The Influence of Switching Arcs on Contact Resistance of Ag/SnO$_2$ Materials

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***Abstract*—Silver tin oxide (Ag/SnO$_2$) contact materials are widely used for relays and contactor applications. Device approbation in accordance to standards requires several types of temperature rise test in new and switched conditions. Significant differences in temperature rise after the various switching sequences are experienced. In addition, differences between individual phases of one device – especially in switched condition - are known from test.**

In this work, the contact resistance evaluation under different load conditions has been studied. Therefore the arcing events at make and break operation during different endurance tests (AC-3 and AC-4) have been analyzed and correlated to the contact resistances at rated current level during temperature rise test. Surface layer changes of contact materials after load are characterized by metallurgical methods. The paper shows the formation of different surface layers as a function of arcing energies during make and break operation. The results demonstrate that make and break arc together are creating the surface layers defining the final contact resistance.

Keywords*—*contact material; silver tin oxide; contact resistance; arcing

I. INTRODUCTION

Silver tin oxide (Ag/SnO$_2$) contact materials are widely used for relays and contactor applications. General trends in this application field are device miniaturization and steadily increasing power densities. Furthermore, electrical loads switched by these devices become more diversified and challenging, e.g. increased inrush currents of energy saving lamp starter units or energy efficient machines. Contact materials applied in such devices cope these demands by higher metal oxide contents [1, 2] to provide improved anti sticking behavior and reduced material loss under high power switching.

Ongoing miniaturization drives electro mechanical switching devices to the limits. Device approbation in accordance to standards requires several types of temperature rise test in new and switched conditions. Significant differences in temperature rise after the various switching sequences are experienced. In addition, differences between single phases of one device – especially in switched condition – are known from test [3]. Therefore, the understanding of the interaction between switching arc under different load conditions, contact material, and temperature rise is key for further development of switching devices and materials. The influence of thermal effects on decomposition of silver metal oxide materials along with the creation of silver droplets on the contact surface has already been studied in [4]. In this work, the contact resistance evaluation under different switching load conditions will be analyzed.

II. TEST CONDITIONS

A state of the art 11 kW contactor was chosen as representative for the studies. Contact material under test was commercially available Ag/SnO$_2$ 86/14 PMT3 – Bi$_2$O$_3$ and CuO additives – processed by powder metallurgical routine via

- blending of silver and metal oxide powders
- isostatic compression
- sintering
- extrusion and rolling to final dimension

Device endurance tests under AC-3 and AC-4 conditions in accordance to [5] have been performed applying the parameters shown in Table I. Contactors from one batch have been taken from production and were pre-selected by mechanical measurements, e.g. static contact force, to provide comparable boundary conditions for the tests.

TABLE I. ELECTRICAL TEST PARAMETERS

	Parameters for Test Sequence		
	AC-3	***AC-4***	***Temp. Rise***
voltage U	400 / 67 V	400 V	approx. 5 V
current I	150 / 25 A	150 A	45 A
power factor $\cos\varphi$	0.35	0.35	-
switching frequency	600 h^{-1}	360 h^{-1}	1 h^{-1} w/o load
number of operations n	500,000	10,000	24

The make and break operations were closely monitored during the endurance test. Therefore, phase currents and voltages across contacts $u_c(t)$ were measured. Arcing energies stressing the contact material were calculated based on these measurements. The average bounce arc energy at contact make W_{make} per phase was estimated by applying Eq. 1:

$$W_{make} = \int_{t_{bounce}} u_c(t) \cdot i(t)\, dt \tag{1}$$

where t_{bounce} represents the bouncing time (open contacts after initial contact make).

The calculation of average arcing energy at contact break W_{break} per phase of a contactor providing a double breaking system was done in accordance to Eq. 2. Here, two times (double breaking) the anode cathode voltage drop U_{AC} is multiplied with the integral of the phase current from contact opening t_1 until an arcing voltage of 100V is reached, which equals the commutation time.

$$W_{break} = 2 \cdot U_{AC} \int_{t_1}^{t_{100V}} i(t)\, dt \tag{2}$$

Table II shows average arcing energies for the three contactor phases calculated at endurance test. Comparable bounce arc energies were observed for both load conditions – as the currents at make are identical. However, significant differences on break arc energies due to lower current and voltage under AC-3 conditions were calculated.

TABLE II. AVERAGE ARCING ENERGIES

	Test Sequence and Phase					
	AC-3			***AC-4***		
	L1	L2	L3	L1	L2	L3
avg. bounce arc energy W_{make} [Ws]	0.32	0.82	0.60	0.46	0.89	0.53
avg. break arc energy W_{break} [Ws]	1.1	1.3	0.8	12.3	15.2	7.9

A temperature rise test - starting at $n = $ zero switching cycles – was performed in intervals of 20% of total number of operations during the endurance tests. Therefore, the endurance tests were interrupted, and the contactor was loaded with the nominal current $I_{th} = 45$ A on AC-4, which had to be reduced to 30 A for AC-3 due to high temperatures reached under switched conditions at AC-3. After one hour, a stable temperature had been reached on the terminals. The maximum measured temperature value of the six terminals was stored and a dry switching cycle was performed. Subsequently the rated current was applied again for one hour. This procedure was carried out for 24 hours at one number of operations to collect data for statistics. In addition, the contact resistance per phase was measured during the current carrying phase.

III. CONTACTOR ENDURANCE TEST RESULTS

After the temperature rise test sequence the contact parts were disassembled from the contactor and the weight was measured. By this, the erosion of contact material per phase over average arcing energy at break operation under AC-4 conditions can be estimated (Fig. 1), applying the mass loss average after each temp rise sequence for each phase as basis. The influence of the bounce arc at make operation on the material loss can be neglected for AC-4 conditions [6]. Two contactors have been tested under AC-4 conditions, and both erosion rates are plotted in Fig. 1, proving the repeatability of this method.

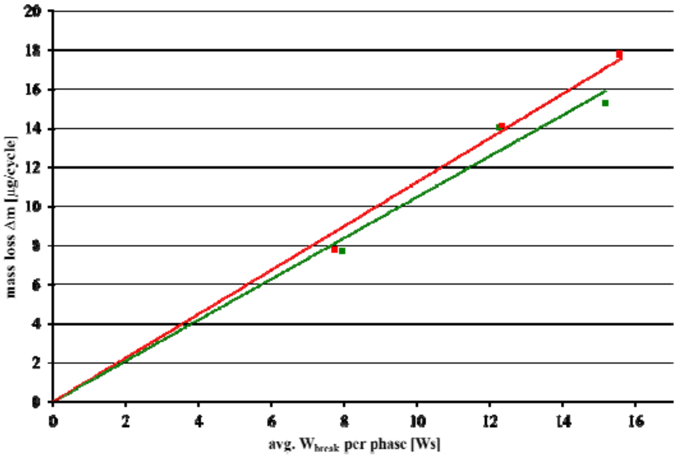

Fig. 1. Material loss per break arc energy under AC-4 load

In general, the material loss per arcing energy is strictly non-linear [2]. For the studied small break arc energy interval (8 – 15 Ws), and under the given boundary conditions of the tested contactor, an erosion rate can be approximated to 1 µg/Ws for AC-4 load.

In recent years, especially since usage of FEM software during device design phase, the bouncing behavior of contactors has been optimized, and bounce arc energies have been minimized. Therefore, arcing energies at make due to bouncing and these generated by break arcs are on a comparable level for AC-3 conditions. One has to consider both to judge about material loss, as both arcs are equally responsible for the physical reactions on the contact surface.

According to this, the material loss of contact material per phase over average arcing energy at make and break operation under AC-3 conditions is shown in Fig. 2 – assuming both arcing energies contribute equally to erosion, neglecting self-healing effects – as they are described in [7] – caused by the interaction of both arcs. By this, an erosion rate of 0.2 µg/Ws can approximated from Fig. 2 for AC-3 load.

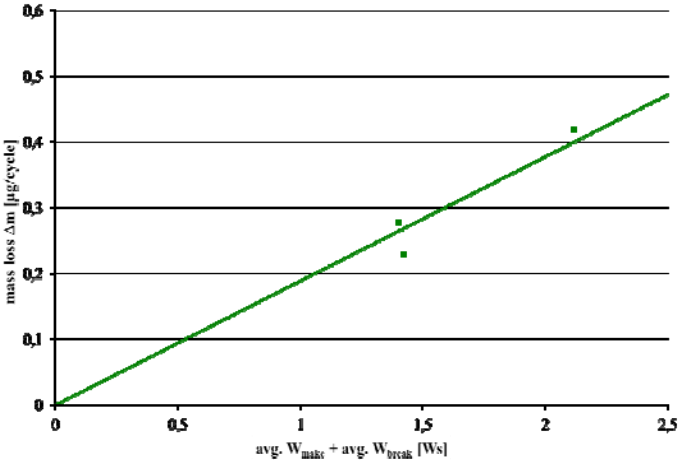

Fig. 2. Material loss per make and break arc energy under AC-3 load

In intervals, the temperature rise ΔT compared to ambient temperature on the contactor terminals carrying rated current I_{th} was studied. The maximum values, 95% quantiles, and average values out of a single 24 hour cycle at $n = 0$ and of 5 times 24 hours cycles under AC-3 and AC-4 conditions are plotted in Fig. 3.

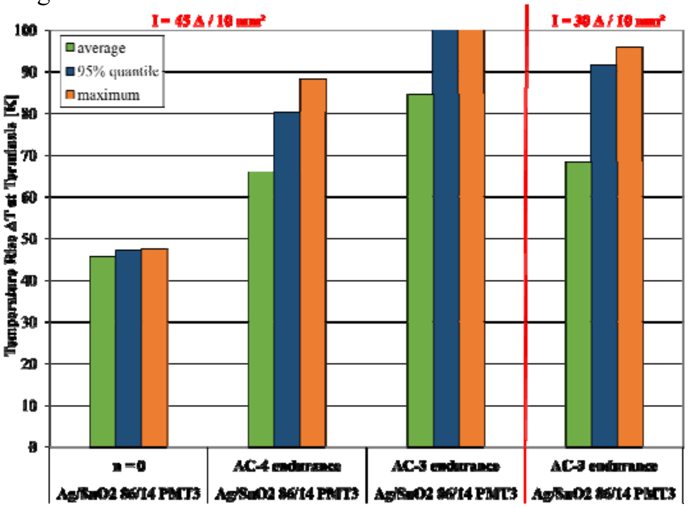

Fig. 3. Temperature rise test results

Stable and reproducible test results regarding temperature rise can be observed for new conditions ($n = 0$). After the devices have been loaded by a certain number of operations during the endurance tests, 95% quantiles and maximum temperature values significantly rise. Under AC-4 load temperature rise increases by a factor of 2, and in single phases even more under AC-3, where test current had to be reduced to 30 A due to this effect.

IV. INTERPRETATION OF TEST RESULTS

After finishing the endurance tests, cross sections of the Ag/SnO_2 contact tips have been prepared to analyze the root cause for the differences in temperature rise at different switching loads. Fig. 4 and Fig. 5 show typical contact surfaces after AC-4 and AC-3 endurance test, respectively.

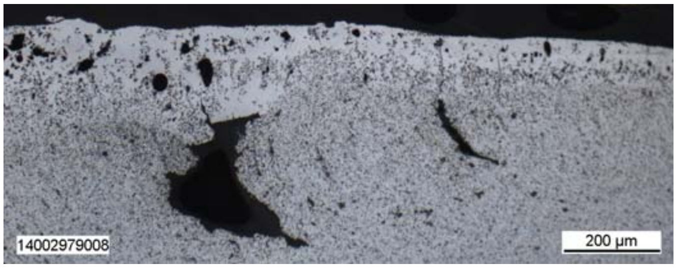

Fig. 4. Cross section after AC-4 endurance test

Fig. 5. Cross section after AC-3 endurance test

The cross sections after both load conditions show vertical cracks in the contact material due to the thermo-mechanical stress by arcing. In addition, the material is decomposed in heat-effected zone close to the contact surface. Energy-dispersive X-ray spectroscopy (EDS) has been performed in the cross section to further analyze this decomposition effects in the contact surface near areas. Figure 6 and 7 show the secondary electron image (SL) and the material contrast (CP), and element mappings for silver (Ag), tin (Sn), bismuth (Bi), and copper (Cu).

The element mappings for AC-4 (Fig. 6) provide growth of coarse metal oxide agglomerates in the heat-effected zone, coming along with an enrichment of silver on the contact surface. For AC-3 conditions (Fig. 7), the silver is agglomerated as well, while copper is depleted from the surface, and tin and bismuth build up a layer covering the contact surface. This tin-bismuth-oxide surface layer provides a comparatively low conductivity, and builds a barrier layer between the closed contacts. Therefore, this metal oxide surface layer can be considered root cause for the high temperature rise (Fig. 3) results even at reduced current.

In parallel to the temperature rise, the contact resistance per phase was measured during temperature rise tests as well. The influence of ambient temperature on contact resistance due to temperature dependent material properties was studied in [8].

The dependency of the temperature rise on arcing energies was analyzed based on the measured resistance values. As temperature rise is only a result of Joule heating due to contact resistance, and depending on device design, the impact of arcing and contact material surface layers has to be studied based on the resistance values. However, no correlation or trend of contact resistance compared to bounce or break arc energies alone could be found.

In a next step, the contact resistance per contactor phase was compared versus the quotient of average arcing energies per phase during make and break operation W_{break}/W_{make}. The result of this study is plotted in Fig. 8. As an example the resistance values per contactor phase at half of the endurance test – equals $n = 250{,}000$ for the contactor under AC-3 and $n = 5{,}000$ for the contactor under AC-4 test conditions – have been chosen.

Under AC-4 switching conditions, break arc energies are dominant compared to bounce arcs. Therefore, the typical arc energy ratio can be found as $W_{break}/W_{make} > 10$. In accordance to the temperature rise results under AC-4, also contact resistances are comparatively low, with an average of 2 mΩ and maxima from 2.5 – 3.2 mΩ.

For a ratio of $W_{break}/W_{make} < 1$, which equals to bounce arc energies during make operation being higher than or almost equal to break arc energies, relatively low contact resistances (2 – 3.5 mΩ) are observed as well. This arc energy situation is typical for AC-3 conditions.

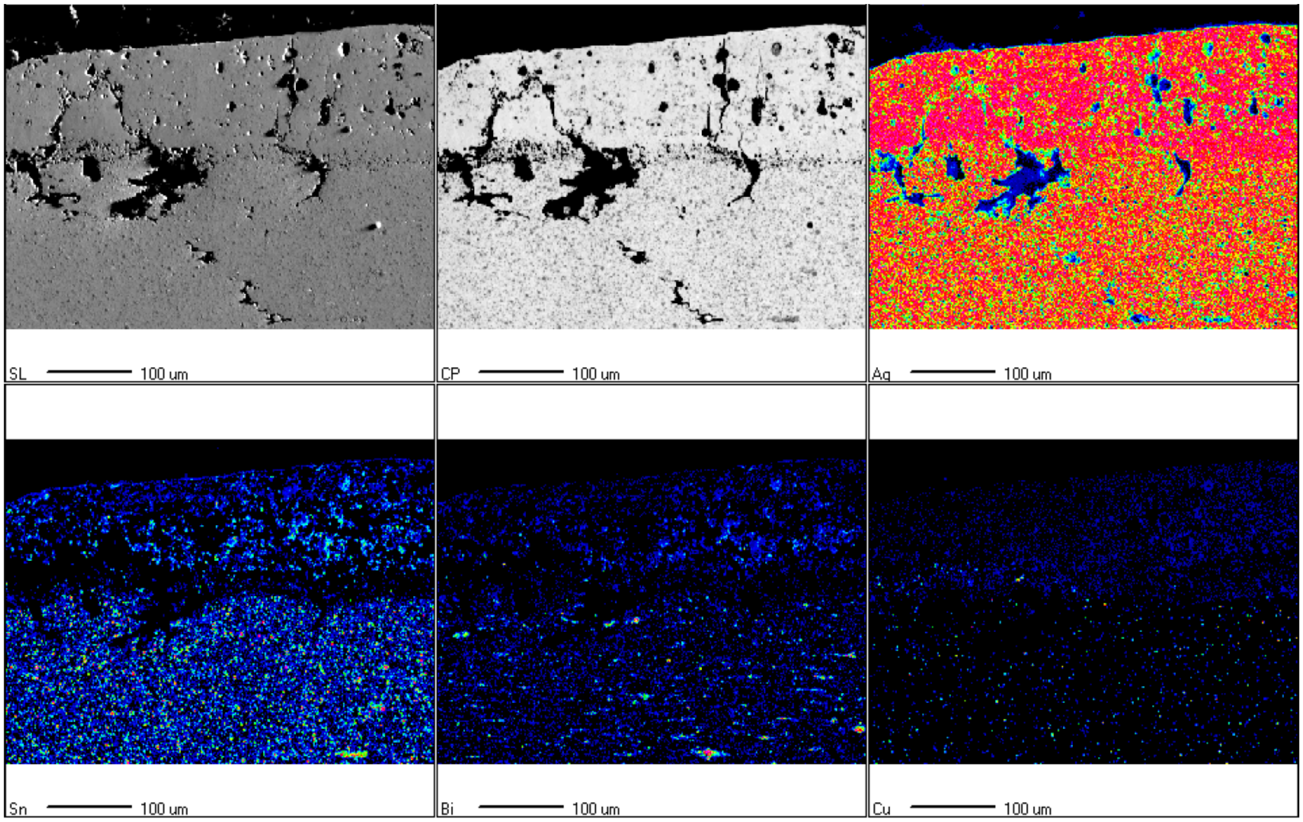

Fig. 6. EDX on cross section after AC-4 endurance test

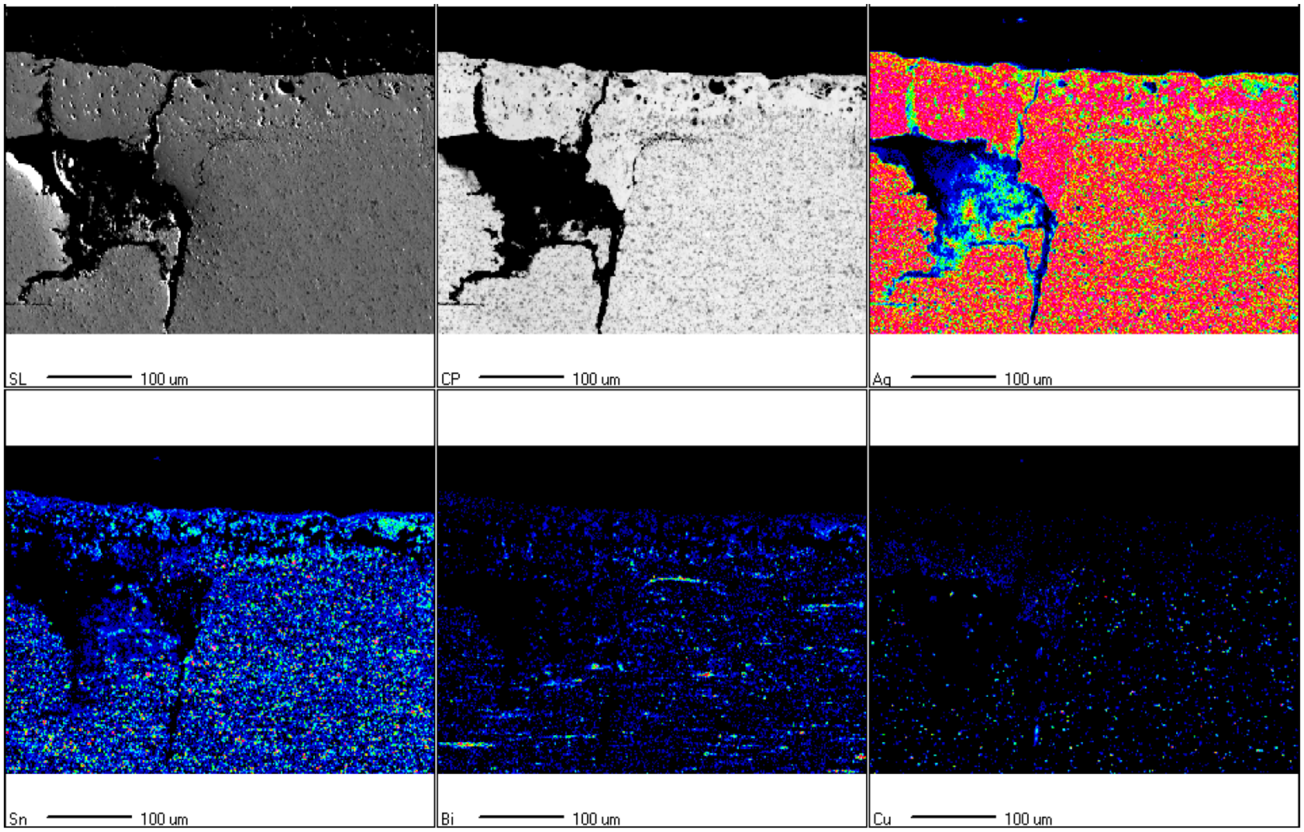

Fig. 7. EDX on cross section after AC-3 endurance test

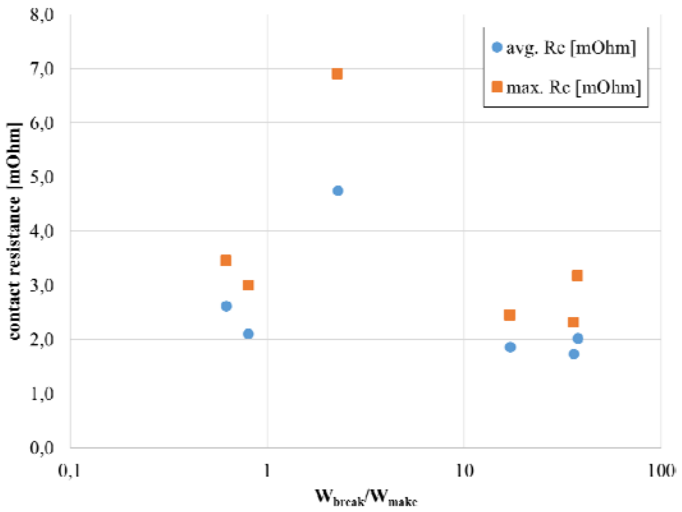

Fig. 8. Contact resistance in relation to switching arc energies

One out of the three phases of the contactor tested at AC-3 conditions provides a ratio W_{break}/W_{make} between 1 and 10. This ratio is due to synchronization effects. In our case phase L1 always was the first phase to close and bouncing appeared to be mostly a mechanical opening without arc, as no current was flowing due to ungrounded neutral, before the second phase closed as well. These boundary conditions almost lead to a break-only condition in the affected phase, resulting in the by far highest contact resistances, and limiting temperature rise test by the formation of a non-conductive tin-bismuth-oxide surface layer. This case is clearly shows the sensitivity of the system (switching device – contact material) regarding contact resistances. Therefore, even minor changes in device design need to be considered carefully on the results they may cause.

V. CONCLUSIONS

Endurance tests under AC-3 and AC-4 load have been performed with an 11 kW contactor, applying Ag/SnO_2 86/14 PMT3 as contact material. Special focus of the studies was the temperature rise and contact resistance evaluation after contact surfaces have been stressed by the different arcing modes.

Significant differences in contact resistance and temperature rise were observed. Contact resistance in a single phase were even double the values compared to others. The high contact resistances were explained by the formation of a low-conductive tin-bismuth-oxide surface layer under these specific boundary conditions.

The most important finding of this work is that this boundary condition can be described as an unfavorable ratio of W_{break}/W_{make} creating this non-conductive layer by arcing.

Further understanding of switching arc and contact material interactions and the reactions in the material can be seen as basis for development of new and improved contact materials.

REFERENCES

[1] F. Hauner, D. Jeannot, K. McNeilly, “Advanced AgSnO2 Contact Materials with High Total Oxide Content,” 21st International Conference on Electrical Contacts, Zurich, Switzerland, 2002

[2] T. Mützel, R. Niederreuther, “Contact Material Combinations for High Performance Switching Devices,” 58th IEEE Holm Conference on Electrical Contacts, Portland, OR, USA, 2012

[3] T. Mützel, P. Braumann, R. Niederreuther, “Temperature Rise Behavior of Ag/SnO2 Contact Materials for Contactor Application,” 55th IEEE Holm Conference on Electrical Contacts, Vancouver, BC, Canada, 2009

[4] T. Schöpf, F. Hauner, I. Hundt, “Effects of Different Loads on the Surface of Silver Metal Oxide Contacts for General-Purpose Relays,” 19th International Conference on Electrical Contacts, Nuremberg, Germany, 1998

[5] IEC60947-4-1:2009 Low-voltage switchgear and controlgear - Part 4-1: Contactors and motor-starters - Electromechanical contactors and motor-starters

[6] P. Braumann, H. Kolb, K.-H. Schröder, W. Weise, “Optimization of Ag/SnO2 Contact Material for Use in Contactors,“ 16th International Conference on Electrical Contacts, Loughborough, UK, 1992

[7] E. Hetzmannseder, W. Rieder, “The Influence of Bounce Parameters on the Make Erosion of Silver/ Metal-Oxide Contact Materials,” 39th IEEE Holm Conference on Electrical Contacts, Pittsburgh, PA, USA, 1993

[8] J. Schreiber, V. Behrens, T. Honig, M. Finkbeiner, „Contact Resistance and Overtemperature of new and pre-arced Power Engineering Contacts as a Function of Ambient Temperature and Contact Force,“ 27th International Conference on Electrical Contacts, Dresden, Germany, 2014