RESEARCH ON POWER-FUSE CO-ORDINATED WITH VACUUM CONTACTOR

Wang Jimei

INTRODUCTION

In recent years so many industrical departments in China commenced to adopt the vacuum contactor as main switch in high voltage arc furnace, controlling and starting switch in high voltage motor and high voltage switch for frequently operated equipments. It has the features of small volume, light weight and fitness to frequent operation. However, the vacuum contactors in China are still in lack of back-up fuse co-ordinated with them. In this case, once the heavy overload or short-circuit fault occurs, not only the vacuum contactor itself will damaged, but also the interruption of power supply will happen. For this reason, the vacuum contactor co-ordinated with power-fuse to undertake heavy overload and protect from short-circuit fault is necessary.

The performance of high voltage H.R.C. fuse has much improved, such as the raise of rated current, enhancement of interrupting capacity and use of high stress glass-fibre cartridge.

DESIGN OF FUSE CONSTRUCTION

The fuse should be so designed that it possesses high ability to withstand multi-time low overload impulse current many times, e.g., it can withstand the heating cycle more frequently than that of ordinary distribution power fuse. Hence, if a fuse of general construction is used, the fuse element around the sand may have a displacement due to heat expansion and cold shrinkage, so it causes the fuse element itself undertaking more stress. Thus, there is a possibility to crack the fuse element. For this purpose, we selected the fuse element with larger section ares and adopted self-support construction without support-structure in designing fuse conctruction. But, there is expansion ribbon in both ends and middle part of the fuse element.

To meet the requiments of back-up fuse performance (e.g., delaying the operating time of current-time characteristics of fuse-element under multi-time low overload and fasting operation under short-circuit fault), the geometric form of element was specially designed, which is different from ordinary distribution power fuse.

Professor Wang Jimei is a Head of Electrical Apparatus Section at Xi'an Jiaotong University, a consultant of Xi'an Fusegear Factory, a member of State Council Academic Degree Committee, a member of National Science Committee of China and a councilor of Chinese Society of Electrical Engeering in China.

To satisfy the ability of interrupting capacity under large rated current, a cartridge made of glass-fibre cemented with inorganic glue was used. The wall of cartridge is thinner and lighter than that of porcelain one, so it eliminates any dangerousness of crack of cartridge.

In order to proceed our research work smoothly, we performed beforehand a series of theoretical calculation for the main performance of fuse as follows:

(1) Calculation for steady-state temperature-rise

The average value of steady-state temperature rise of fuse element was estimated with the formula recommended by K. K. Namintokoff et al.[1].

$$T=(k^2+T_0)/(1-k^2B)=((I^2R/aS)+T_0)/(1-(I^2R/aS)B) \qquad (1)$$

where

I——current passing through fuse element, A;
R——resistance of fuse element, ohm;
a——coefficient of heat dissipation, $w/cm^2\cdot{}^\circ C$;
S——dissipated area of fuse element, cm^2;
T_0——ambient temperature, °C;
B——resistance-temperature coefficient of fuse element, $^\circ C^{-1}$.

when $I=300$ A, $R=0.00095$ ohm, $a=25\times10^{-4}$ $w/cm^2\cdot{}^\circ C$, $S=350$ cm^2, $T=20\,^\circ C$ and $B=4\times10^{-3}\,^\circ C^{-1}$, we have

$$T=(300^2\times0.00095/25\times10^{-4}\times350+20)/$$
$$/(1-(300^2\times0.00095/25\times10^{-4}\times350)(4\times10^{-3}))$$
$$=(98+20)/(1-0.392)=165\ ^\circ C.$$

The average temperature rise of cartridge surface can be calculated through the following formula:

$$T_1=I^2R/a_1S_1 \qquad (2)$$

where a_1——coefficient of heat dissipation on fuse cartridge surface, $w/cm^2\cdot{}^\circ C$;
S_1——surface area of fuse cartridge, cm^2.

when $a_1=10\times10^{-4}$ $w/cm^2\cdot{}^\circ C$, $S_1=1470$ cm^2, then

$$T_1=300^2\times0.00095/10^{-3}\times1470=58\ ^\circ C.$$

(2) Estimation of rated interrupting capacity

In accordance with IEC Standard, after testing the rated interrupting capacity, the interrupting ability of H.R.C. fuse under maximum arc energy should be also examined. The value of this tested current should be selected in satisfying the following formula, when $\phi_i=0\sim20^\circ$,

$$I_{fusing} = (0.6\sim0.75)I_m \qquad (3)$$

where I_m——the peak value of prospective current to be determined.

For obtaining this peak value, it is necessary to use a certain quantity of sample fuse for test. Before the test, a calculation of maximum arc energy was made on the newly designed fuse. It showed that the result of calculation was close to that of maximum arc energy test. The calculation is recommended as follows.

When the fuse is inserted in a source supply, the general expression is

$$U_m \sin(wt+\phi_i)=L\frac{di}{dt}+(R+R_o(1+BT))i \qquad (4)$$

where L——circuit inductance, henry;
R——circuit resistance, ohm;
B——resistance temperature coefficient of fuse element, $°C^{-1}$;
T——temperature rise of fuse element, °C;
ϕ_i——phase angle at closing instant, electrical degree.
If the resistance of fuse element is negligible, the equation (4) can be written as follows

$$U_m \sin(wt+\phi_i)=L\frac{di}{dt}+Ri \qquad (5)$$

Solving equation (5), we get

$$i=I_m(e^{-t/\tau}\sin wt_o+\sin(wt-wt_o)) \qquad (6)$$

where $\tau=L/R$, $wt_o=\phi-\phi_i$, $\cos^2\phi=1/(1+w^2\tau^2)$ and $I_m=U_m\cos\phi/R$. From equation (6), the square of current density integrates to time, then we have,

$$\int\left(\frac{i}{s}\right)^2dt=\int_0^{t_{fusing}}\delta^2dt=$$

$$=\int_0^{t_{fusing}}\left(\frac{I_m}{s}\right)^2(\exp(-t/\tau)\sin wt_o+\sin(wt-wt_o))^2dt \qquad (7)$$

In according to equation (7), if ϕ_i and ϕ are given and the material of fuse element be known, (for instance, silver as fuse element it is $C=\int_0^{t_{fusing}}\left(\frac{i}{s}\right)^2 dt=8\text{x}10^4\ A^2s^2/mm^4$)

a relationship between the density of prospective current and fusing time can be obtained. Then we take equation (6) to calculate the density of fusing current. Figure 1. shows the results of this calculation, when $\cos\phi=0.2$, $\phi_i=0°$ and 45° in which a series of given values of prospective current density are taken. Correspondently, with the similar procedures we got the curves by the calculation of fusing current density.

Meanwhile, the slop-curves of $\delta=f(\delta_m)$, $\delta=f(0.75\delta_m)$ and $\delta=f(0.6\delta_m)$ plotted by the prospective current density and its correspondent current density were taken. We may obtain the range of prospective current density of maximum arc energy from the slop curves $0.75\delta_m$ and $0.6\delta_m$ intersected at $\phi_i=0°$ and 45° curves respectively.
When $\phi_i=0°$, the range of maximum arc energy from Figure 1. is $1.15\text{x}10^4\ A/mm^2<\delta<1.5\text{x}10^4\ A/mm^2$, when $\phi_i=45°$, it is $1.2\text{x}10^4\ A/mm^2<\delta<1.6\text{x}10^4\ A/mm^2$. When the rated current are 150A and 300A, total cross-section areas of fuse-notch will be

$$S_{150}=3\text{x}0.2\text{x}0.4\text{x}5=1.2\ mm^2 \text{ and } S_{300}=6\text{x}0.2\text{x}0.4\text{x}5=2.4\ mm^2$$

respectively.
Therefore, the possible ranges of prospective current of Max. arc energy are $I_{150}=(1.15\sim1.6)\text{x}10\text{x}1.2=13.8\sim19.2$ Ka and $I_{300}=(1.15\sim1.6)\text{x}10\text{x}2.4=27.6\sim38.4$ Ka respectively.

(3) Calculation of cut-off characteristics
For estimation of the cut-off current values at different condition of short-circuit current, we used the formula reported in reference [2] for calculation. There are two cases for calculation i.g. symmetrical short-circuit and unsymmtrical short-circuit currents.
One of the calculated results is shown in table I. for prospective short-circuit current values 20Ka, 24Ka, 30Ka, 36Ka, 40Ka and 48Ka.

(4) Starting characteristics
For selection of reasonable rated current fuse to co-ordinated a motor under different starting conditions, the selection charts were plotted between starting current, number of starts per hour, run up time and fuse current rating on the basis of the thermal characteristic of fuse.
One of them is shown in Figure 2.

TESTS AND ANALYSIS OF RESULT

In order to testify the performance of fuse in conformity with the design data required, the type test was carried out on fuse samples. IEC Standard was adapted as the conditions of type test criteria. The test items and specific contents of test are as follows.

(1) Temperature-rise test
The temperature-rise test is to check the temperature-rise of fuse under normal working condition. It should not exceed permissible value. As stipulated in IEC Standard, the maximum permissible temperature of the fuse knife-terminal should not exceed 65 °C.
For testing, we set up 6 pieces of sample fuse in vertical parallel position on the frame, to which the rated currents were flowed. These currents were supplied by low-voltage transformers. The temperature was measured with thermocouple at the knife-terminals of fuse. The section areas of connected bus-bar were 25x3 mm and 40x4 mm for 150A and 300A respectively. Ambient temperature was 15 °C under the test. The highest temperature rise of 300A sample fuses was 58 °C, while 150A sample fuses was 48 °C. There is much room for temperature rise of sample fuses.

(2) Interrupting capacity test
The interrupting capacity tests consist of rated interrupting current test, approaching to maximum arc energy interrupting current test and minimum interrupting current test.
These tests were performed in Xi'an High-voltage Apparatus Institute in China. The transient recovery voltage of sample fuse after interrupting was measured by cathode-ray oscillograph.

(a) Rated interrupting current test According to the design requirements, rated interrupting current was defined for 30Ka. The actual prospective current under test was 29.5Ka (r.m.s.), $\cos\phi < 0.15$, testing voltage was 6.3Kv, amplitude coefficent of recovery voltage $K_1 = 1.6$, inherent oscillating frequency f_o=3.48 KHz. After testing, the instant interrupting current measured was 31Ka (peak), operating time was 7 ms and overvoltage recorded by the mechanical scanning cathode-ray oscillograph was 1.2 times of rated voltage, one of recorded wave form is shown in Figure 3.

(b) Approaching to maximum arc energy interrupting current test This test was proceeded after the rated interrupting current test and through analysis of the magnitude of cut-off value from the waveform of rated interrupting current test to estimate the prospective current of maximum arc energy. As requested in the stipulation of IEC Standard, if the test of rated interrupting current is carried out at 150 times or more, the estimated prospective current I_2 of maximum arc energy should be calculated from the following equation

$$I_2=i_1\sqrt{i_1/I_1} \qquad (8)$$

where i_1——instant value of prearcing current of the prospective current I_2.

The prospective current I_2 under actual testing was 27.5Ka (r.m.s.), $\cos\phi<0.15$. Testing voltage 6.3~6.6 Kv, amplitude coefficient of recovery voltage and inherent oscillating frequency adjusted to K=1.3 and f_o=7.6KHz respectively. After testing, the instant value of interrupting current was 28.3Ka (peak) which was obtained from the recorded curve. Operating time was 6.2 ms, and no overvoltage appeared from the recorded curve. The results are shown in Figure 4.

From both the recorded curves of rated interrupting current test and maximum arc energy interrupting current test, we think the fuse interrupting test met with success. The body of fuse cartridge was dissected, then we examined the surface of fulgurite structure. All of the burned structure appeared quite homogeneous.

(c) Minimum interrupting multiple current test. For the back-up fuse, the minimum interrupting multiple current test must be performed in according to IEC Standard. The value required is 8 times of the rated current, e.g. 150x8=1200A and 300x8=2400A. This test was also successfully passed.

(3) Time-current charateristics test

Time-current characteristics are shown in Figure 5. These curves were plotted on the basis of actual tests.

CONCLUSION

In the power fuse co-ordinated with vacuum contactor, a self-support fuse body is adopted in construction. The cartridge which is made of temperature resistant and high strength glass-fibre cemented with inorganic can meet the ability of interrupting capacity under large rated current. The construction of this type will be the main trend in high voltage H.R.C. development.

Through the rated interrupting current test and the maximum arc energy interrupting current test of the power fuse, it showed that the theoretical analysis was in conformity with the actual results of the tests. After the examination of fulgurite surface of sample fuse, it appeared that the interrupting action was rather easy, and was much room for operation.

TABLE I Cut-of current peak value at symmetrical short-circuit current with rated current 150A

Prospective Short-circuit Current Value (Ka)	Fusing Time (ms)	Angle Refer to Fusing Time (degree)	Value of sine	Peak Value of Cut-off Current (Ka)
20	1.56	28.1	0.47	9.4
24	1.47	26.4	0.44	10.7
30	1.37	24.6	0.41	12.3
36	1.29	23.2	0.39	14.1
40	1.23	22.1	0.38	15.4
48	1.16	20.9	0.37	17.8

REFERENCES

(1) K.K. Namintoff et al. , "Fuse" , Power publishing house, USSR. , 1979.

(2) Wang Jimei , "Low-voltage Fuse" , Machine-building industrical publishing house , China. , 1979.

(3) E. Jack , "High Rupturing Capacity Fuses" , E. & F.N. SPON LTD , London , England. , 1975.

(4) J. Feenan , "Trend in the desugn of high-voltage high-rupturing-capacity fuses" , Proc.IEE , Vol.118 , No.1 , 1971.

(5) IEC Standard , 282-1 , 1974.

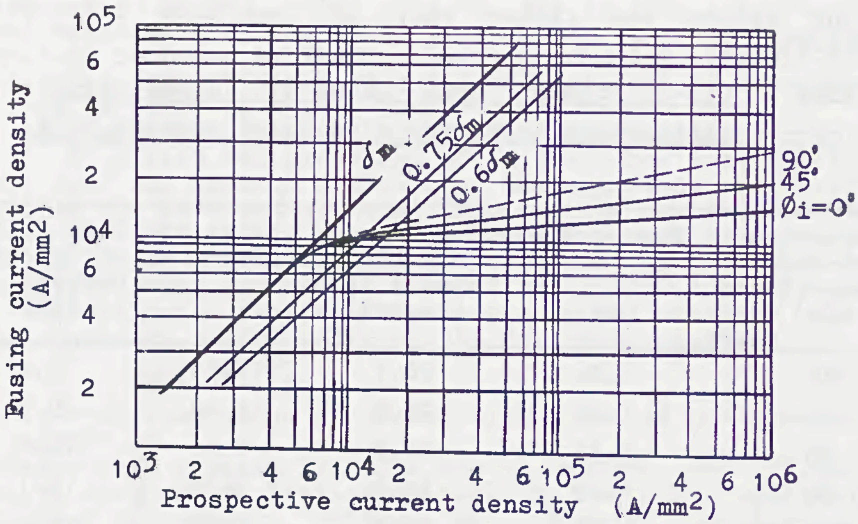

FIG.1. Curves for determination of current density under maximum arc energy.

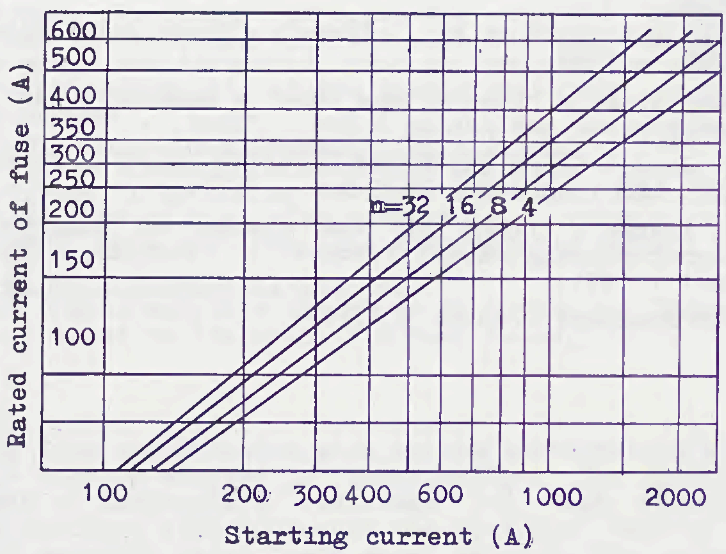

FIG. 2. Fuse selection chart for motor with run up times not exceeding 6 seconds.

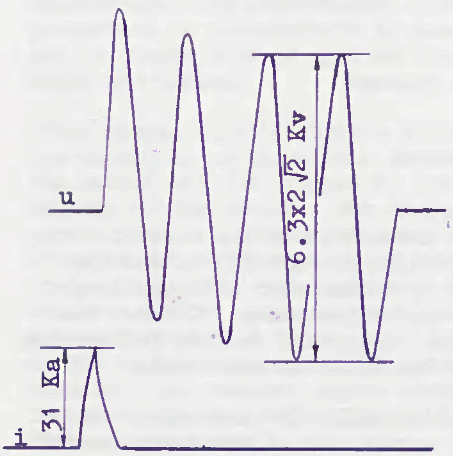

FIG.3. Wave forms from rated interrupting current test.

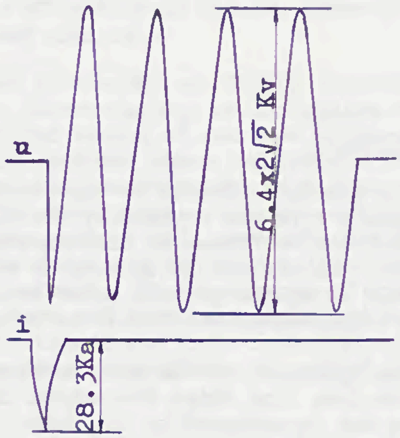

FIG. 4. Wave forms from interrupting current test under maximum arc energy.

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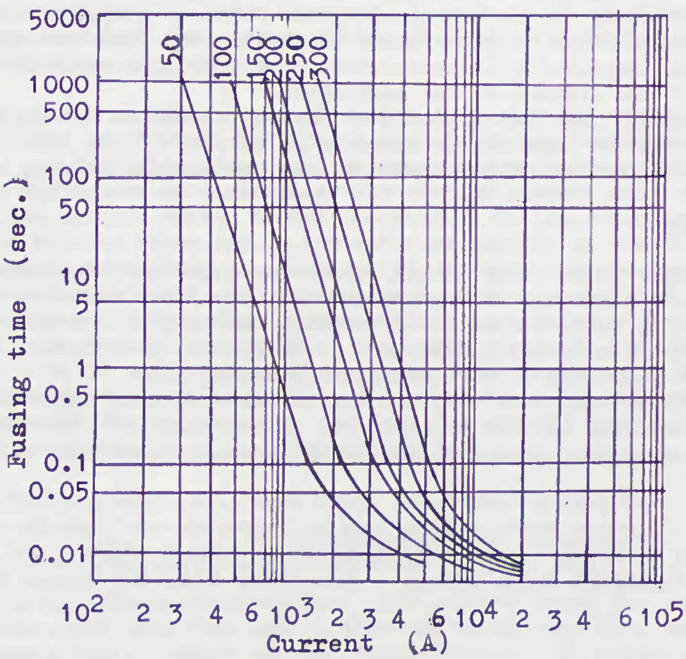

FIG.5. Time/current charactristics