overlap at the same place and concentrate near the centre of plane, but most of negative flashover points overlap at the same place. Their characteristic curves show that the electric field does not concentrate locally on the surface of plane.

(6) The left down V-t characteristics (V-type characteristics included) are considered from the relation between the building-up velocity of impressed voltage and the behavior of space charges.

Appendix

The actuating principle of the generating circuit summarized in the previous paper(2) is detailed below. The wave shapes of the secondary voltage v_2, the primary voltage v_1 and the primary current i_1 are shown in Fig. 12-a. Fig. 12-b shows the wave shapes in actuating the circuit, leaving the manual switch S to be open. The distinct difference between Figs. 12-a and 12-b is that, in addition to much distorted wave shapes, the peak value of i_1 in Fig. 12-b is about 7 times more than that in Fig. 12-a. It is interpreted as follows : ——(i) In contrast to AC voltage, the single-wave voltage of commercial frequency always magnetizes the iron core of testing transformer in one direction. (ii) Under the influence of the residual magnetism, the magnetizing inrush current flows in one direction for the time over half a cycle of 50 Hz. (iii) The thyristor SCR is not turned off at the time 10 ms after. (iv) The distorted



(**a**) pre-excited

v_2 (40 kV/div, 2 ms/div)
v_1 (100 V/div, 2 ms/div)
i_1 (10 A/div, 2 ms/div)

(**b**) not pre-excited

v_2 (40 kV/div, 2 ms/div)
v_1 (100 V/div, 2 ms/div)
i_1 (50 A/div, 2 ms/div)

Fig. 12. Wave shapes of the secondary voltage v_2, the primary voltage v_1 and the primary current i_1 when the input voltage is 200V (effective value).

wave shapes are accompanied by the magnetic saturation phenomenon causing the inrush current.

Therefore, the best and easy way to prevent the inrush current and to normalize the wave shapes is to magnetize the iron core beforehand in the direction opposite to AC excitation.

Let us consider the magnetic behavior of the iron core in DC opposite exitation. The assumption is that the static characteristic curve of hysteresis of the iron core is shown by the dotted line and the dynamic characteristic curve of hysteresis by the solid line (Fig. 13). The latter, under the influence of the eddy current, is wider than the former. First when S is closed, the magnetic flux level by DC opposite excitation is at point A on the static characteristic curve. When the single-wave voltage of commercial freqency is impressed, the magnetic flux level transfers from A to B on the dynamic characteristic curve. After this, it is changed along curve BCD. After SCR is turned off at point D, it transfers toward the balance point A where it was. The last change of magnetic flux level from D to A gives the induced voltage of the iron core after the turning-off of SCR.

The above-mentioned DC opposite excition can apply to testing transformers

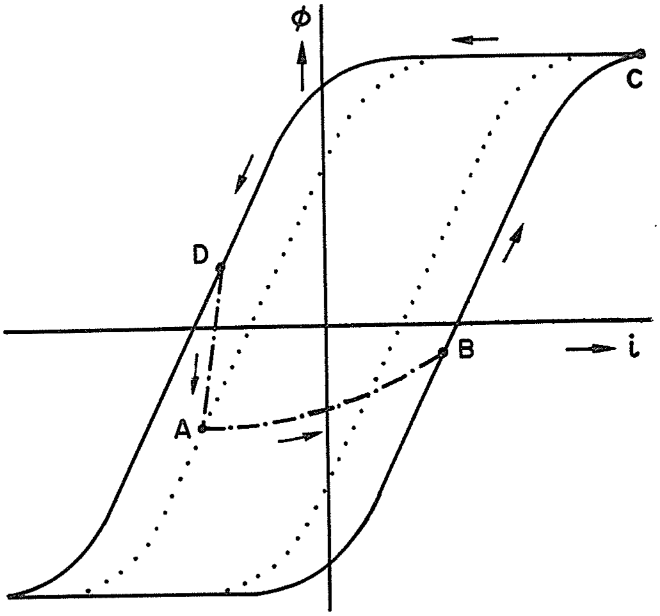


Fig. 13. Hysteresis curve of the iron core of a testing transformer. (ϕ:magenetic flux, i : magnetizing current)

with cascade connections. The iron core of each stage should be pre-excited in the direction of negating the residual magnetism, when insulation needs to be taken into careful consideration.

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山形大学紀要（工学）第12巻　第1号　昭和47年1月

不平等電界における単発商用周波電圧のフラッシオーバ特性

菅野勝弥*・庄田新一*・佐藤智暉**

*工業短期大学部　電気工学科
**大学院工学研究科　電気工学専攻

針-平板電極による不平等電界でのフラッシオーバ特性を求めた。V-t特性はギャップ長10～100mmの範囲で求め，その形が正極性で左下がりであり，V字形V-t 特性を暗示している。50%フラッシオーバ電圧特性はギャップ長5～50mmの範囲で求め，正極性電圧・負極性電圧・交流電圧のフラッシオーバ電圧を比較した。さらに，それらのすべてについて紫外線によるギャップの照射効果を調べた。

最後に平板面上のフラッシオーバ点の分布・電圧波形の検討から著しい極性効果を考察し，印加電圧の立上がり速度と空間電荷の応動の関係から左下がりV-t特性のフラッシオーバ機構を考察した。