

Differences in Current Zero Behavior between Bipolar and Quadrupolar AMF Contacts

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ABSTRACT

AMF contacts are applied in vacuum circuit breakers to interrupt high short-circuit currents. A magnetic field parallel to the current flow in the arc column improves the breaking capacity by affecting the arc mode. In dependence of the design of the contacts this magnetic field can take different directions over the contact surface. In this paper measurements of bipolar and quadrupolar AMF contact systems are presented. For bipolar arrangements, the polarity of the field changes once and for quadrupolar arrangements twice. Due to different eddy current paths the residual magnetic field at current zero is significantly higher for the quadrupolar arrangement. The breaking capability of two contact systems was investigated, completed by measuring the post arc current.

1 INTRODUCTION

A vacuum interrupter consists of a fixed and a movable contact, vapor shields, and the vacuum vessel. If the short-circuit current exceeds the range of approximately 10 kA the arc will constrict due to its magnetic self field and thermal effects. The thermal stress on the contacts increases strongly and restricts the breaking capability. To overcome this problem two different contact designs have been known for higher short circuit currents:

The RMF-contact: The constriction of the arc is accepted, self-generated radial magnetic fields force the constricted arc to rotation, resulting in more even distribution of the thermal stress and to higher breaking capabilities.

The AMF contact: This contact type is designed to generate an axial magnetic field (AMF) by the short-circuit current. This field limits charge carrier movement perpendicular to the arc [4, 5]. This confinement leads to much lower power generation in the arc and keeps the diffuse arc mode up to higher current levels. Constriction associated with higher thermal stress is reduced. While for lower and medium breaking capacities the RMF contact prevails because of its lower costs, AMF contacts of various designs are

being increasingly developed for circuit-breakers with high breaking capabilities.

In this paper results of experiments with bipolar and quadrupolar AMF-contact systems with different vapor-shields are presented. Post-arc current and post-arc charge were observed in order to find correlations between post-arc current / post-arc charge, contact type and breaking capability [6].

2 POST-ARC CURRENT AND POST-ARC CHARGE

A vacuum circuit breaker interrupts the short circuit current in current zero. At this point the highly conductive plasma changes to a highly insulating state. The plasma feeds itself from the vaporized contact material. Driven by the transient recovery voltage (TRV) reappearing across the gap after polarity change at current zero, a small current of around some amperes caused by the residual charge can be measured for several microseconds. Fig. 1 shows a typical post-arc current pattern. In this paper the post-arc current peak and the post-arc charge are evaluated.

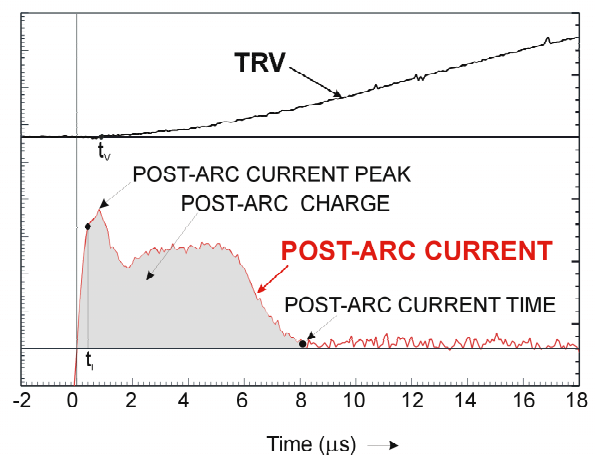


Fig. 1: Typical TRV and post-arc current pattern

This behavior after current zero can be explained with a simplified post-arc model [8]. Before and at current zero

the plasma between the electrodes is neutral. Activated through the special conditions in the cathode-spots electrons and ions both move toward the anode. At current zero the polarity of the electrodes changes. It is assumed that the ions due to their inertia keep their original speed ($\approx 10^4$ m/s [9], $\approx 8 \cdot 10^3$ m/s [10]) and direction for the first moment. While the post-arc current rises with opposite polarity, electrons become slower and finally their speed becomes zero [11]. At this moment t_i (fig. 1) the whole post-arc current is carried by the ions. It is

$$i = e \cdot A \cdot Z \cdot n_i \cdot v_i \quad (1)$$

with i = current, e = elementary charge, A = discharge area, Z = mean ion charge state (average 1.8), n_i = ion density, v_i = ion velocity

The post-arc current peak is in close neighborhood to this point. Therefore this current is a direct measure for the product $n_i \cdot v_i$.

Until t_i the electron and ion densities are equal, the voltage across the gap is zero (fig. 1). From this time on the electrons reverse and move to the new anode. In front of the new cathode a positive space charge sheath of thickness s grows and takes up the whole transient recovery voltage TRV. The post-arc current density j of the post-arc period beginning with t_i can be described by the following equation:

$$j = n_i \cdot Z \cdot e \cdot (v_i + ds/dt) \quad (2)$$

j - current density, n_i - ion density at the edge between sheath and neutral plasma, e - elementary charge, v_i - ion velocity, s - sheath thickness.

The first term is due to the directed ion motion with v_i from the old cathode towards the new cathode. With a ion velocity of approximately 10^4 m/s this term disappears after about $1 \mu\text{s}$ for a 1 cm gap. The second term ds/dt characterizes the expansion of the positive space charge sheath.

It can be shown that under certain simplifications the integral over the post-arc current (= post-arc charge) is a direct measure for the total residual charge present in the contact gap at the moment of current zero [10, 13]. Therefore both the post-arc current peak and the post-arc charge are a direct indication of the residual charge in the gap at current zero.

3 INVESTIGATED AMF CONTACT SYSTEMS

Two out of various basic principles of AMF-contact designs are the bipolar and the quadrupolar AMF-contact system. Fig. 2 shows the current path and the

generated magnetic field. The bipolar axial magnetic field is generated by a special coil construction behind the contact surfaces. The current path splits from the stem into two circular spokes and is divided into half-rings generating two magnetic fields with equal magnitude and opposite direction. [3]

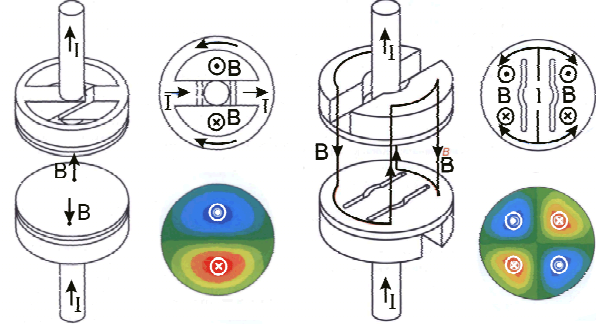


Fig. 2: Basic principle of bipolar AMF contact designs and magnetic flux density between contacts: Bipolar (left) and quadrupolar (right) [3]

In contrast to the bipolar and most unipolar AMF contact systems the quadrupolar magnetic field design shown here is not based on coil-shaped conductors but utilizes ferromagnetic flux concentrators ("pole shoes"). The magnetic circle and the slotted contact plate generate the axial magnetic field shown in fig. 2. The magnetic flux crosses the contact plates four times [3].

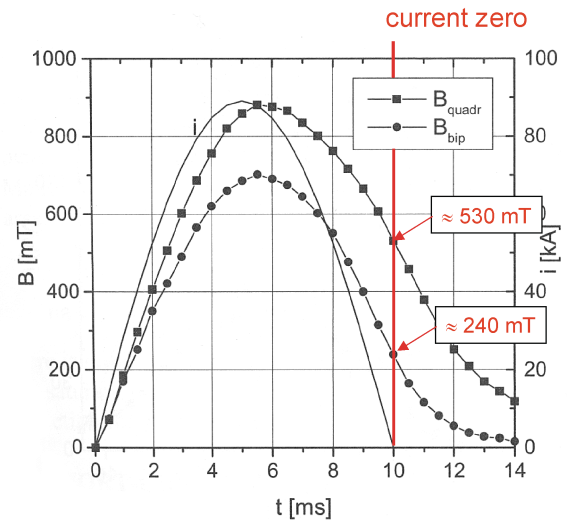


Fig. 3: Maximum value of the axial component of the magnetic flux density in the middle plain of the contact gap; gap distance 10 mm, current 63 kA RMS [7]

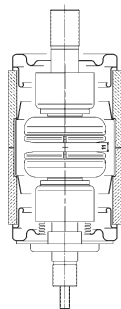
Both contact designs generate a different axial magnetic field. In fig. 3 the maximum value of the axial component of the flux density is shown. During the whole high-current phase and also after current zero the quadrupolar contact system generates a higher magnetic flux density. The phase shift between current and axial magnetic flux density is about 1 ms around the current

peak for both contact types. At current zero the residual flux density of the quadrupolar contacts is with 530 mT by a factor of 2.2 higher than that of the bipolar system. (240 mT). The damping time constant is also much higher for the quadrupolar contact system (3,5 ms) than for the bipolar contact system (1,7 ms) [7].

The residual AMF after current zero is caused by eddy currents, mainly in the contact plates. The main interest is to design a contact geometry where the generated axial magnetic field spreads the thermal stress from the vacuum arc over a contact plate area as evenly as possible [12]. With both the quadrupolar and the bipolar AMF contact system the effective area (areas of AMF ≥ 4 mT/kA [12]) is about 75% of the electrode area [7].

4 EXPERIMENTAL CONDITIONS AND RESULTS

The experiments were carried out with experimental vacuum interrupter tubes manufactured in an industrial process and equipped with the AMF contact systems described before. The main parameters are given in fig. 4.



Contact systems	Bipolar and quadrupolar AMF contact systems
Contact material	CuCr 75/25
Contact diameter	100 mm
Gap distance at current zero	11 mm
Voltage level	36 kV
50 Hz – RMS - Current	30, 40, 50, 60 kA
Arcing time	8-10 ms

Fig.4 : Experimental setup for the investigations

The electrical test circuit is a Weil-Dobke circuit that supplies a maximum 50 Hz current of 60 kA RMS and a peak of the transient recovery voltage of 160 kV.

The tubes were investigated with 50 Hz currents of 30, 40, 50 and 60 kA RMS. Each of the four test series consisted of 10 measurements with alternating polarity. The TRV-level was chosen according to 36 kV three-phase, with a frequency of 10 kHz and a first peak of 62 kV. Before each test series the contacts were conditioned with 10 times 10 kA arc current (without high-voltage TRV) and 10 times 100 kV (peak) voltage oscillation (without high-current). The pause between two successive interruption tests was more than 30 minutes.

The breaking capability and especially the behavior in the time range of microseconds around current zero were observed.

In fig. 5 the results of the switching experiments are summarized. Three types are differentiated: Successful

interruptions, re-ignitions during the first rising part of the TRV ($< 45 \mu\text{s}$), and re-ignitions after the first TRV peak ($> 45 \mu\text{s}$), named “late re-ignitions”. For the bipolar contact system, while up to 50 kA no failure occurred, two late re-ignitions out of 10 tests followed on 60 kA. The quadrupolar system showed already one failure (10%) at 50 kA, and 50% failure rate at 60 kA. Thus the system with quadrupolar contacts has a lower interruption limit.

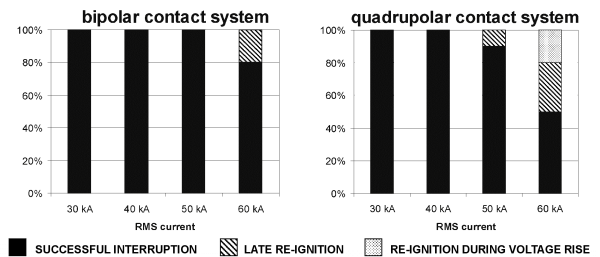


Fig. 5: Statistics of switching results for the bipolar and quadrupolar AMF contacts

Fig. 6 depicts post-arc current traces at 50 and 60 kA RMS from several individual measurements to demonstrate the scatter. Though both polarities were used, the results are plotted together in the same direction. A polarity influence could not be found.

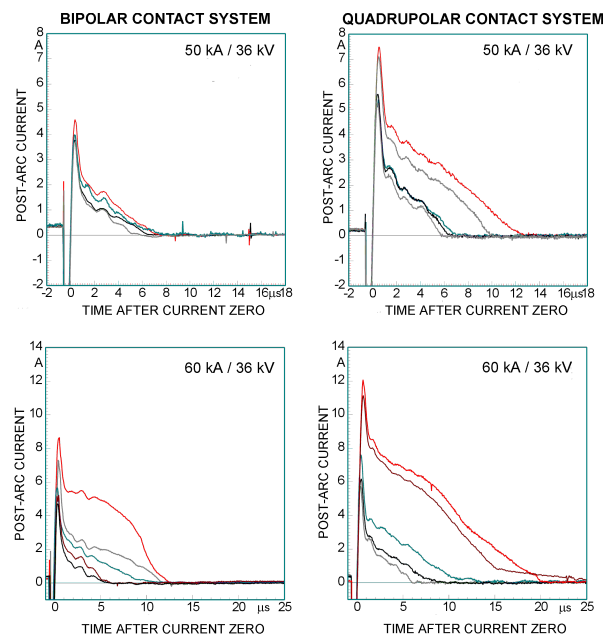


Fig. 6: Scatter of measured post-arc currents

A large scattering range is an indication that the limit of breaking capability is being reached [2]. Both for 50 and 60 kA the scatter in post-arc currents of the quadrupolar contact system is larger than for the bipolar contact system. Also the measured currents of the quadrupolar contact system reach a higher post-arc current peak, their duration is longer, and consequently their post-arc

charge is higher. These facts are underlined by fig. 7, where the characteristic quantities “post-arc current peak” and “post-arc charge” are summarized for all investigated arc currents between 30 and 60 kA. The quadrupolar system clearly exhibits higher current and charge values as well as larger scatter, the latter especially under 50 and 60 kA conditions. There is also a very clear correlation between failures and the post-arc peak and charge, respectively. Though the failure events always occur definitely after the visible post-arc currents have ceased, the cases of failures are always associated with the highest and longest post-arc currents prior to them.

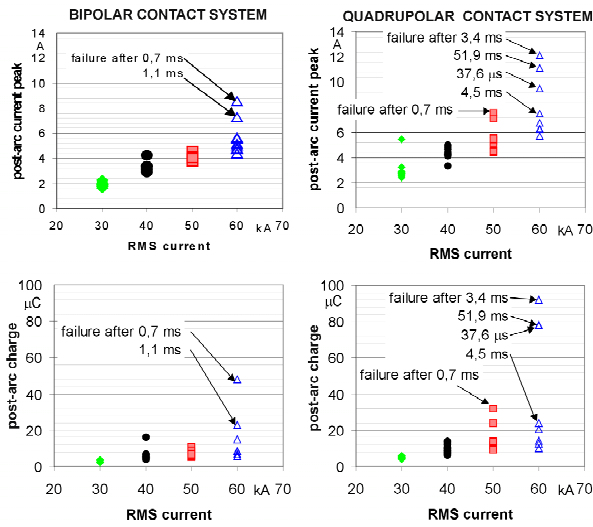


Fig. 7: Measured post-arc current peaks and post-arc charge, bipolar contact system (left) and quadrupolar contact system (right)

5 DISCUSSION

The post-arc current peaks and the post-arc charges differ significantly between the two investigated designs of AMF contacts. All results clearly indicate that the plasma density at and shortly after current zero is higher for the quadrupolar contacts under investigation than for the bipolar contacts.

From the fact that the re-ignitions always happened after the end of the post-arc period, which lasts less than 20 µs, a direct influence of the residual ionization on the re-ignition tendency, e.g. due to space charge enhanced field in front of the new cathode, should be excluded under the investigated conditions. However, there is still a clear correlation between post-arc current and failure tendency, as has been already shown before [6, 8]. The re-ignitions are likely to be caused by the ionization of metal vapor still present in the gap at a later time [15]. The metal vapor density and the density of ions (= ionized metal vapor) at current zero are expected to be strongly correlated. While the ionization is quickly removed due to recombination and by the flowing post-arc current, the metal vapor lasts longer and is still

supplied from boiling pools at the contact surfaces. Thus the correlation is logical.

Following this picture, the somewhat earlier failure of the quadrupolar contacts can be attributed to higher residual vapor density. The reason for the differences may lie on the one hand in differences of the arc shape and thermal stress on the contacts during the high-current arc phase. To clarify this measurements of the optical arc appearance would be necessary. A second reason could lie in the magnetic confinement of the arc plasma due to the axial magnetic field. In [14] it has been shown in a comparison between RMF spiral contacts and AMF contacts in the current range below 10 kA that the post-arc charge and ion density, respectively, is somewhat higher and decays more slowly for AMF contacts, despite the fact that the power dissipated in an AMF arc is much lower during the high-current period than in an RMF arc. Obviously under these conditions the “memory” of the arc gap does not last back to the high-current period where there are considerable differences in arc stress on the contacts. The higher residual ion concentration for the AMF contacts has been explained with plasma confinement by the AMF field, which due to eddy currents still exists when the current approaches zero. This explanation can also be transferred to AMF contacts with considerably different residual magnetic fields at current zero. The one with higher magnetic field confines the plasma – a mixture of neutral vapor, electrons and metal ions - longer within the contact gap when the current approaches zero, yielding higher plasma density at the moment of zero and thereafter. The consequence is a higher amplitude and longer duration of the post-arc current, but also a higher vapor density.

6 SUMMARY AND CONCLUSION

Two AMF contact designs, one with a bipolar, the other with a quadrupolar structure, have been compared in switching experiments. The second one yields a higher field magnitude, especially a considerably higher and more slowly decaying residual magnetic field at current zero.

The interruption capability of the bipolar design was higher, associated with lower post-arc currents. Though failures always occurred after the decay of post-arc current, the post-arc currents and charges, respectively, were always highest for the experiments that failed.

The differences between the two designs may be attributed to differences in metal vapor density after current zero. The post-arc current is an indication of the residual plasma and vapor densities, respectively. One of the reasons for the different behavior could lie in different plasma confinement due to the magnetic flux density at current zero. It is stronger for the quadrupolar contacts.

It should be mentioned that the different results between bipolar and quadrupolar contacts are rather specific to details of the designs under investigation, and they should not be generalized without caution.

7 REFERENCES

ISDEIV = Int. Symp. on Discharges and Electr. Insulation in Vacuum

- [1] M. Lindmayer: Medium to high current switching. In P. G. Slade (editor): *Electrical Contacts*. Marcel Dekker, New York 1999
- [2] B. Fenski: Verhalten von Axialmagnetfeldkontakten in Vakuumleistungsschaltern, Thesis, Techn. Univ. Braunschweig, Germany, 1998
- [3] H. Fink, M. Heimbach, W. Shang: Vakuum-schaltkammern mit Axialmagnetfeldkontakten für Mittelspannungsschalter. *ABB Technik* 1/2000
- [4] S. Yanabu, E. Kaneko, H. Okumura, T. Aiyoshi: Novel electrode structure of vacuum interrupter and its practical application, *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-100, No. 4, 1981, pp. 1966-1973
- [5] J.V.R. Heberlein, D.R. Porto: The interaction of vacuum arc ion currents with axial magnetic fields, *IEEE Trans. on Plasma Science*, Vol. PS-11, No. 3, 1983, pp. 152-159
- [6] M. Lindmayer, F. Unger-Weber: Events associated with the interruption of high voltage vacuum arcs. XIIIth ISDEIV, Paris 1988
- [7] H. Fink, M. Heimbach, W. Shang: Vacuum interrupters with axial magnetic field contacts based on bipolar and quadrupolar design, 19th ISDEIV 2000 Xi'an, p.375
- [8] B. Fenski, M.Lindmayer: Post-arc currents of vacuum interrupters with radial and axial magnetic field contacts – measurements and simulations. 19th Int. Conf. on Electric Contact Phenomena, Nürnberg 1998, VDE Fachberichte 51, 1998
- [9] C. Rusteberg: Bestimmung von Plasmaparametern in Vakuum-Hochstrombögen, Thesis, Techn. Univ. Braunschweig, Germany, 1993
- [10] G. Düning, M. Lindmayer: Energy of ions in vacuum arcs between axial and radial magnetic field contacts, ISDEIV 2000 Xi'an, p. 355
- [11] S.E.-Childs, A.N. Greenwood: A model for DC interruption in diffuse vacuum arcs, *IEEE Trans. PS-8*, p. 289, 1980
- [12] B. Fenski, M. Lindmayer, M. Heimbach, W. Shang: Characteristics of a vacuum switching contact based on bipolar axial magnetic field, ISDEIV 1990 Eindhoven, p. 459
- [13] G. Düning, M. Lindmayer: Plasma density decay of vacuum discharges after current zero, *IEEE Trans. Plasma Science* 27, pp. 923-929, 1998
- [14] G. Düning, M. Lindmayer: Energy and density of ions in vacuum arcs between axial and radial magnetic field contacts, *IEEE Trans. Plasma Science* 29, pp. 726-733, 2001
- [15] E. Schade, E. Dullni: The characteristic features of recovery of the breakdown strength of vacuum switching devices after Interruption of high currents, 19th ISDEIV 2000 Xi'an, p. 367