A Survey about High-Current Interruptions Results in Resistive Increase of Vacuum Interrupters

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Abstract— The resistance of vacuum interrupters can be calculated from the geometry and resistivity of current carrying parts and the additional resistance of the contact points between movable and fixed contacts. Since vacuum interrupter contacts are designed as flat contacts facing each other, the resistance is mainly determined by contact force, hardness and resistivity of the contact material. It is known that the contact material changes consistency and structure during short-circuit interruptions within melting depth. Indeed, the overall resistance of a vacuum interrupter has been observed to increase by up to 60% after short-circuit making and breaking tests. Since the resistance increase across the switching device is considered by IEC and IEEE standards as one of the acceptance criteria for the integrity of the interrupter after tests, it is essential to understand the origin of this increase. Different causes are discussed, among them the change of grain structure, resistivity and hardness of the molten top layer of the contact, and flatness of the contact surface. An increase of hardness and a different position of contact points seem to be the main factors responsible for the increased resistance.

Key words: Vacuum interrupter, contacts, current interruption, contact resistance

I. INTRODUCTION

VACUUM interruption technology has been used for decades for circuit breakers in electrical networks. These breakers have proven high reliability in short-circuit interrupting and current carrying abilities. Electro technical standards dictate specific type tests to verify the ratings with respect to making and breaking performance of circuit breakers [2]. Resistance of the test object before and after the tests is considered in this standard as one of the acceptance criteria proving the integrity of the vacuum interrupter. Continuity of the main current path along the whole switchgear ensures that no parts have been destructed, in particular those which are not readily accessible.

It is also evident that the resistance across the switching contacts determines the continuous current carrying capability of the breaker. Therefore, an increase of the resistance after making and breaking operations might have an influence on this capability though it is not anticipated that a circuit breaker experiences as many full short-circuit interruptions as applied during a type test and as high a continuous current as rated. This paper lists resistances of a variety of vacuum interrupters before and after current interruption tests, correlates the resistance increase with circuit- breaker ratings and explains its origin. In particular, the impact of a modification of contact material properties such as electrical conductivity and hardness are investigated in theory and experiment.

II. BREAKER RESISTANCE AFTER INTERRUPTION TYPE TESTS

The resistance of circuit breakers having different ratings was measured across their terminals including the resistance of the vacuum interrupter, that of the movable contacts (either flexible copper connections or multi-lamella elements) and that of all current leads (Figure 1). Most often in these type tests – according to IEC 62271-100 clause 6.106, for example - only the resistance across the breaker terminals is determined by the test laboratory and not the resistance across single parts e.g. the vacuum interrupter itself.

Assuming the current leads and external contacts do not change their resistance during the making and breaking tests, the measured resistance increase can be accounted for by a change of the contact resistance inside the vacuum interrupter. This is confirmed by detailed measurements. Table 1 provides an overview of different kinds of vacuum breakers with different current ratings, where the resistance over the breaker terminals was measured before and after interruption tests according to IEC 62271-100 i.e. applying more than 10 full short-circuit currents. The measuring device consists of a current source providing a DC-current of 100A and a multimeter for the voltage drop. All breakers contained vacuum interrupters with spiral-type contacts using the same contact material CuCr 75/25.\

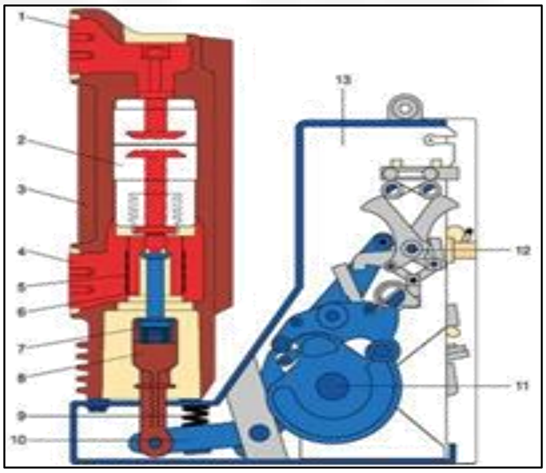


Fig. 1: Cross section of a circuit breaker with vacuum interrupter cast in epoxy material and operation mechanism. The measuring path for resistance is typically from point 1 to 4 in the above illustration.

Mean resistance Rating	before tests R/ μΩ	after tests R/ μΩ	increase R/ μΩ	increase R/ R
16kA, 630A	57.1	74.1	17.0	13.8%
21kA. 630A	29.4	43.7	14.3	36.9%
25kA, 1250A	19.3	24.7	5.4	34.7%
25kA. 1250A	22.7	28.4	5.7	25.6%

31.5kA, 1250A	27.5	38.0	10.5	35.9%
31.5kA, 2500A	12.4	19.0	6.6	58.9%
40kA, 2500A	12.0	15.4	3.4	24.4%
40kA, 2500A	11.0	13.4	2.4	17.1%
50kA, 2000A	12.1	14.5	2.4	18.9%

Table 1: Resistance of breakers measured before and after interruption type tests according to IEC 62271-100

Table 1 shows that the overall resistance of different types of vacuum circuit breakers is higher for lower rated continuous currents and smaller short-circuit currents. This is mainly due to the higher resistance of the terminals, current leads and the movable contact (Figure 1), which are adapted to the continuous current. The design of the vacuum interrupter, on the other hand, is determined by the magnitude of the short-circuit current: A larger interrupter for higher currents comprises more copper, higher contact force and has lower resistance.

The absolute increase of resistance, R, measured in µΩ after short-circuit interruptions is higher for interrupters with lower rated short-circuit currents, which is a clear trend obvious from Figure 2. However, the scatter of values is high and may vary, for example, with the actual imposed series of short- circuit tests or depends on the design of the vacuum circuit breaker or vacuum interrupter.

The increase of resistance related to the overall resistance of the breaker measured between its terminals is in the range of 20 to 60%. The plot of the resistance increase related only to the resistance of the vacuum interrupter also gives the same trend as seen for the complete breaker. Here, the relative increase is in the range of 40 to 140%.

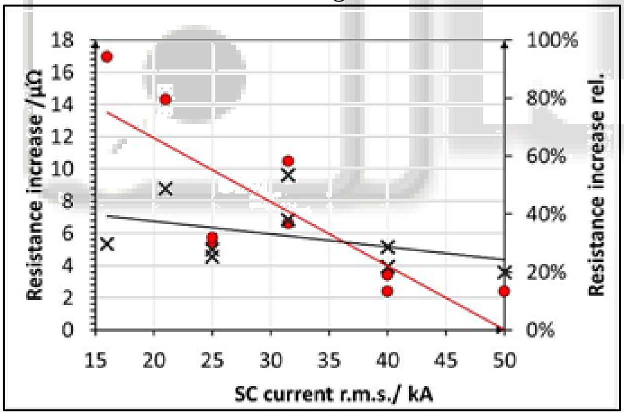


Fig. 2: Absolute (o) and relative (x) resistance increase of different vacuum circuit breakers as a function of rated short-circuit (SC) current after short-circuit interruption tests with trend lines (linear regression).

III. Dependence of Contact Resistance on Contact Force

Theoretically, the contact resistance, RE, can be derived [2] from the resistance of a sphere having radius a representing the physical contact point between two electrical contacts (Figure 3):

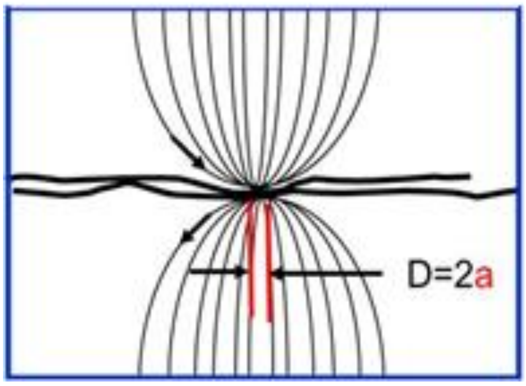


Fig. 3: Scheme of contact point between the surfaces of two flat contacts. The contact point is assumed to be a sphere.

$$R_E \quad _{el} \frac{(\ 2)a}{a^2} \quad \frac{_{el}}{2a} \qquad (1)$$

The electric resistivity ρel is that of the bulk contact material at the contact temperature, the effect of which is not considered here. Radius a can be calculated from the balance of yield strength, σy , of the material and contact force, F. The yield strength defines the force, where the material begins to deform plastically

$$a^2 \quad _y \quad F \qquad (2)$$

This area is similar to the area of indentation of a metal ball pressed with force *F* onto a metal surface for measuring the hardness of the material in *HB* (hardness Brinell). Brinell hardness, *HB*, and Vickers hardness, *HV*, can be converted by a factor of 0.95. Vickers hardness is measured with a pyramid instead of a steel ball. The resulting equation for R_E does not distinguish between oxidized or clean surfaces. In a vacuum only reduced oxidized (clean) surfaces exist.

$$R_E \quad 0.89 \ _{el} \sqrt{\frac{_y}{F}} \qquad (3)$$

The contact force dependence can be measured for vacuum interrupters before any current switching, thus for machined surfaces in a high quality vacuum. Here, a vacuum interrupter designed for 20 kA was measured (Figure 4).

The contact resistance was determined from equation

(3) using a hardness *HV 5* of CuCr 75/25 of 82, which results in a yield strength of 261 N/mm², and a resistivity of ρ_{el} = 0.036 µΩm, according to the supplier's specification. The fit also has to consider the non-variable resistance, R_{const}, of the two copper terminals of the vacuum interrupter and the bulk of the contact plates assuming a central touching of the contacts. Thus, the total resistance of the vacuum interrupter is composed of two parts:

$$R_{total} \quad R_E \quad R_{const} \qquad (4)$$

For the particular vacuum interrupter analysed in Figure 4, a resistance of 7.1 µΩ was added to the contact resistance. This shifts the curve calculated from equation (3) as a whole to higher values above the actually measured values. Thus, it has to be concluded that the contact resistance R_E is smaller. The reason is that not only one contact point exists, but several. It is a well-known fact that a stable state is, in general, obtained for a mechanical support providing three points like a tripod. Multiple contact points can be easily implemented into equation (3). The resistance is divided into *n* points, each experiencing *1/n* of the total contact force finally giving equation (5). Thus, with two or three instead of only one contact point, the resistance decreases as shown in Figure 4, fitting the measured dependence on the applied contact force quite well. However, there is a tendency to even lower contact resistance at higher contact forces, which cannot be explained by the simple equations.

$$R_E \quad \frac{1}{n} 0.89_{el} \sqrt{\frac{v}{F/n}} \qquad (5)$$

Furthermore, the resistances of two types of vacuum interrupters were measured as a function of contact force before and after short-circuit interruption tests. The interruption tests consisted of up to 30 full short-circuit interruptions at rated short-circuit current. The results are shown in Figures 5a and 5b. The resistance before tests as a function of the contact force is the mean value of 50 vacuum interrupters of type A and 14 vacuum interrupters of type B, whereas the resistance after tests was determined from only six interrupters of each type. The standard deviation is up to 15% of the total resistance for lower contact forces and reduces to 5% for higher forces. The curves fitting the data are calculated with the material properties of CuCr provided in Table 2 and will be discussed in the next section

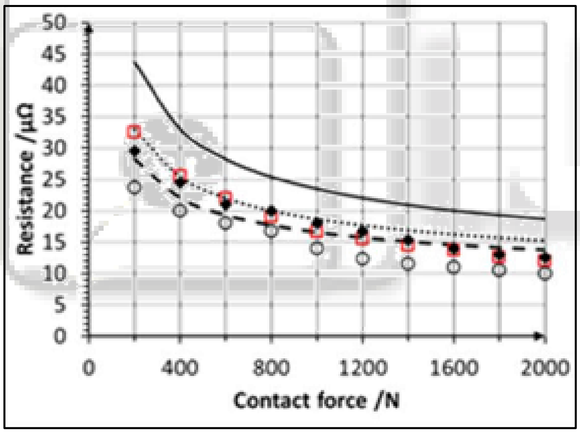


Fig. 4: Resistance of three identical vacuum interrupters measured as a function of contact force (points). The upper curve is calculated from equation (3) with only one contact point, the two lower curves are from equation (5) with two and three contact points, respectively.

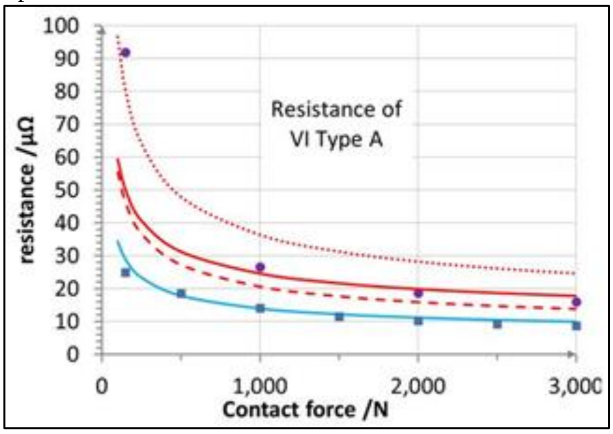
Lower full line: before tests with n=3; upper full line: after tests with n=3; dotted line: after tests with n=1; dashed line: after tests with n=3 with same Rconst as before the tests.

IV. Explanation of Resistance Increase after Interruption Tests

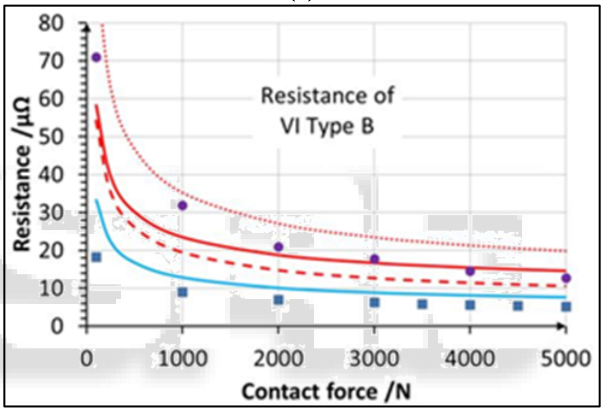
In this section it is tried to explain the increase of resistance by several effects and to exclude other effects.

A. *Position of Contact Points Relative to the Centre*

The resistance of a vacuum interrupter is determined by the distribution of current in the copper leads and contact plates and by the resistance of the contact points. The current distribution within the copper stems and therefore their resistance should be non-variable. However, the current distribution in the contact plates may change during and after interruption tests depending on the location of contact points. After intensive melting and the redistribution of melted material, the contacts have a different appearance and may touch at any point between the centre and the outer edge instead of the central area (Figure 6), where they are supposed to touch in a new condition due to a trapezoidal shape of the contact surface



(a)



(b)

Fig. 5: Mean resistance of type A (a) and B (b) vacuum interrupters measured as a function of contact force before tests (squares) and after short-circuit interruption tests (circles). The curves are calculated from equation (5) with the values of hardness and electrical resistivity as given in Table 2 and the number, n, of contact points

In finite element calculations [4] simulating the current distribution over the full length of the vacuum interrupter type A three different scenarios were considered: first, current conduction over the full centre area, which gives the smallest possible resistance of 7.836 µΩ. Then, in accordance with the model of three separate contact points and applying equation (5) with a contact force of 3,000 N, the contact area in the centre was reduced to three contact points each having an area of 5 mm². This scenario increases the resistance to 10.06 µΩ, which is the measured value of a new interrupter at a contact force of 3,000 N. In a third scenario, the three contact points each with an area of 5 mm² were placed on the outer edge of the contact, which increases the resistance to 17.185 µΩ. Figure 7 shows the current distribution in the two latter scenarios.

Fig. 6: Photo of spiral contacts before and after 30 short-circuit current interruptions

A resistance increase of 7 μΩ is well within the range of observed values after short circuit current interruptions. This increase is independent of the contact force, which is in line with the measurements. The curves in Figure 5 were fitted to the data with an increase of the constant resistance by 4 μΩ, which is arbitrary, yet reasonable when the three contact points are distributed somehow over the whole contact surface. It has to be noted that the measured data are mean values. The following effect could even explain a variation of this part of the resistance with contact force: At low contact force, the contact points may have the tendency to be at the edge of the contact, whereas at higher contact force - due to the elastic deformation of the contact plate - the contact points may be relocated to the centre region of the contact. The elasticity of the contact plate prevents the exertion of the full contact force on the outer, not supported contact radius. This effect could explain the mismatch of the curves fitted to the measured data in Figure 5a and 5b concerning lower contact forces.

B. Precipitation of Cr In Cu

Current interruption modifies the properties of the CuCr sintered contact material by melting and the subsequent rapid cooling of the surface. The grain structure becomes much finer and up to 0.8 % of Cr can dissolve into the Cu grains. According to Müller [3], this reduces the specific conductivity of copper. The same effect can be produced by re-melting sintered CuCr material. This effect has to be considered in the determination of the contact resistance using equation (3) or (5). The increase of the specific resistance taken from [3] amounts to less than 20 %. This value is used for the resistivity of the contact material after short-circuit current interruptions (see Table 2).

The specific resistance of a sintered material such as CuCr is determined by the percentage of copper and chromium. The current flows mainly in the copper material, since the current density in the chromium grains is about one order of magnitude lower than in copper due to their much higher resistivity. Precipitation of Cr in Cu reduces the conductivity of Cu and therefore increases the overall resistivity. However, this effect should only concern the molten top layer of the contact, which only has a thickness of approximately 100 μm. Therefore, the 20 % increase of resistivity is perhaps an overestimation.

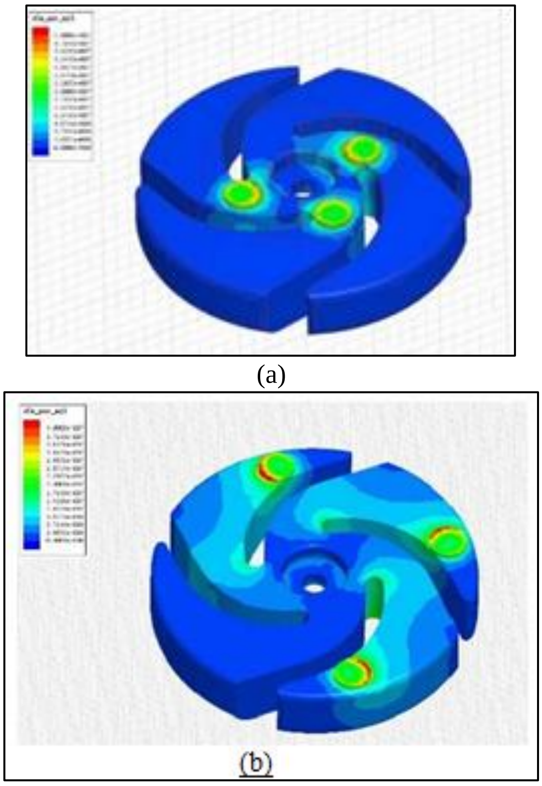


Fig. 7: Simulation of current distribution with spiral-type contact for different positions of three assumed contact points each having an area of 5 mm2

C. Orientation of Cr Grains

A dependence of the conductivity on the pressing direction during the sintering process has been reported. The longitudinal conductivity (i.e. along elongated grains) is up to 25% larger than the transversal conductivity as published by [5]. During short-circuit interruption the surface melts and removes any preference. Since the Cr grains are preferably oriented parallel to the contact surface before the tests and become irregularly oriented, the resistance would rather decrease. Thus, this effect cannot explain the observed increase and is not further considered here.

D. Resistivity in Dependence of Cr Grain Size

As seen in Figure 8, the grain size distribution is quite different between the bulk CuCr 75/25 and the molten CuCr 75/25 found in a top surface layer of approximately 100 µm thickness. The typical size of grains is in the range of 100 µm in the bulk and in the range of 200 nm in the molten layer (Figure 9) [6]. This can raise the question of the influence of the grain size on the resistivity. Such studies do not exist for CuCr material to our knowledge. However, results for copper processed by accumulative roll bonding [7] suggest no change in electric conductivity for copper grains larger than 200 nm, while it decreases for smaller grains. Since also the concentration of chromium in the molten layer might be different, a resistivity increase due to size and concentration of grains could be possible just for the thin molten layer on top of the contact surface.

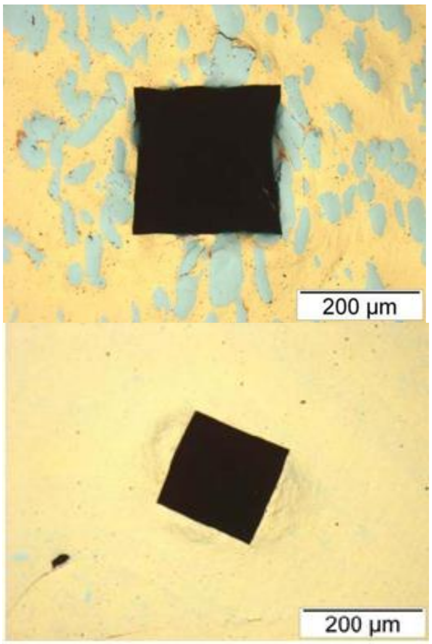


Fig. 8: Hardness measurement on cross sections of bulk CuCr 75/25 (upper photo) and on the molten top layer of CuCr 75/25 after making and breaking tests (lower photo); Cr grains have a grey colour.

It would be desirable to directly measure the resistivity of this molten layer. However, this is difficult due to its small thickness (approximately 100 m) and the surface roughness. The common resistivity measurement with an Eddy current probe requires a flat surface and a layer thicker than approximately 200 m. Grinding the surface of an electrode after arcing eliminates its roughness, but also decreases its molten layer thickness to values too thin for a reasonable measurement.

Preliminary measurements of the resistivity with a 4-point probe on a ribbon of CuCr obtained by fast cooling (105 K/s) of heated-up sintered CuCr 75/25 in a melt-spinner [6] indicates a resistance increase of at least a factor of two compared with bulk material. However, the impact on the overall contact resistance is small due to the small thickness of this layer. Equation (3) resulting from the simple model (Figure 3) assumes a sphere of contact material and results in a diameter of several millimetres for the prevailing conditions. Thus, the impact of a 100 µm layer is not large even if the resistance is much higher than in the bulk material. This effect needs further investigation.

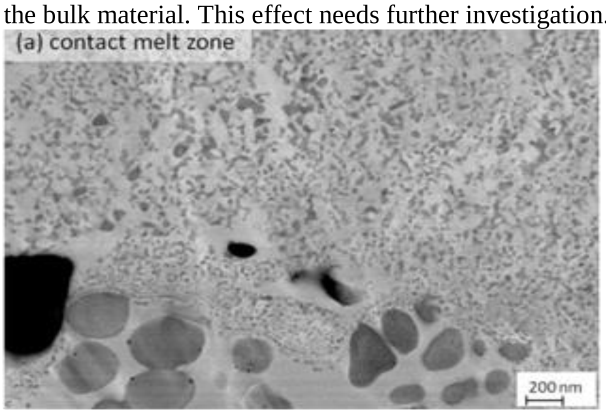


Fig. 9: Microstructure of the molten layer on top of the contact surface (re-solidified). The chromium grain size is in the range of 200 nm; in addition fine-dispersed chromium exists [6].

Taylor et al have indeed measured only an increase of 6%. [8]. However, few details are given on how the measurement was performed. It seems that an Eddy current probe was used with an unknown surface condition (rough or grinded). The layer thickness indicated (~100 m) might have been too small for the application of the Eddy current technique.

E. Hardness in Dependence of Cr Grain Size

It is known that the molten and re-solidified Cr grains in the molten layer increase the mechanical hardness [3]. Therefore, it was tried to measure the hardness in the molten layer directly. It was determined by the Vickers method exerting a small force in order not to penetrate the thin layer. Figure 8 shows hardness measurements on bulk CuCr 75/25 material, and on the molten contact surface after current interruption. Typical results are: 82 HV5 for the bulk CuCr 75/25 and 166 HV 5 for the molten top layer. In accordance with equation (5), the increase of hardness alone contributes to an increase of 41% of the contact resistance and thus, seems to contribute the largest.

F. Flatness of Contact Surface

Finally, the surface of the contacts is no longer a machined, flat surface after current interruptions, but becomes irregular and undulated (Figure 6). Thus, the points of real contact will be different from those before tests. This effect is already handled under the section titled: Position of contact points relative to the centre. The effect addressed now is the effect of matching two irregularly undulated surfaces.

From the rupture of welding spots, the size of the real contact areas can be estimated to several tens of mm², which corresponds to the area calculated from equations (1) and (5) using typical parameters. For an undulated surface, it will be difficult to reach such areas in only two or three spots even for the highest contact forces and with plastic deformation of the surface. Mechanical operations of the circuit breaker after short-circuit interruptions decrease the resistance by approximately 1 μΩ. Obviously, the molten surface layer is so hard that it is not effectively deformed under the contact forces. Thus, this effect might also give an increase of the resistance by a reduction of the contact area beyond that calculated from equation (5). The contrary effect is known as the conditioning effect. The resistance of a new vacuum interrupter can be reduced from the original condition just after manufacturing by mechanical operations obtaining stable values after a number of operations.

V. CONCLUSION

Short-circuit current interruptions modify the contact surface of vacuum interrupters. Since the vacuum technology only allows flat – however shaped – contacts, the contact surface is used for carrying the continuous current as well as the short-circuit current. Therefore, any increase of the resistance during making and breaking tests directly impacts the continuous current carrying capability. The measurements presented here show a contact resistance increase of between 20 and 60% related to the overall resistance of the vacuum circuit breaker. A resistance increase of 56% would implement a 20% smaller current carrying capability assuming the heat generated with the higher resistance being equal to the heat generated in a new breaker at rated current.

A simple equation relating material hardness, bulk resistivity and applied contact force to the size of the actual contact points and thereby the contact resistance was fit to the measured data as presented in Figure 5. For the best fit the parameters from Table 2 were taken.

	Before tests	After tests	
ρel	0.036	0.043	μΩm
σy	261	530	N/mm²
HV 5	82	166	
No. of points	3	3	
Rconst of VI (A)	4.5	8.5	μΩ
Rconst of VI (B)	3.4	7.4	μΩ

Table 2: Parameters of contact material for the use of equation (5) in Figure 5

The yield strength σ_y in Table 2 is converted from Vickers hardness using tables from DIN 50150. The electrical resistivity ρ_{el} after tests is evaluated from Figure 9 in [3].

The increase of resistance after short-circuit current interruptions and in particular its dependence on the contact force can be explained by the increase of hardness of the molten CuCr surface layer by a factor of two. However, a contribution to the resistance increase not dependent on the contact force also has to be assumed, which probably can be traced back to a different position of contact points relative to the centre. The increase of the electrical resistivity of the thin surface layer molten by the vacuum arc probably is high, however, it seems to play a minor role.

It is remarkable that in [9] a resistance increase in dependence of the arcing current has also been measured for CuCr of different mixtures, however, not for contacts made of pure Cu. This indicates the importance of the sintered material CuCr, which changes its properties during melting and fast cooling. For pure Cu contacts only a change of the surface flatness and roughness is expected.

The conduction of continuous load currents up to the rated value has little effect on the resistance of contacts after current interruptions. Tests over at least 12 hours at 1250A – even up to 1600A – increasing the temperature of the contacts to more than 100°C showed a reduction of the higher resistance after current interruptions by only 0.8 to 1.8 μΩ. The continuous current is surely not able to change the Cr composition and grain size of the surface structure. Still, an effect is noticeable, which might be traced back to local softening of the surface.

Switching of currents in the range of up to 1000A does not modify the contact resistance. Under these diffuse arcs, melting only occurs in the cathode spots within µm depth. This modifies the microstructure or roughness of the surface, but not the gross material properties.

The resistance increase of vacuum interrupters by short-circuit interruptions is an intrinsic effect, which depends on the contact material and its modification during current interruption.

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