Vacuum switches contact resistance

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Contact resistance of coupled electrodes, in particular the ones used in high current switches, is a fundamental parameter in determining their rated current (continuous operation) and limit theirs short-circuit current (above which contacts are welded). The paper presents the simulation results of the transition resistance of selected types of contacts calculated with different mathematical models, and assess the extent of their compliance with the results of real objects.

KEYWORDS: contacts, contact resistance, contact materials, vacuum switches

1. Introduction

A part of the current path, containing a connection of the two conductors is called the contact, wherein due to the nature of the work can be removable or non-removable element. Separable contacts are the main functional component of the electrical switches, allowing turning on and off electrical circuits. For this reason they are called switching contacts. Due to the shape of the contact surface of a pair of contacts stand idealized forms usually are distinguished in the form of contact point, line or surface [1]. In practice, the contact point is considered to be an adjoin surfaces, wherein the contact surface is similar to that of a circle with a very small radius. For technical reasons, the contact surface topography has always micro-elevations and micro-pockets (roughness) so that in case of line and surface contacts the actual surface is the sum of the elementary contact points surfaces. They are arranged, respectively, in a line patter (line contact) or with a random distribution on an apparent (resulting from the contact geometry) contact surface. Actual (total) size of contact surface is only a few percent of the apparent surface and largely depends on the hardness of the contact material and the method and accuracy of their realization.

The existence of elementary contact areas on the contact surface, highly smaller than apparent contact surface, is locally reducing the cross-section of the conductor and therefore locally increases current density. In macroscopic terms, this means the creation of the additional resistance in the current path associated with a narrowing of conductor cross-section, which is defined as the so-called constriction resistance or shape resistance. The essence of the constriction resistance model is shown in Figure 1.
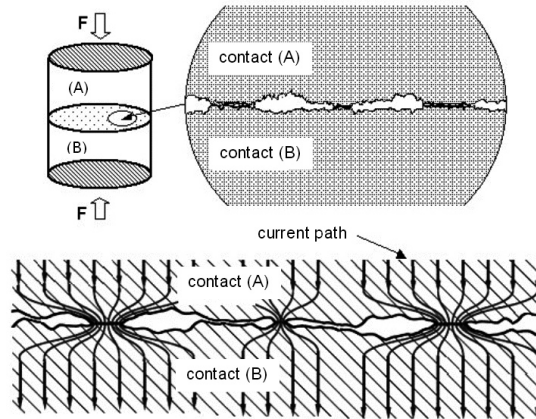
Fig. 1. Model structure of flat contact surface

The actual (overall) contact resistance, also called the transition resistance, is actually higher because the contact surfaces adsorbs gas molecules and gas contact coating is easily created. Their importance may be less important or even negligible in the case of vacuum contact switches. While in the vacuum environment or in an environment of inactive gas coating layer may not exist, adsorption layer is always present. In summary, the contact resistance is the sum of the constriction resistance and the non-metallic surface layers [2, 3]. Assessment of its value relative to the minimum resistance value (calculated for equivalent, clean and slightly deformed contact surfaces) should be an important indicator of the technical condition of the contacts of switches in service.

2. Analytical presentation of contact resistance

Contacts are pressed against each other by the mechanism of the connector, resulting in interfaces, micro-surfaces are subjected (Figure 1) to elastic deformation (at low contact forces) or plastic (with large forces, exceeding the yield point of the material contact). In case of large compressive forces, compressive strength of each micro-elevation turns out to be lower than that resulting directly from the hardness of materials (as defined for example, with Brinell and Vickers methods). Increase in contact pressure results in flattening the initial contact surface, increasing not only the actual area of contact, but also additional connection points between two electrodes are created. The dimensions and the number of contact points are nonlinear functions of crushing force, but can be assessed based on the relationship [2, 4]:

$$n = 2,5 \cdot 10^{-5} \cdot H^{0,625} \cdot F^{0,2} \qquad (1)$$

where: n – number of contact points, H – contact material hardness (as defined by Brinell or Vickers, N/m^2), F – contact force, N.

and:

$$r = \sqrt{\frac{F}{n\pi\zeta}}$$ (2)

where: r – average radius of contact point, m, ξ – empiric coefficient with values between 0,3 and 0,6 [4].

An example of number of contact points and their average radius in function of contacts force, for contacts made of silver and tungsten, is shown in Figure 2.
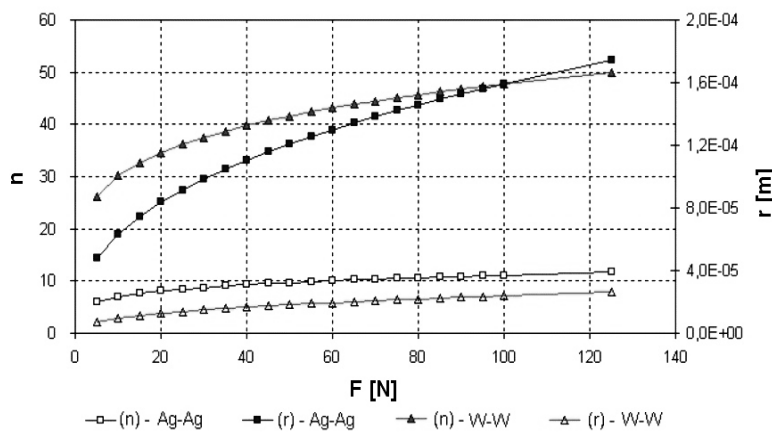

Fig. 2. Relationship between the number (n) and size (radius – r) of contact points as a function of the contact force for the sample materials with greatly varying hardness

Contact materials used in electrical connectors must meet a number of (often conflicting) user requirements, of which the most important are: good electrical and thermal conductivity and high resistance to the erosive action of the electric arc. The vacuum connectors currently produced are usually sintered materials or alloys of silver or copper tungsten alloy (in contractors) and copper-chromium (in switches).

If the transition resistance depended only on the number of contact points, as shown in Figure 2, hard materials would preferably be used for contact strips. Unfortunately contact points tend to have small dimensions in such case. Increase in contact force has a positive effect on the increase in both the number and surface area of contact points. The tendency of the materials used for the vacuum circuit breakers - CuCr (shown in comparison with copper contacts) is shown in Figure 3.

Electric current density increases locally with current flowing through the conductor with contacts present (according to Fig. 1). Therefore, contact resistance is lower with lower degree of compaction of elementary current streams and with greater the number of contact points together with a more even

distribution of them. Additionally contact resistance is affected by the resistivity of contact material and the resistance of surface layers so that, consequently:

$$R = R_k + R_p$$

$$(3)$$

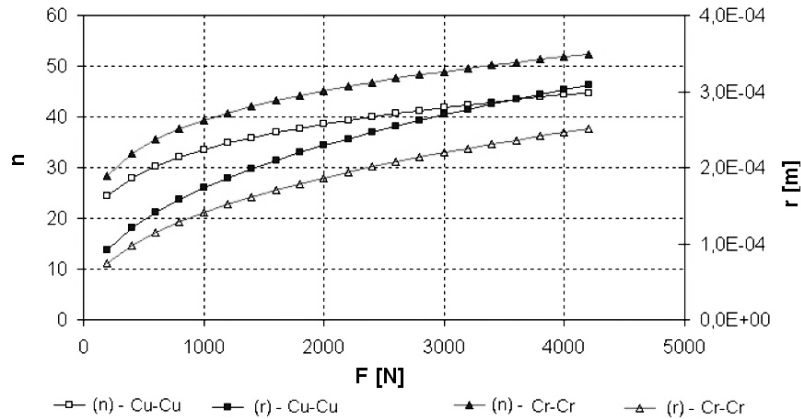where: R are respectively resistances: R - contacts, R_k - shape, R_p - surface layer.

Fig. 3. Calculated number (n) and size (radius - r) of contact points as a function of contact force for contacts made from CuCr and Cu

Contact resistance is described by the relationship [4, 5]:

$$R = \frac{\rho}{2nr} + \frac{\rho_p}{n\pi r^2}$$

$$(4)$$

where: ρ – resistivity of the contact material, $\Omega \cdot m$, ρ_p – resistivity of the surface layers, $\Omega \cdot m$.

In regard to the expressions (1) and (2) dependence of the contact resistance as a function of the biasing force of the electrode can be represented as follows:

$$R = \left(\frac{\rho}{2} \sqrt{\frac{\pi\zeta}{2,5 \cdot 10^{-5}}} \cdot H^{0,1875} \right) \cdot F^{-0,6} + \frac{\rho_p \cdot \zeta \cdot H}{F}$$

$$(5)$$

The non-metallic surface layer is formed naturally as a result of the surrounding gas adsorption and chemical reactions occurring on the contact surfaces. In view of how many factors are responsible for the above processes evaluation of thickness of the clear layer and the rate of their formation is extremely difficult. However analytical calculations allow to estimate their impact on the total value of resistance of electrical contacts.

Adsorption layer is always present and covers the space between the boundary surfaces of the electrodes. Its thickness is in the range of several to approximately of 20 Å [1, 5]. The minimum value is equal to twice the diameter of the particles of the surrounding gas (monolayer coating on each of the pins).

For example, the resistivity of the oxygen coating adsorbed on the surface of the copper contacts can be represented by the following formula [4]:

$$\rho_p = 3{,}15 \cdot 10^{12} \cdot s^{2{,}68} \tag{5}$$

where s is the thickness of the adsorption layer, Å.

Table 2.1. summarizes the calculated values characterizing the adsorption layer resistance for copper contacts coated with single, double and triple layer of oxygen molecules.

Table 2.1. Oxygen adsorption layers parameters on copper contact

Number of gas layers	s	ρ_p	R_p		
	Å	$\Omega \cdot m^2$	$\mu\Omega$		
	----	----	F = 10 N	F = 100 N	F = 1000 N
1	5.4	$4.58 \cdot 10^{-13}$	11.3	1.13	0.11
2	10.8	$2.94 \cdot 10^{-12}$	72.8	7.28	0.73
3	16.2	$8.71 \cdot 10^{-12}$	216	21.6	2.16

For effective arc-extinguishing insulating properties and behaviour, it is assumed that the cut-off level of the residual gas pressure in the vacuum switches extinguishing chambers should not be higher than 10^{-2} Pa [6]. The pressure at the beginning of their exploitation is even lower – 10^{-4} – 10^{-6} Pa. These ranges are called high vacuum. On the surfaces of details placed in such environment monomolecular adsorption layer (single layer) is formed, and the time of their creation is just up to few seconds [7]. To evaluate the resistance of vacuum switches contacts the monomolecular adsorption layer must therefore be taken into account. A significant increase in the transition resistance of thicker layers (Table 2.1) may be an indicator of damage to the quenching chamber. The absorption layers are corrosive and are usually produced by the oxidation of the contact surfaces. The thickness of these layers is significant, reaching values of 10^2 - 10^4 Å [1]. In a high vacuum environment, while maintaining proper purity during the production of the extinguishing chambers, absorption layers do not occur.

Based on the relationship developed by Holm [2], in [5] shows the relationship describing the contact resistance of flat contacts subjected to compressive forces, causing plastic deformation:

$$R = \frac{\rho}{2n} \sqrt{\frac{\pi\sigma}{F}} \tag{6}$$

where: σ – plastic stress deformation of contact material N/m^2.

For simple form of formula describing the resistance of the contacts made from different materials indicates Rachowski [3]:

$$R = \frac{\rho_1 \cdot \rho_2}{2} \sqrt{\frac{H}{F}} \tag{7}$$

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where ρ_1 and ρ_2 are resistivity of individual materials, and H is the hardness of the softer contact.

Simple to interpretive formula, but limited to a very modest set of metal (generally not used today in the construction of contats) represent the work [8] and [9]:

$$R = \frac{c\rho}{(0,1F)^m} \qquad (8)$$

wherein the values of few parameters ($\rho \cdot c$) and (m) are given in [5, 8, 9].

Example values of contact resistance, designated for copper contacts (Cu-Cu) are shown in Figure 4. For further calculations the averaged values of hardness and resistivity of copper and the coefficient ξ, served in the literature [4, 5, 8, 9, 10], are used.
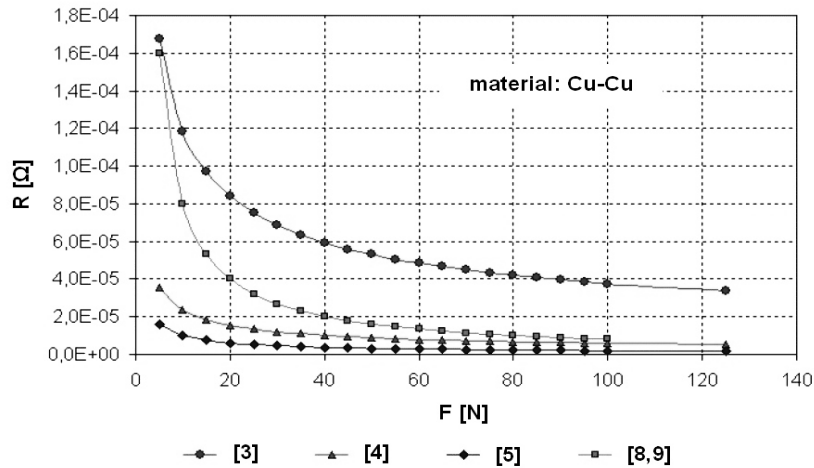

Fig. 4. Calculated values for transition contact resistance for copper contacts based on the literature

Due to the limitations of the use and availability of data for range of earlier equations mainly used in further calculations is the universal relationship proposed by Johannet'a [4].

Figure 5 shows calculated dependence of the transition resistance in function of clamping force of the electrodes, for materials used in the construction of the vacuum contacts. Although the single metal materials are not of any practical use, but data obtained for them form the boundaries of the expected resistance values for composites of copper and silver with tungsten and chromium. The WCu70/30 material is a composite powder, commonly used in vacuum switches, including extinguishing chambers VK-7, produced in Poland SV-7 contactors. Pressure forces used typically in vacuum relays do not exceed the value of 100 N, so the range of calculations was limited to 125 N.
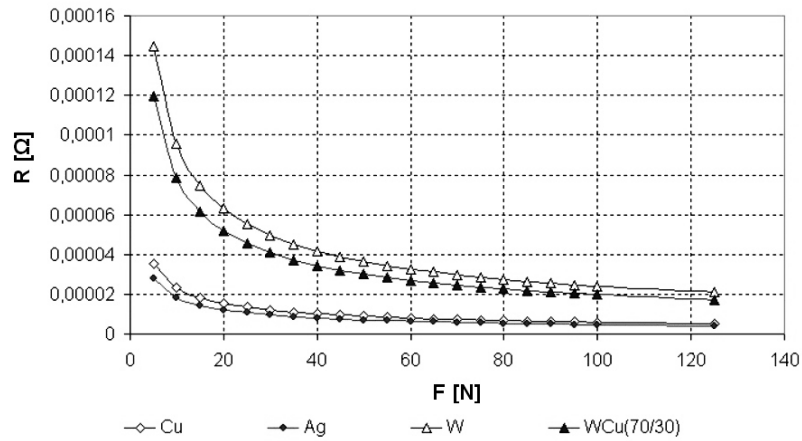
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Fig. 5. Contact resistance of clean contacts for exemplary materials and typical contact forces applied in vacuum contactors

Commonly used materials in medium voltage vacuum circuit breakers are sintered CuCr with a relatively high resistance to the effects of erosive action of high current arc. Clamping force of such relays are significant and reach values of several kilo newtons. Contact resistance of composites CuCr25 and CuCr40 for such conditions was determined. The obtained values are shown in Figure 6, the boundary plots are calculated for pure copper and chromium.
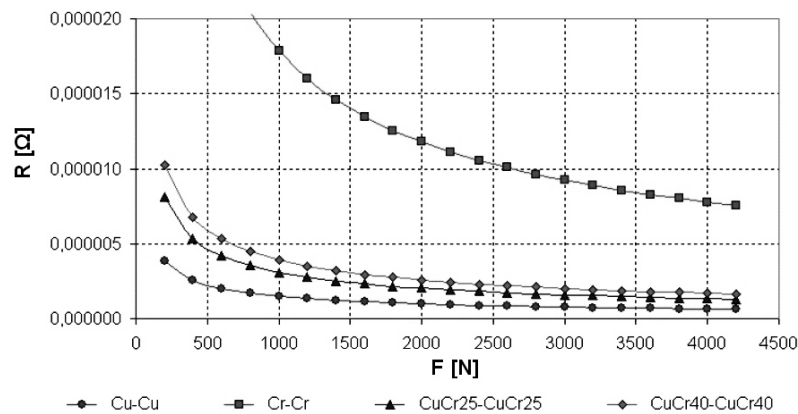

Fig. 6. Contact resistance for clean contacts for selected materials and typical pressure forces used in vacuum switches

As expected predominance of copper in the composites CuCr25 and CuCr40 affects the location of their resistance curves and brings their characteristics closer to the curve of copper contact resistance.

3. Calculation results in relation to experimental research

The measurements were performed for verification of extinguishing chambers for vacuum switches (VK-7) and breakers (type PKG and KG). Pictorial form of the chamber is shown in Figure 7, and the information on the construction and materials of the contacts is included in work [10] and [11].
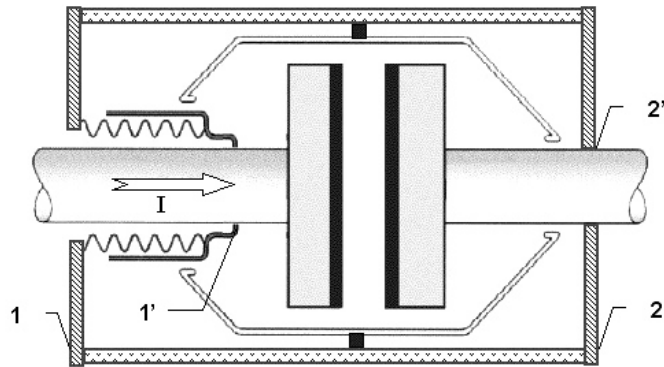
Fig. 7. Illustrative design of the vacuum chamber and available contact resistance measurement points (1, 1' , 2, 2' - available for voltage drop measurement points)

The figures 8 and 9 show example results of contact resistance measurements for extinguishing chambers as compared to the calculation of their transition contact resistances, determined from the formulas (5) and (7).
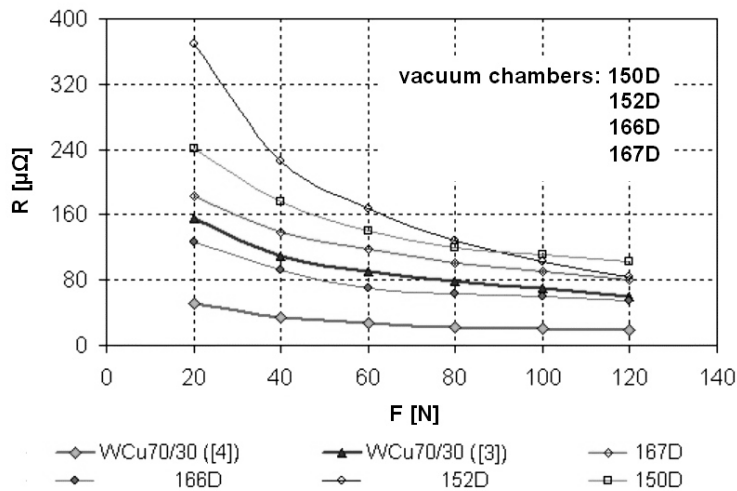
Fig. 8. Calculated and experimentally determined values of resistance for the example vacuum switch chambers VK-7
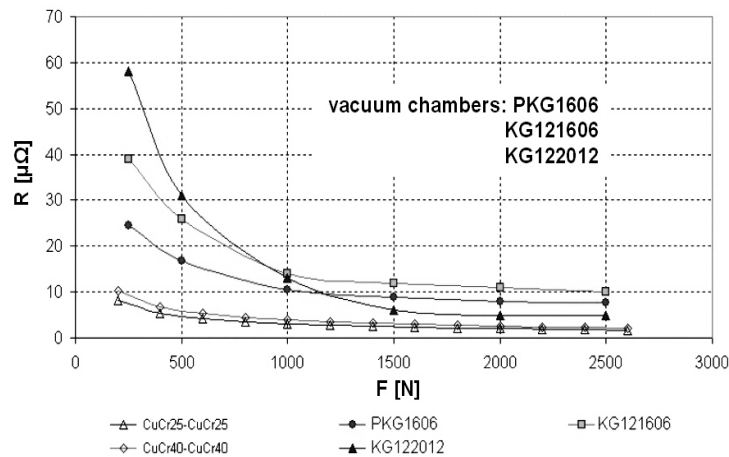
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Fig. 9. Results of resistance measurements for the example vacuum breaker chambers

Due to the hermetical nature of the usable quenching chamber resistance measurement in the immediate vicinity of the contact is not possible. The available measuring points 1' and 2' for switch chambers (Fig. 7) are located at distances of less than 5 mm from the contact point, so the resistance of the current path has a small share of the total resistance measured. Despite this, only the chambers numbered 166D, from all examined ones, has a transition resistance similar to that obtained from calculations (in range between the results of calculations according to [3] and [4] - Fig. 7). For breaker chambers resistance of current carrying elements has a value close to the contact resistance and definitely increases total measured value. It is also noticeable the wide slope variation of resistance characteristics for each extinguishing chambers.

3. Summary

The results of calculations and measurements indicate considerable differences in the obtained data. For relays chamber measurements, compared with the analytical results, can be a direct point of reference for the assessment of the technical condition of the chambers operated. In the case of circuit breaker chambers (with a very small transition resistances) for such assessment it is required to take into account the resistance of the conducting paths. The values of these resistances are in fact close to the contact resistance values. It should be noted that the share of the surface layers resistance of contacts in vacuum switches does not exceed 10% of the resistance of contacts and is far less important for contacts of vacuum circuit breakers, operating at high pressure forces. Measurement of r contact resistance is an important indicator of its condition, also from the hermetical conditions.

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