INVESTIGATION FOR THE USE OF COPPER AS AN ELEMENT MATERIAL IN HV-HBC-FUSES

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ABSTRACTS

The starting point of our investigations has been the question wether one can substitute the silver by copper in high voltage fuses without changing the geometry of the fusible elements.

Some results will be presented about the prearcing and the arcing phase of copper wire fuses related to the silver wire fuse with the same geometry.

Furthermore, it is reported on investigations of the life time of copper fuses. The results of the experiments will be compared with numerical computations. By the investigations conclusions were derived for using copper in high voltage fuses.

1. INTRODUCTION

In low-voltage high breaking capacity fuses copper is often used as fuse element. In case of high-voltage high breaking capacity fuses, however, silver serves as the material for the fuse element.

For producing cheaper hv-hbc-fuses, the problem of replacing silver by copper had to be taken into our consideration. The investigations made regarded high voltage fuses with fuse element wires which were manufactured in the former German Democratic Republic. Caused by the conditions of the manufacturing process the geometry of the fuse element should always be the same, while the parameters of the switching process should not deteriorate.

The use of copper as the fuse element seems to be difficult because of the possible oxidation. Fuse elements made of copper can oxidate already at low rated operation temperatures (/1/, /2/). The oxidation decreases the conductive cross-section, and the current density increases. Thus, the temperature of the fuse element also increase, the oxidation being further accelerated. This might lead to the early break-up of the fuse link and could possibly destroy it.

For these reansons it was necessary not only to perform current breaking test duties of copper fuse-links and to check the t-I-characteristic, but also to investigate the behaviour of copper fuse-links in case of rated current operation.

2. TEST PARAMETERS

2.1. Physical properties of fuse-element metals

If silver is replaced by copper, the changed properties of the material have to be considered. For our calculations we used the values according to /3/.

In some cases, copper fuse elements with silver coatings are used for low-voltage fuse-links. Therefore, besides silver and copper fuse elements copper wires with silver coatings,were investigated, too. Wires with 10, 30, 150 and 260 gramms silver layer per 1,000 gramms basic material were used, respectively. For these cases, the following designations are introduced: Cu/Ag 10 etc.

2.2. Test samples

For the necessary investigations both test fuse-links and modified hv-hbc fuse-links were used. In fuse links type HWsF-B 3,6kV/10A the Ag-wires was replaced by Cu-wire or Cu-wire with Ag-coating of the same dimensions. The current breaking tests demanded according to IEC 282-1 were performed in the test plant "Institut Prüffeld für elektrische Hochleistungstechnik"(IPH) in Berlin.

The investigations of test fuse-links which were made in the test field of the Ilmenau Institute of Technology served as basic investigations of the behaviour of the various metals for fuse elements. Model 1 (Fig. 1a) is used for short- circuit current breaking tests, while model 2 (Fig. 1b) is used for investigating the fusing by overload, where the fuse element is so long that the axial heat conduction to the fuse end caps can be neglected similar to the conditions in a hv fuse-link.

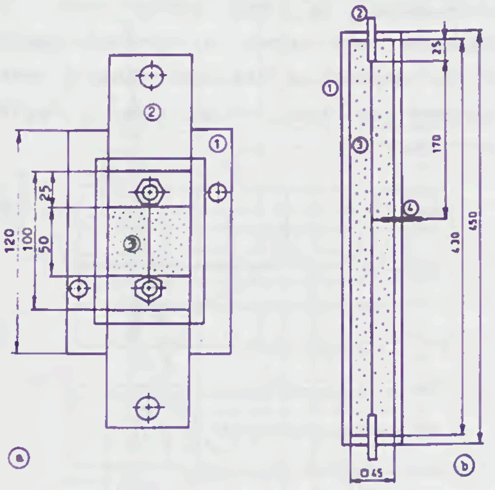

Fig.1: Test fuse-links: (a)-Model 1, (b)-Model 2
1=body, made from organic textolite, 2=terminal and fuse element connection, 3=fuse element, 4=thermoelement

3. INVESTIGATION OF THE SHORT-CIRCUIT CURRENT BREAKING

3.1. Investigation of test fuse-links

Both wires with uniform cross-section and wires with restrictions were investigated.

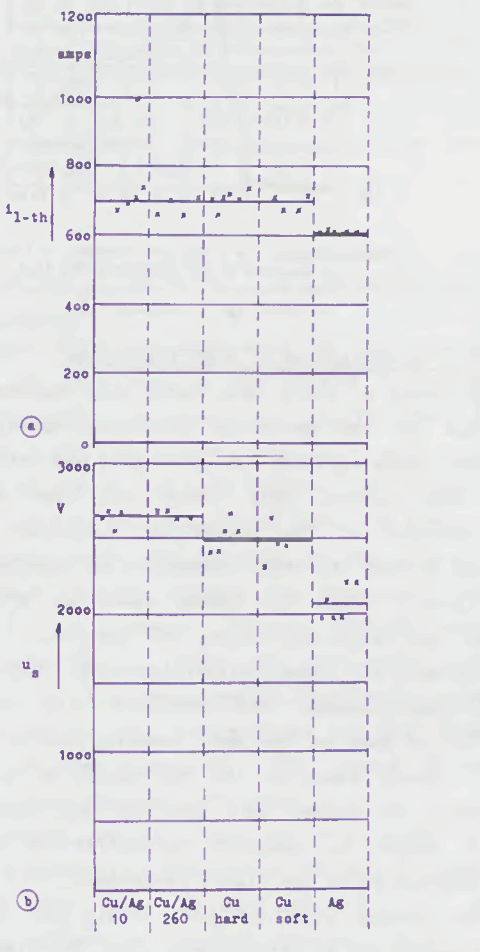

Fig.2: Let-through current (a) and switching voltage (b) of uniform fuse-element wires with model 1

The results gathered in the investigation of a wire with uniform cross section are illustrated in Fig. 2: Silver has the lowest let-through current and the lowest switching voltage. The let-through current of the various copper wires is approximately the same, while the switching voltage of Cu/Ag-wires is considerably higher than that of uncoated Cu-wires, which was not expected. The oscillograms in Fig. 3 show the differences in the peaks of the switching voltage of the respective materials.

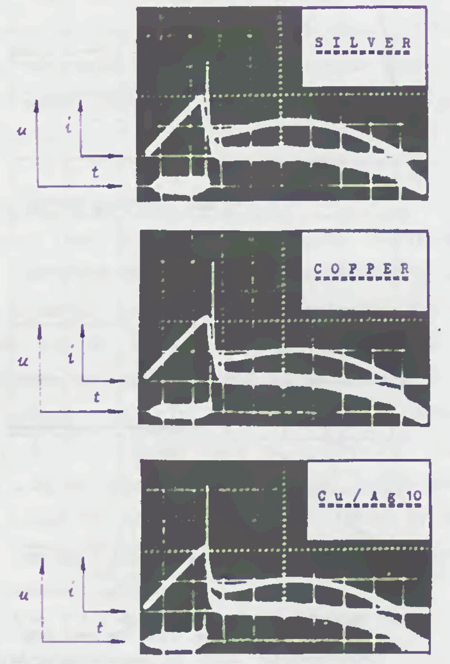

Fig.3: Oscillograms with model 1
i: 316 amps/div.,u: 500 volts/div.,t: 1msec./div.

The generally very high switching voltage is generated by the uncontrolled disintegration of uniform wires due to self-magnetic forces and surface tension. As a result, a large number of single arcs is formed which cause the high switching voltage. Out of a variety of calculations possible for this kind of voltage, the formula by Johann /4/ matches best with our results.

3.2. Modified hv-hbc fuse-links

Modified 3,6kV/10A fuse-links with copper fuse elements and Cu/Ag 10 fuse elements, respectively, were tested for the test duties 1 and 2 and compared to silver wire fuse-links. All fuse-links with copper fuse elements (about 100) stood the tests, safely interrupting the current. The Figures 4 and 5 illustrate the results. These results confirm our measurements of the

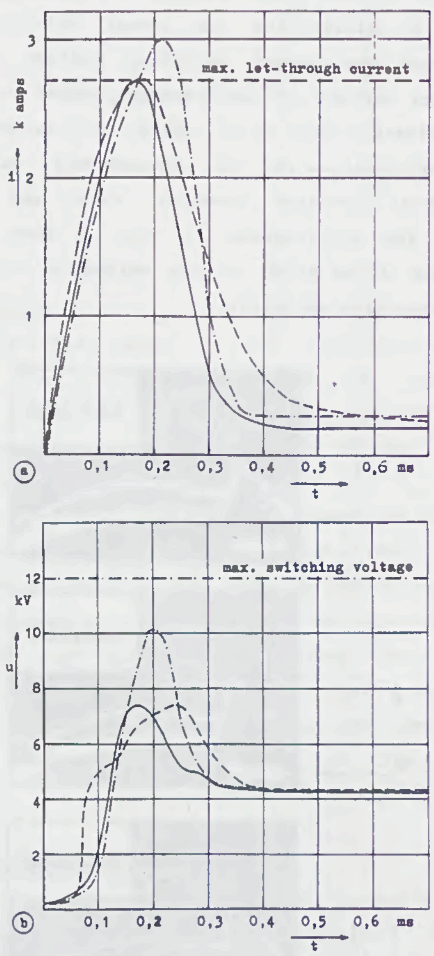

Fig.4: Current (a) and arc voltage (b) as a function of the time from the test duty 1
——— Ag ------ Cu —·—·— Cu/Ag 10 (cut - out)

test fuse-links: Cu/Ag-wires have worse breaking characteristics than copper wires and silver wires. Copper wires can be compared to silver wires with regard to their current-breaking capability, in fact they are even better in some cases because of their lower switching voltage with equal arcing time.

4. MEASUREMENTS OF THE t-I-CHARACTERISTIC

The fusing time of the fuse-wire in case of overload depends not only on the material properties of the fuse element such as resistivity, heat capacity, fusion heat, and cross section, but also on the properties of the quartz sand surrounding the fuse element. The smaller the current and the longer the fusing time, the greater the influence of the heat transfer to the surroundings by the quartz sand. The investigations were aimed at proving whether or not the material of the fuse element exerts an influence on the fusing time - current characteristic.

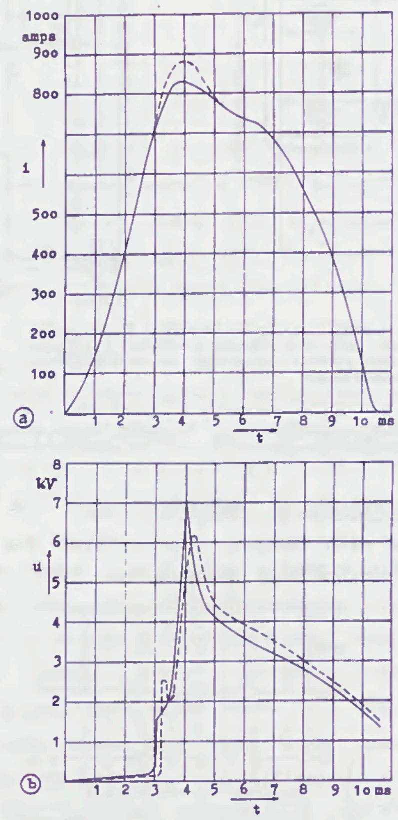

Fig.5: Current (a) and arc voltage (b) as a function of the time from the test duty 2
——— Ag -------- Cu

4.1. Investigation of test fuse-links

In model 2 there are used long uniform wires made of the materials mentioned above. Within our investigations we did not use wires with solder spots. This leave out the different behaviour of the solder on the fuse elements and enables the sheer comparison of materials.

Figure 6 shows the fusing times as a function of the effective value of the a.c. breaking current for some materials. The fusing time is approximately the same for all materials. This is due to the heat transfer characteristics of quartz sand, on the one hand. On the other hand, the higher heat capacity and fusion heat of copper as compared to silver is obviously compensated by the higher resistance.

The dashed line is the result of numerical calculation by Wintergerst /5/ for the copper elements.

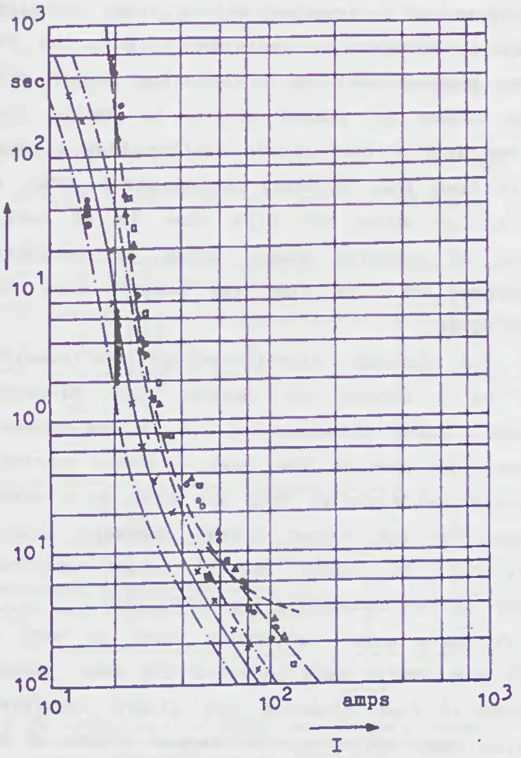

Fig.6: Fusing time versus current
- model 2 with uniform cross-section wires
  ○ Cu, □ Ag, △ Cu/Ag 260, test results
  ----- calculation by Wintergerst /5/
- HV-HBC-fuses 3,6kV/10A, related of the current per one element
  × Cu, ■ Ag, ● Cu - test duty 3
  ——— time-current-curve with —·— the permitted tolerance range

4.2. Modified fuse-links: t-I-characteristic and test duty 3

The results of the measurements of the fusing time and of test duty 3 for HWsF-B 3,6kV/10A copper fuse-links as well as single results of HWsF-B 3,6kV/10A silver fuse-links are also indicated in Fig. 6. For this purpose, the characteristic curve of the latter ones with the permitted tolerance range was included in the diagram. The current flowing through the fuse-link was related to the current flowing through each single conductor in order to facilitate the comparison to the measurements performed with model 2. Due to the restrictions of the fuse elements of the fuse-links, the fusing times are below those measured with model 2.

The conditions are the same as with model 2: the fusing times of Cu-fuse-links are only slightly different from those of Ag-fuse-links, all of them being within the permitted tolerance range.

The HWsF-B 3,6kV/10 A fuse-link has a minimum breaking current of 40 A (see test duty 3). This current was also used for testing the Cu-fuse-links. With the fusing times resulting from these tests being within the tolerance range according to the IEC 282-1 standard. The fuse-links safely switched off the current. Some fuse-links were additionally tested with I = 30 A under the conditions of test duty 3. The current was safely switched off. The fusing times are within the tolerance range, as can be seen in the figure 6, too.

These results and the results of the investigations of test fuse-links were confirmed. Silver and copper used as fuse elements do not have different breaking characteristics. The copper-fuse-links meet the conditions of the test duties extra ordinarily well.

5. OXIDATION ON OF FUSE ELEMENTS

The thermal load of the fuse element that occurs in the operation may cause irreversible changes of the material by diffusion processes and the formation of an alloy between the solder and the conductor material as well as by the oxidation of the conductor material. The process of material changing in the solder spot is generally called "ageing". It is often the subject of investigation e.g. by Klepp /6/ and Hoffmann /7/. This process, however, was not investigated within the framework of our research programm.

5.1. Determination of the temperature of the fusible element

As described in another paper /8/, the temperature of the fuse element determines decisively the oxidation rate. In the range of rated current, the temperature was calculated according to Vermij /3/ by measureing the heat transfer coefficient G, and theoretically by using the finite element method. For both procedures, the material values and, as in case of the latter, also the properties of the quartz sand had to be taken from literature. Since the values indicated by the various authors differ very much, we used the results gathered from the measurement of the temperature of the fuse element as a basis for our investigations.

The measurements were made with NiCi-Ni thermocouples, mainly for model 2, and with potential probes of thin Cu-wires, the latter method being applied for the modified HV-hbc-fuses. Here, the voltage drop at the respective current measured over a definite part of the fuse element by two probe wires was used for determining the resistance of this part. Its temperature was determined on the basis of the well-known temperature dependence $R = R_o\,(1 + \beta\vartheta)$. Preferably, R_o ist not determined by the help of the material values taken from literature as in /9/, but are measured with the same arrangement. If the distance between the probe wires is small, the course of temperature along the fuse element can be determined. On the other hand, the respective measurements revealed that, due to the trapezoidal course of temperature, it is sufficient to determine a mean temperature of the fuse element on the basis of the measurement of the resistance of the fuse-link.

5.2. Life tests of various materials for fusible elements

For these investigations, the uniform wires of model 2 were fixed in open air and periodically loaded with a current 1.4 times higher than the rated current of the fuse element. The duration of current flow was 1 hour, the currentless break being 1 hour, too. Caused by the "breathing", a high thermal load of the fuse element follows from the repeated heating-up to a temperature of 400 to 600 ^{o}C and the following cooling to room temperature, so that the effects of oxidation can be determined already after a relatively short time. The resistance is measured at the end of the currentless break. The results of the increase of resistance with the number of cycles are illustrated in Fig. 7.

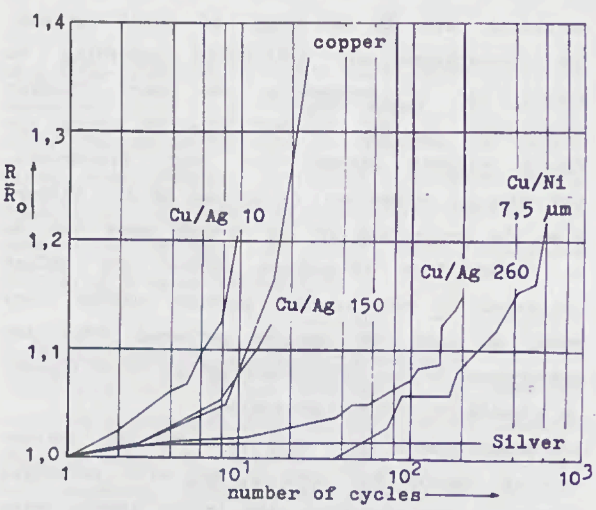

Fig. 7: Relative increase of resistance of fuse element materials

As it was to be expected, silver wires practically show no increase of resistance. Thus, the tests were stopped after 240 cycles. For copper wires, the number of passed cycles is small. Copper wires with a thin silver coating have a shorter life time than uncoated copper wires. Only with Cu/Ag 150 wires the life time is as long as that of uncoated copper wires. A considerable increase of life time was proved with Cu/Ag 260 wires.

In the plating, nickel-coatings are considered to be a barrier for oxygen. The Ni-coatings with a layer thickness of 7,5 µm are relatively dense and provide the best possible protection against oxidation if they are used as a covering layer for the copper wires. However, they are difficult to deform and to solder and, thus, they can not be applied for fuse-links.

Life tests under continuous load in both open air and quartz sand revealed the same tendency: Cu/Ag 10 fuse elements are always considerably worse than those made of copper. Figure 8 shows a metallographic for illustrating oxidation even below thicker Ag-coatings.

Fig.8: Metallographic of Cu/Ag 260 wire

5.3. Calculation of the life time of modified HV-hbc-fuse-links

As mentioned above, the authors of /8/ introduced a simple model for calculating the life time of fuse-links in case of continuous load. The calculations are based on the equation by Vermij /3/ for determining the temperature of the fuse element, into which the decrease of radius by oxidation was included.

$$\vartheta_{max} = \frac{\vartheta_o}{\left(1 - \frac{x}{r_o}\right)^4 - \beta\vartheta_o} \qquad (1)$$

with $\vartheta_o = \dfrac{\rho_o \cdot I^2}{G \cdot A_o^2}$ = constant

$x = (k \cdot t)^{1/2} = r_o - r_t$ = decrease of radius

The rate of reaction coefficient k for copper wires in quartz sand was determined experimentally (see /8/) as a function of the temperature of the fuse element as

$$k = A \exp(-B/T) \qquad (2)$$
$$= 9{,}17 \cdot 10^{-11}\ \mathrm{cm}^2\ \mathrm{s}^{-1} \exp(-4048\ \mathrm{K}/T)$$

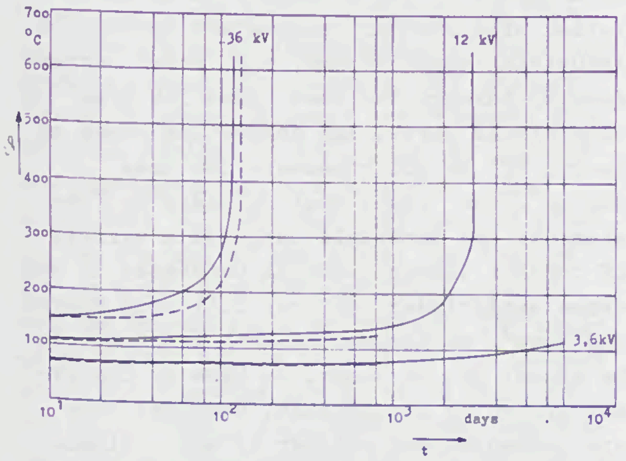

Fig.9: The temperature ϑ of fuse elements versus life time t for different fuses with rated current I = 10 amperes -------- experiment, ———— calculation

For more than two years long-time tests have been made with 10 A copper fuse-links of different rated voltage values for checking the calculation model. Figure 9 illustrates the results gathered with this calculation model and compares them to the measured values gathered before December 31st, 1990. Here, the temperature of the fuse element was determined as mean temperature from the voltage drop of the fuse-link at rated current. The measurement results confirm the trends following from the calculation.

6. CONCLUSIONS

- The life time to be reached with a fuse-link is determined by the initial rated operational temperature.
- With a given fuse element, the initial rated operational temperature depends on the design of the fuse link. The rated power dissipation per fuse length being a decisive influencing factor.
- Out of the number of fuse-links investigated by us, only the 3,6kV/10A fuse-link provides a sufficient life time of 20 years.
- The dimensions of the fuse element being maintained, fuse-links with Cu-fuse elements, too, will meet the demands with regard to the t-I-characteristic and the test duties according to IEC 282-1.
- The tolerances of the tests provide some freedom in varying the geometry of the fuse element, which can be used for lowering the rated operational temperature.

  This offers the chance to guarantee a low enough oxidation rate for all types of fuse-links investigated.

  The investigations necessary for this purpose are not yet completed.

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