FLASHOVER MODEL FOR ARCING HORNS AND TRANSMISSION LINE ARRESTERS

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Abstract

Transmission line arresters with a series air gap have been installed to protect an overhead power transmission line from a back flashover caused by lightning. It has been required to develop an accurate model of the transmission line arrester together with an arcing horn which can deal with multiple flashovers for an analysis of a transient behavior of the arrester.

The paper propose a new flashover model of the arcing horn represented by a nonlinear inductance, a nonlinear resistance and two switches. The transmission line arrester with a series air gap is modeled by a composite circuit of the above arcing horn model and a nonlinear resistance. The calculated results of the flashover voltage and predischarge current waveforms by the proposed model are compared with actual measurements, and the accuracy of the model has been confirmed to be satisfactory. The model is expected to be useful to analyze multiple flashovers of an arcing horn and an operational characteristic of a transmission line arrester.

Keywords: Flashover, Lightning surge, Arcing horn, Transmission line arrester, EMTP

1. Introduction

In recent years, office and/or factory automation equipment has been used extensively and higher quality of electric power without instantaneous interruptions is required. However, electrical faults caused by lightning are responsible for more than a half of power interruptions in Japan and can not be avoided, since the overhead transmission lines are exposed to nature. As a countermeasure to prevent such power interruptions, transmission line arresters with a series air gap have been installed to protect an overhead power transmission line from a back flashover caused by lightning.(1)

On the other hand, the lightning surge analysis of the electric power system is performed mainly by digital computer and many models of electric power apparatus for analysis have been developed. It has been required to develop an accurate model of the transmission line arrester together with an arcing horn that can deal with multiple flashovers for an analysis of a transient behavior of the arrester.

A conventional arcing-horn flashover model has generally adopted a method, such that a flashover time is first determined on the assumption that a flashover occurs at an arcing horn when a voltage appearing at the arcing horn gap crosses the V-t characteristic and that short-circuiting is caused through an equivalent inductance at the time of the flashover. And the method called the integration method has been also used.(2)(3) Recently, a new approach for lightning surge analysis has been proposed, by the name of the leader method that simulates horn-to-horn impedance variation with time in consideration of presence of a predischarge current.(4)(5) When this leader method is used for analysis, equivalent impedance of arcing horn is obtained by the leader development method based on the horn-to-horn voltage that is obtained from transient phenomenon analysis while no flashover takes place, and this equivalent impedance is linearly approximated to establish a flashover model as a combination of linear inductance and a time control switch. Therefore, analysis of multiple flashovers with this model becomes quite complicated. To eliminate this difficulty, another arcing horn flashover model has been newly proposed, which expresses the variation in arcing horn's equivalent impedance in a form of nonlinear inductance.(6)

These models, arranged in consideration of predischarge currents, are based on a long gap of several meters. This paper deals with flashover characteristics of a nonlinear inductance model having an arcing horn whose gap length is comparatively short. In this paper, a new flashover model is proposed, which is a combination of a nonlinear inductance and a nonlinear resistance. In addition, for power transmission line arrester equipment composed of a short gap and an arrester, another flashover model is proposed. This model is a combination of the above-mentioned arcing horn model and a nonlinear resistance that can express characteristics of an arrester. Lastly, the result of measurements is compared with that of calculations conducted on the proposed models. The result of comparison indicates that sufficient accuracy is assured by these new models.

2. Examination of Arcing Horn Flashover Simulation Method

A new flashover model proposed in this paper is based on the leader development method. In this section, the leader development method is briefly explained, and then descriptions are related to a nonlinear inductance model of an arcing horn with a short gap length and a new model proposed in this paper.

2.1 Leader Development Method

The leader development method is intended for the modeling of a leader development aspect changing with time, by dealing with the leader development velocity as a function of voltage, leader length, etc. An outline description of this method is given below.

Leader development velocity v is defined by Expression (1) below.

$$v = K_1 \frac{V^2}{D-2x} + K_2 \frac{Vi}{D-2x} \bullet \frac{x}{D} \qquad (1)$$

where v = leader development velocity (m/s)
x = leader length (m)
V = voltage in gap (V)
D = gap length (m)
i = predischarge current (A)
K_1, K_2 = constants independent of gap length and voltage waveform

Predischarge current i is defined by Expression (2).

$$i = C \bullet V \bullet v \qquad (2)$$

where C = equivalent capacitance of gap

By combining a circuit equation with Expressions (1) and (2), it is possible to calculate the conditions of leader development with time, variation in predischarge current, and equivalent impedance. Start and stop of leader development can be defined as follows;

Start time t_1 of leader development can be given by the following expression:

$$t_1 = A/\ (Vp/\ D - B) \quad (\mu s) \qquad (3)$$

where Vp = peak value of applied voltage (MV)
A, B = constants dependent on voltage polarity

When the leader length evolving from both ends of the gap is greater than the gap length, such a condition is defined as flashover. When the applied voltage decreases in the middle of leader development and average electrical field at the unbridged part of the leader [V/(D-2x)] is below 0.45MV/m, such a condition is regarded as no occurrence of flashover and calculation becomes over. Parameters of a model for the leader development method in the case of positive polarity is $K_1=1\times10^{-7}$, $K_2=2.5\times10^{-3}$, A=0.5, B=0.42. These values are applied to a gap of several meters long. Since the gap length dealt with in this paper is short being less than one meter, it is somewhat difficult to apply the parameters of Table 1 to this case.

Therefore, an analytical circuit shown in Fig. 1 has been adopted. This is a series circuit of a back impedance (R_b = 200 Ω) and an impulse voltage source (1/50 μs ramp wave). In this circuit, V-t characteristics have been calculated by changing parameters of Expression (1) in the positive polarity, assuming that the gap length is 650mm. The calculated V-t characteristics have been compared with those of a rod-to-rod gap in positive polarity. Fig.2 shows a result when K_2 was changed. This figure suggests that the best result is obtainable when K_2 is set at 3.5 times.

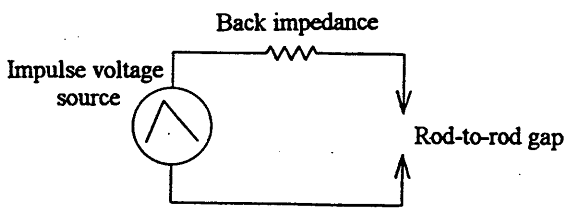

Fig.1 Calculation circuit

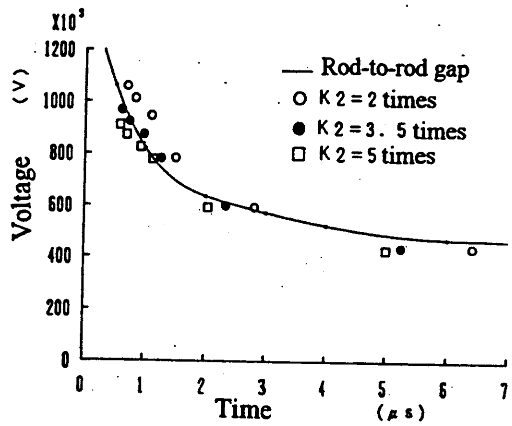

Fig.2 V-t characteristic calculated by the leader development method

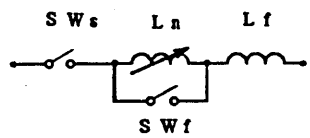

Fig. 3 Nonlinear inductance model

2.2 Nonlinear Inductance Model

Fig. 3 shows an equivalent circuit of nonlinear inductance model. SWs is a switch to express start of leader development, Ln is equivalent nonlinear inductance of arcing horn, SWf is a switch to express flashover, and Lf is equivalent inductance (1 μH/m) of steady-state arcs.

Since the leader development method assumes that the leader development start time is a function of applied voltage, as shown in Expression (3), the crest value of voltage must be known in advance. To obtain a result through only one analysis, it is necessary to express the leader development start time in a different form since the voltage crest value is unknown. In this paper, in the same manner as described in Literature (6), it is approximately assumed that leader development begins to occur when the critical flashover voltage of an arcing horn is attained. It is also assumed that the critical flashover voltage for a short gap length is given by the following expression:

$$Vc = 0.55 \cdot D + 80 \quad \text{(kV)} \qquad (4)$$

where D = gap length (mm)

The flashover voltage obtained from this expression roughly coincides with the critical flashover voltage of the V-t characteristics in the rod-to-rod gap (Fig.2).

To use equivalent inductance Ln of an arcing horn as a circuit element of EMTP, an equivalent impedance is obtained from the arcing horn voltage and predischarge current-time characteristics resulting from the leader development method and the resultant value is used as the current-flux (I- ϕ) characteristics. Switch SWf used to express flashover is closed when the horn gap voltage is rapidly lowered. in this case, this switch is assumed to be closed when the horn gap current exceeds 1000A.

Under the conditions that the gap length is 650mm, source voltage is 1MV, and the back impedance is 200ohm, discharge voltage characteristics of a nonlinear inductance model have been analyzed, by using the I- ϕ characteristics obtained by the leader development method and changing the source voltage in the calculation circuit of Fig.1. Fig.4 shows V-t characteristics of a rod-to-rod gap and the calculation result.

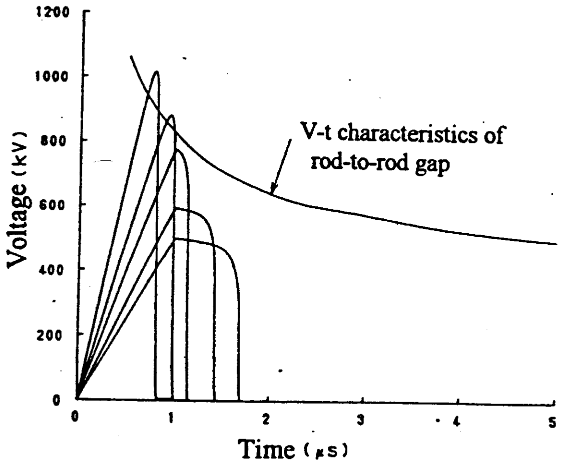

Fig.4 V-t characteristics of nonlinear inductance model

According to this figure, it is known that discharge characteristics at the wave front approximately coincide with V-t characteristics in the rod-to-rod gap. At the wave tail, however, flashover occurs earlier in the case of calculation result. This is because the source voltage varies flat at the wave tail while nonlinear inductance decreases excessively, and this difference is considered to result in a sudden rise in current.

2.3 Flashover Model for Short-gap Arcing Horn

As stated previously, simulation of an arcing horn having a short gap length with a nonlinear inductance model involves a problem such that the V-t characteristics of an arcing horn cannot be expressed only by its I- ϕ characteristics and hence the V-t characteristics are excessively lowered at the wave tail. Consequently, a model as shown in Fig. 5 is proposed. In this model, the horn gap voltage is shared by a nonlinear inductance and a nonlinear resistance. Rn is a nonlinear resistance used to express the voltage level at which leader development start and stop, and it holds the voltage of Expression (4) irrespective of the current. SW1 is a switch that is closed when the predischarge current begins to increase suddenly. This switch is set so that it is closed when the horn gap current exceeds 200A. SW2 is used to simulate flashover in the same manner as for the nonlinear inductance model. Equivalent inductance can be obtained by subtracting the characteristic component of nonlinear resistance from the characteristics of the nonlinear inductance model. Fig.6 shows the calculation result under the same conditions of Fig. 4. As shown in this figure, the flashover characteristics at the wave tail have been improved, and they approximately coincide with the characteristics of the rod-to-rod gap. This can be explained as follows; When flashover occurs at the wave tail, applied voltage is lower than the case when flashover occurs at the wave front, and this voltage lowers with time. Therefore, the voltage sharing rate of Rn becomes large and nonlinear inductance Ln in Fig. 5 cannot decrease rapidly at the wave tail.

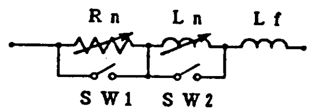

Fig.5 Flashover model for short-gap arcing horn

In the next process, characteristics of this model have been investigated under actual system conditions where back impedance and voltage waveforms are not kept constant. Comparison has been made with the leader development method under the conditions that the

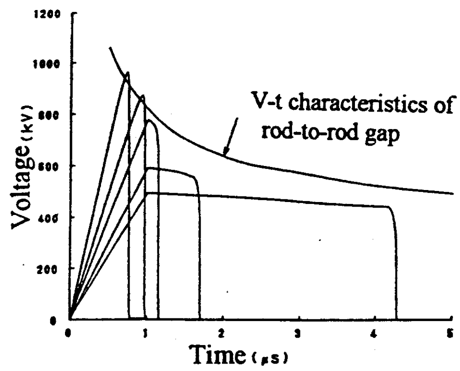

Fig. 6 V-t characteristics of a short-gap arcing horn

gap length is 350mm, the duration of wave front is 1, 2, or 3μs, and back impedance is 100, 200, or 400ohm. The calculation result with the proposed model approximately coincides with that of the leader development method even when the steepness of wave front is changed. Even when back impedance is changed, there is good coincidence with the leader development method in the mode of wave-front flashover. Regarding flashovers at the wave tail, approximate coincidence is observed for flashover voltages. Regarding flashover time, however, it seems to have been slightly earlier in the case of the proposed model. Since characteristic deviation due to difference in back impedance is minimal at both wave front and wave tail, the proposed model can be practically useful even though back impedance is changed, if dispersion of arcing horn flashovers is taken into account.

3. Flashover Model for Transmission Line Arrester

It is possible to simulate flashovers of transmission line arresters by combining a short-gap arcing horn model in 2.3 with nonlinear resistance that expresses the voltage-current characteristics of an arrester, as shown in Fig. 7.

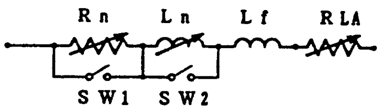

Fig. 7 Flashover Model for Transmission Line Arrester

To examine the V-t characteristics of this model, analysis was carried out for a combination of the arcing horn model in section 2.3 and an arrester's nonlinear resistance under the conditions that the serial gap length of the transmission line arrester is 350mm, the back impedance is 200ohm, and the arrester's characteristics are those shown in Fig.8. Fig.9 shows the result of comparison of characteristics actually measured on transmission line arresters. The result of calculation Case1 almost coincides with that of actual measurements, but there is no flashover if the source voltage is 450kV or below. This is because the leader extinction voltage is raised by the amount of voltage shouldered by in the model shown in Fig.7, since the leader development start voltage and extinction voltage are determined by the sum of a constant voltage retained by Rn and voltage at which of the arrester begins to generate a current flow.

Then, comparison was made with the result of actually measured characteristics under the conditions that the sparkover voltage component of the arrester is reduced from Rn to lower the leader extinction voltage, and that a component of the characteristics of the reduced is subtracted from the characteristics of the nonlinear inductance model. Fig.9 (Case 2) shows the result. Under these conditions, the characteristics look somewhat lower than the actually measured values at the wave tail part, but there seems to be a good coincidence with actual measurements to the area of wave tail discharges.

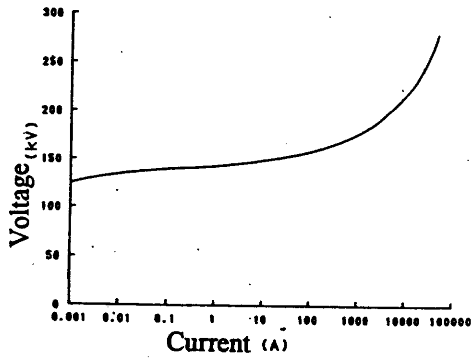

Fig.8 Residual voltage characteristic of a transmission line arrester

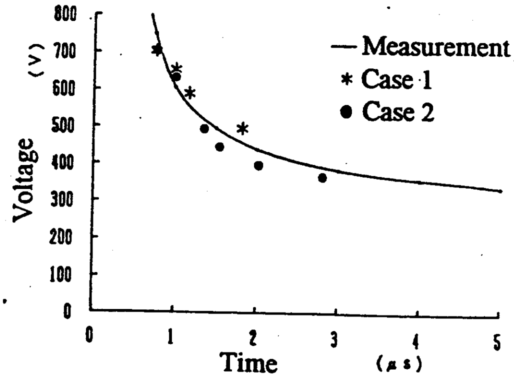

Fig.9 Comparison of V-t characteristics of a transmission line arrester

Namely, using a flashover model for a transmission line arrester as shown in. Fig.7, the characteristics can be accurately expressed, if the value is defined to make the leader development start voltage given by Expression (4) equal to the sum of a constant voltage retained by and an arresters sparkover voltage, and if the characteristics component of is subtracted from the characteristics of the nonlinear inductance model.

4. Comparison Between Actual Measurements and Calculation Result

This chapter deals with comparison of actual measurements and calculation result. For this purpose, voltages and currents in the horn gap were measured, and compared with the calculation result obtained by the leader development method and by the proposed model. Fig.10 shows a test circuit for standard lightning impulse voltages. Both arcing horn and transmission line arrester had a gap length of 350mm. The characteristics used for the arrester are those shown in Fig.11. The back impedance used for analysis is a series resistance of 390mm in the test circuit and the testing lightning voltage waveform is a lightning impulse voltage waveform obtained at no load (not connected to any specimen).

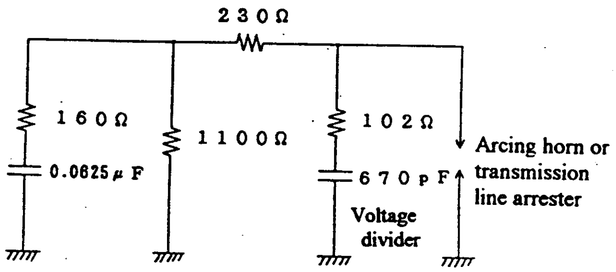

Fig.10 Test circuit for lightning impulse

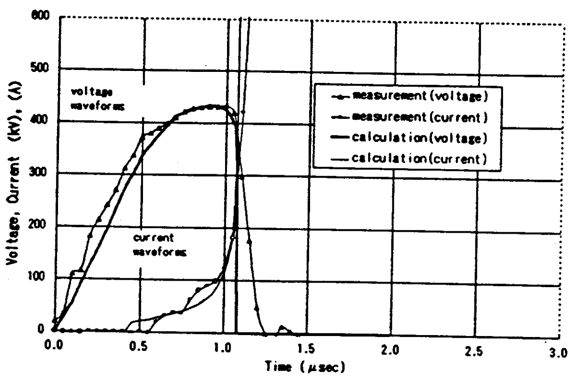

Fig.11 Measured and calculated results for an arcing horn

Fig.11 shows the result of measurements on arcing horn voltages and currents, and also the result of calculation by the proposed model. This figure clearly indicates that the calculation result by the proposed model well coincides with actual measurements.

Fig.12 shows a result of comparison between actual measurements on transmission line arresters and calculation by the proposed transmission line arrester's model. The proposed model provides a good coincidence with actually measured voltages and currents (waveforms.)

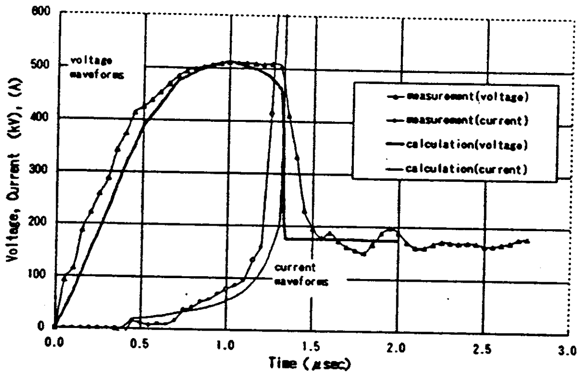

Fig.12 Measured and calculated results for a transmission line arrester

As described above, it has been verified that the model proposed in this paper provides a result that is close to the result of actual measurements, and it is a very useful method for simulation. The leader development method, which is the basis of the proposed models, has been also proven to be applicable to considerably short gap lengths if their parameters are adequately selected.

5. Conclusions

In this paper, examinations have been made on flashover models of arcing horns with short gap lengths and transmission line arresters with a series gap. According to the result of these examinations, a new flashover model has been proposed.

The arcing horn model with a short gap length is an improved version of a nonlinear inductance model already proposed. It has a feature of enabling accurate simulation of a wide range of characteristics, inclusive of predischarge current and wave-tail flashover. Therefore, if this model is used, it is considered possible to accurately analyze multiple flashovers by lightning surges in circuit that contains arcing horns having a short gap length, irrespective of voltage waveforms and circuit conditions.

The flashover model of a transmission line arrester is a combination of a nonlinear resistance element that expresses an arrester, and the above-mentioned arcing-horn model. It features that the V-t characteristics of a transmission line arrester with a series gap can be accurately simulated. This model is expected to enable accurate analysis of multiple flashover phenomena in circuits including transmission line arresters, together with the effectiveness of arrester applications.

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