THE COMPUTER ANALYSIS OF BREAKING CURRENT PROCESS IN SAND FILLER FUSES

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ABSTRACT

This paper describes breaking current process in sand filler fuses under the short circuit conditions, and analyses the basic characteristic of anode, cathode and arc column during arcing process. A mathematical model that describes the arc phenomena is set up. The results using this model to calculate the arcing process agree with the experiment results well.

1 Introduction

The arc model in sand filler fuses is one of the main subject in fuse research area, a great progress has been made, especially the variations of arc cross-sectional area during the arcing process have been taken account into the model, the calculation results of model become more accurate. However, there are some problems in all of the existing models, all kinds of models are expressed in different mode, angles and respects considered in the models are disparate, so it must be proved that which kind of the model should be used exactly in a specific situation and which one be universal. Meanwhile, a great deal of work need to be done to get some experiment formulae or constants in the models. In order to gain a universal arc model, this paper analyses the breaking current process in sand filler fuses, sets up a mathematical model based on the physics characteristic. The experiment formulae or constants are used in the model as rarely as possible.

2 The mathematical model of arc

When the arc emerge, the voltage across the fuse increases rapidly, so arcing phenomena can be described by the variation of arc current and arc voltage with time.

Generally, the arc can be split into three regions: anode, cathode and arc column, these are considered separately in the following subsections.

2.1 The cathode fall region

A great part of electrons resulting in arc discharge generates in cathode fall region or emits from cathode. This region is about 10^{-3} millimetre long, but there is a regular voltage across it, for low boiling-point cathode, the cathode drop is supposed to be 10V in this paper.[1]

2.2 The anode fall region

This region is also about 10^{-3} millimetre long as with the cathode fall region. However, the process taking place in this region is quite different from that in the cathode fall region. Above 99 percent of electrons and ions generates in the cathode fall region, while below one present of ions is engendered in the anode fall region.[2] The main function of the anode fall region is to change directional motion energy of ions in this region into thermal energy in arc column.

The anode drop could be any value between zero and the ionization potential of anode element material. It is assumed that the anode drop equal to the ionization potential, because field ionization is the probable mechanism for ion production in case of fuse arcs.

2.3 Analysis of arc column plasma

As mentioned earlier, the cathode fall region and anode fall region in an arc are about 10^{-3} mm long, therefore the arc column may be taken to occupy the whole gap length between the electrodes. To derive the mathematical model of arc simply, it is presumed that arc column be cylinder and all of the parameters in arc column be homogeneous. In case of this presumption, it will be considered that the length, cross-sectional area, and conductivity of the arc column vary with time during arcing process so as to determine the resistance of arc column, then the arcing phenomena could be described by mathematical easily.

2.3.1 Electron density of arc column plasma

Arc plasma consists of ions, electrons and neutral particles, when the electrical field is exerted, the discharge particle in plasma will move directionally, therefor current flow in plasma. The current density could be expressed:

$$J = n_i q u_i - n_e q u_e \quad (1)$$

where u, n are diffuse velocity and density respectively.

According to condition of quasi-neutral in plasma, $n_e = n_i$, then

$$J = n_e q (u_i - u_e) \quad (2)$$

because the discharge particle is accelerated by electrical field, therefore

$$u_i = b_i E \quad (3)$$

$$u_e = b_e E \quad (4)$$

Here, b_i and b_e are removal rate of ions and electrons respectively, since electron mass is much lighter than ion mass, b_e is much bigger than b_i, so

$$J = n_e q b_e (-E) \quad (5)$$

according to Ohm's law, $J = \sigma E$, then

$$n_e = \frac{\sigma}{q b_e} \quad (6)$$

On the basis of gas dynamics theory, electron removal rate can be determined as following:[3]

$$b_e = \frac{q \lambda_e}{m_e V_T} \quad (7)$$

where λ_e is free path of electrons, and V_T is thermal motion velocity of electrons, it is given by the formula

$$V_T = \sqrt{\frac{8KT}{\pi m_e}} \quad (8)$$

Whereas free path of electrons could be expressed[4]

$$\lambda_e = \frac{KT}{\pi R^2 P} \quad (9)$$

where R is radius of gas molecule, P is pressure of arc plasma, T is temperature, K is Botzmann's constant.

therefore electron density is given by the expression

$$n_e = \frac{\sqrt{8\pi m_e} R^2 P \sigma}{q^2 \sqrt{KT}} \quad (10)$$

2.3.2 conductivity of arc column plasma

In arc column plasma, electron mass is much lighter than ion mass, therefore velocity of electron which is acquired by effect of electrical field is much higher than that of ion, It is considered that current be mainly delivered by electrons, if ionizability in fuse arc plasma is more than 0.01 percent, conductivity of arc column plasma could be expressed by Spitzer's formula.[5]

$$\sigma = \frac{1.55 \times 10^{-2} T^{3/2}}{\ln(1.242 \times 10^7 T^{3/2} / n_e^{0.5})} \quad (11)$$

2.3.3 Length of arc column

Element material corrodes continuously due to the effect of anode and cathode during the arcing process, so the length between electrodes enlarge unceasingly, the rate of its enlargement equals to total burnback rate of anode and cathode.

Burnback rate of electrode material is relate to energy balance in anode and cathode fall region. A.Wright considered this energy balance and obtained that the total energy supplied to anode fall region in each unit time was given by the expression[6] .

$$\text{power} = (V_{af} + V_{wf} + V_T) i$$

where V_{af} is anode fall voltage, V_{wf} is voltage associated with the work function of the element material, V_T is voltage associated with the thermal energy of the electrons which enter the anode, i is arc current.

Meanwhile, he found that corroding degree in two electrode fall region is identical from a large number of X-ray photographs of breaking current tests. Therefore, it could be assumed that energy supplied to cathode be the same as that supplied to anode, the burnback rate of anode equals to that of cathode as a consequence.

A very small part of energy supplied to anode is consumed by radiation and heat conduction. The energy is mainly used up by electrode to rise temperature of electrode and evaporated. A.Wright found that about 20 percent of the total energy is used to complete the process of latent heat of fusion. So the enlargement rate of length of arc plasma could be written as

$$\frac{dl}{dt} = \frac{0.4(V_{af} + V_{wf} + V_T) i}{A_e \rho_e L_f} \quad (12)$$

Here, A_e is cross-sectional area of electrode, ρ_e is mass density of electrode material, L_f is latent heat of element material.

2.3.4 Cross-sectional area of arc column

When an arc column is established in a fuse, it receives power from the electrical system, this energy E could be expressed as

$$E = uidt \quad (13)$$

where u is voltage drop along the arc column.

During the earlier part of the arcing period, some of the input power is retained within the arc column and makes dimension and temperature of the arc column increase. However, in the later part of the arcing period, the changes in energy present in a column during the short period may be very small compared with the total energy input, so it could be considered that power given to column be dissipated by the surrounding filler which will consequently melt progressively, the mass m of sand filler which will melt in the time interval dt may be

$$m = \frac{uidt}{\rho_s(C_s\Delta T_s+L_s)} \tag{14}$$

Here ρ_s is the packed density of sand, C_s and L_s are specific heat and fusion latent heat of sand respectively.

Because fuselinks are vibrated after sand is put into them, it is assumed that the volume filling rate of sand should be γ . After sand melts, its volume will increase, the expansion rate of sand on liquefaction is supposed to be β, therefore the volume of liquid sand is $(1+\beta)\gamma$ times of the originally occupied by sand-air mixture. In addition, a column expands into the space previously occupied by the melted electrode. Then, the total variation in volume can be expressed

$$\frac{dV}{dt} = \frac{[1-(1+\beta)\gamma]ui}{\rho_s(C_s\Delta T_s+L_s)} + A_e\frac{dl}{dt} \tag{15}$$

According to the presumption in the earlier, arc column is cylinder, so the cross-sectional area could be given in the following

$$A_a = V / l \tag{16}$$

2.3.5 Energy balance of arc column plasma

When arc column is established, material evaporated from the electrodes often enters it in the form of jets, a number of atoms of this material are accelerated into a column and a fraction x of them become ionised in any short time interval, meanwhile, almost the same number of atoms and ions would be scattered out of the column. To set up model simply, the following equations are assumed to apply any time interval.

$$N_{ai} = N_a \tag{17}$$

and $$N_e = xN_a \tag{18}$$

where N_{ai} is the number of atoms and ions which are scattered from arc column, N_e is the number of electrons which are scattered from arc column, and N_a is the number of atoms which evaporate from the electrodes.

The total mass melted from the electrodes during the time interval dt is given by A.Wright

$$\text{total mass} = 0.4(V_{af} + V_{wf} + V_T)idt/L_f$$

He also found that about 40 percent of this mass will evaporate, if the number N_g of atoms per each mass of electrode material is known, the total number of atoms which enter into arc column in time interval dt could be written as

$$Na = 0.08N_g(V_{af}+V_{wf}+V_T)idt/L_f \tag{19}$$

The energy in arc column is dissipated by the main ways of kinetic energy, compound and radiation.

Kinetic energy could be given in the following

$$\text{kinetic energy} = 1.5\ (N_{ai} + N_e)\ KT$$

and compound energy is

$$\text{compound energy} = N_eE_J$$

where E_J is ionization energy of each atom.

For heat radiation, it could be considered as blackbody radiation because the temperature and pressure of arc column is very high. The surface area S of arc column may be calculated

$$S=(\pi dl)= (4A_a/\pi)^{0.5}l=2l(\pi A_a)^{0.5}$$

therefore heat radiation energy can be expressed as

$$\text{heat radiation energy} = 2l(\pi A_a)^{0.5}K_sT^4dt$$

where K_s is the Stefan-Botzmann constant.

According to the law of conservation of energy, the following equation is gained

$$(m_ac_a\partial T/\partial t)dt=uidt-N_a[1.5KT(1+x)+xE_J]-2lK_sT^4(\pi A_a)^{0.5}dt \tag{20}$$

Here m_a and c_a are mass and specific heat of arc plasma.

At any time the temperatures of ions and electrons in a column will be the same because the mean free path is very short and they must experience many collisions before leaving the column. in this circumstance the following equation is applicable

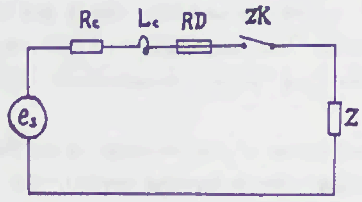
$$\frac{x^2}{1-x^2} = \frac{(2\pi m_e)^{3/2}}{h^3}(KT)^{5/2}\exp(-\frac{E_J}{KT}) \tag{21}$$

where P is pressure of arc plasma, m_e is mass of electron, and h is Planck constant.
and the pressure of arc column plasma can be expressed as

$$P = \frac{1+x}{x}n_eKT \tag{22}$$

2.3.6 Integrated mathematical model of fuse arc

The model of fuse arc are usually described by the equivalent circuit shown in Fig. 1.



Z=0 if short circuit occur

Fig. 1 equivalent circuit

It is often possible to regard a source as having resistance and inductance in series, in this circumstances, the nonlinear equation during the arcing period could be shown as follow

$$e_s = i(R_a n+R_c)+d(L_c i)/dt+n(V_{af}+V_{cf}) \quad (23)$$

Here e_s, R_c, L_c are electro-motive force of source, equivalent resistance and inductance of power system, R_a is resistance of each arc column, V_{cf} is voltage drop of cathode fall region and n is the number of arcs or notches in element.

According to Ohm's law, it could be gained

$$A_a = u / i \quad (24)$$

the resistance of the arc column can also be expressed as

$$R_a = \frac{l}{\sigma A_a} \quad (25)$$

Equations (10), (11), (12), (15), (16), (19), (20), (21), (22), (23), (24), (25) are independent and include twelve unknowns n_e, P, σ, T, l, A_a, V, N_a, u, i, R_a and x, if initial conditions are given, these unknowns can be solved.

3 Calculation of mathematical model of fuse arc

The twelve equations which describe the arc characteristic could be simplified by using difference method, therefore twelve parameters at time t+dt would be calculated easily if these parameters at time t are known.

If the arc length l is more than or equal to the length between two notches of fuse during the calculation, the arcs will join together and become a single long arc, therefore equation (23) should be changed into

$$e_s = i(R_a'+R_c)+d(L_c i)/dt+(V_{af}+V_{cf}) \quad (26)$$

where R_a' is the resistance of a single long arc

If this single long arc burnback continuously until the length of it is up to the element length, the calculation should cease, in this circumstance, it is regarded that the breaking current be failure.

3.1 Determination of the initial value

Because the temperature is very low at the beginning of the arcing period , the value of the parameters l, V, Aa, x are very small and they are taken to be zero, the temperature T are considered to be the boiling point temperature of element material.

The initial value of arc voltage is difficult to determine. During the prearcing period, the voltage across the notches of fuse is very small, and it changes suddenly at the beginning of the arcing period. The value of this sudden change depends on the dimension of the notches. Long notches have slightly higher initial voltage than short notches. In this paper, the initial voltage is assumed to be 33 V.

The initial value of arc current can be determined by calculating prearcing period.[7]

3.2 Calculation of arcing period

According to the earlier analysis, the solving the twelve equations by the ways of step by step. The arc voltage U_f across the ends of the fuses can be calculated

$$U_f = n(V_{af}+V_{cf}+iR_a) \quad (27)$$

If the arcs join together and become a single long arc, the arc voltage will be expressed as

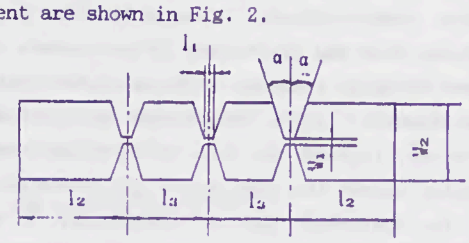
$$U_f = V_{af} + V_{cf} +iR_a' \quad (28)$$

The above arc model are set up on the basis of this presumption which there is only one element in the fuses, if several elements exist in the fuses, the items which are related to current will be changed correspondingly.

4 Results

To verify the accuracy of arc model, the fuses in which only one element exist is used to do many practical tests and theory calculations, the results obtained are compared with each other, and they agree well.

The constructions and dimension of the fuse element are shown in Fig. 2.



$l_1=1$ $l_2=21$ $l_3=15$ $w_1=0.7$ $w_2=15$ $\alpha=22.5$

Fig. 2 element structure of a fuse

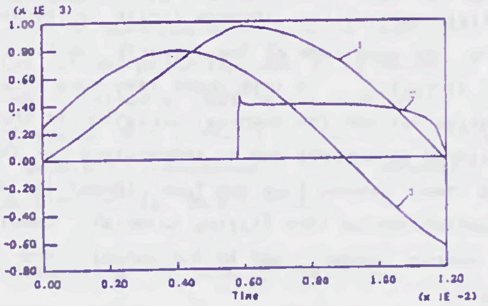
one of the results of tests and calculations are listed in table 1 and Fig. 3.

Table 1 breaking current results under the conditions of U=560V, I=510A, coso=0.28

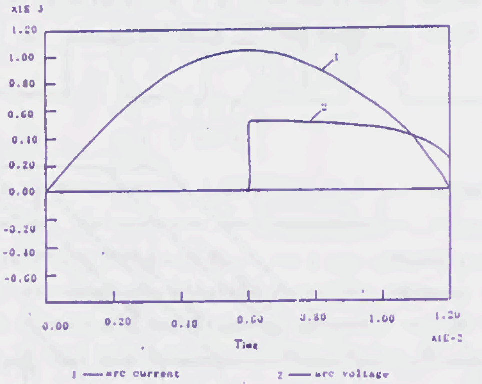
	calculation results	test results
current peak	972.0 (A)	1072 (A)
over voltage	468.6 (V)	531 (V)
arcing time	6.134 (ms)	6 (ms)

5 Conclusions

The mathematical model of fuse arc which is derived in this paper could describe breaking current process of fuses. By using this model to study the influences of many kinds of parameters on breaking current process, the work of fuse research become easy, it will advance quickly and economically as well because it is not necessary to do a lot of tests in the study.



(a) calculation results



(b) test results

Fig. 3 oscillogram of breaking current

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