A New Contact Design Based on a Quadrupolar Axial Magnetic Field and its Characteristics

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Abstract

Axial magnetic field (AMF) contacts are applied within vacuum interrupters especially in case of high short-circuit current. In this paper a new AMF contact design based on a quadrupolar field arrangement and its characteristics are presented. In the first part the basic principle of the new contact design is introduced. This is followed by three-dimensional field simulations performed with the aid of a Finite-Element-program. The magnitude of the axial magnetic flux density, the phase-shift between current and magnetic flux density, and the current flow within the contact plate are investigated during arcing. The impact of quadrupolar AMF on the arc behaviour during the high current phase is analysed by high-speed films and pictures of the contact surface after arcing. The interruption performance of the principle has been validated by short-circuit tests up to 12 kV/63 kA.

1 Introduction

The constriction of vacuum arcs at high current levels depends on the contact material and the electrode principle. By applying a radial magnetic field (RMF), the constricted arc column is forced to move rapidly around the contact surface [1, 2]. Axial magnetic field (AMF) contacts within vacuum interrupters, however, prevent the vacuum arc from constriction due to the limited charge carrier movement perpendicular to the magnetic flux density and the magnetic field, respectively [3, 4]. The diffuse arc results in a reduced energy impact on the electrodes which is also indicated by the small and smooth arcing voltage. Therefore, AMF contacts provide an excellent short-circuit behaviour especially for high short-circuit currents.

Depending on the design the local axial field distribution is different. For single-pole arrangements the direction of the AMF is the same within the whole inter-electrode gap [3, 5, 6]. For multiple-pole arrangements the polarity of the field changes [7–9]. The main interest in designing AMF contact systems is to achieve an AMF distribution which evenly spreads the thermal stress of the vacuum arc on the whole contact surface. Additionally, the mechanical strength and the continuous current performance of the contact system have to be taken into consideration.

In most AMF contact designs [3, 5–7, 9] the magnetic field is generated by a coil construction behind the electrodes. Compared to RMF spiral contacts, where the current directly flows from the stems through the electrodes in closed position of the vacuum interrupter, the continuous current performance is reduced due to the increased resistance of the coil construction. The heat generated by the resistive losses can almost only be dissipated via the copper stems to the outside of the vacuum interrupter. The impact of radiation is very small.

In this paper a new AMF contact design is introduced which provides a quadrupolar AMF. The AMF is generated by a hybrid principle. The first contribution is produced by a magnetic circuit, the second one by slots incorporated into the electrodes. Both measures for generating the AMF do not disturb the direct current flow from the copper stems through the electrodes in closed position of the contact system. The continuous current performance is therefore comparable to RMF spiral contacts which is of vital importance for high continuous current applications.

2 Basic Principle

According to *Ampere*'s law the magnetic field surrounds the copper stem during current flow. By arranging four ferromagnetic pieces as displayed in **Fig. 1a**, a magnetic circuit is built up; the magnetic flux is guided as indicated by the arrow. The magnetic flux is forced to penetrate four times the plain between the ferromagnetic pieces and perpendicular to the current flow.

In case of separating the ferromagnetic pieces as shown in **Fig. 1b**, the magnetic flux has to cross the gap between the ferromagnetic pieces in axial direction four times. Due to the distance between the ferromagnetic pieces in axial direction and therefore the increased magnetic resistance of the magnetic circuit, a part of the magnetic flux does not penetrate the gap in axial direction. Depending on the magnetic resistances of the different circuits a specific part of the magnetic flux closes in azimuthal direction as indicated in Fig. 1b by the dashed arrows. Resulting from this phenomenon the value of the axial magnetic flux density decreases with increased gap distance.

Fig. 1c shows the principle of the proposed magnetic circuit applied to a contact system of a vacuum interrupter. After opening the electrodes in order to interrupt a current, the above described quadrupolar AMF forces the arc to adopt a diffuse mode. By incorporation of slots into the electrodes (**Fig. 1d**) a part of the current is prevented from flowing in direct way through the contact plate to reach its position for crossing the contact

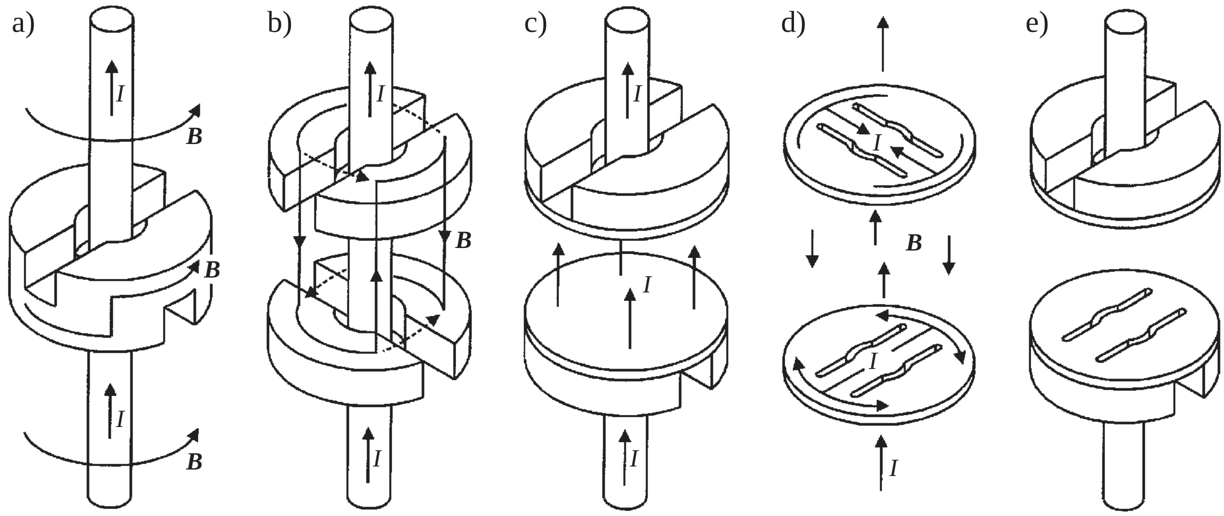

Fig. 1. Basic principle of the quadrupolar axial magnetic field contact
a) Arrangement of the ferromagnetic circuit
b) Ferromagnetic circuit in open position
c) Contact system without slots incorporated in the electrodes
d) Incorporated slots in the electrodes
e) Principle of the complete hybrid quadrupolar contact system

gap by means of the vacuum arc. Due to the forced current loops also a quadrupolar AMF is generated reinforcing the AMF provided by the magnetic circuit. **Fig. 1e** displays the principle of the complete hybrid quadrupolar contact system. A similar contact system without slots was investigated in [8]. In the following paragraphs the impact of the slots of this hybrid principle on the AMF performance is discussed. In closed position, the direct current flow from the copper stems through the electrodes results in a continuous current performance similar to RMF spiral electrodes. Compared to RMF spiral electrodes, additional losses are evoked by the eddy currents and the hysteresis within the ferromagnetic pieces.

3 Theoretical Investigations on the AMF Performance

The simulations are carried out by means of a commercial 3D Finite-Element-Method (FEM) software program. For the simulations a plasma with a homogeneous conductivity fills the inter-electrode gap. The conductivity of the plasma is assumed to be $\sigma = 3 \cdot 10^3$ S/m. The value of the plasma conductivity influences the simulation very weakly since this value is much smaller compared to the conductivity of the copper stems ($\sigma = 56 \cdot 10^6$ S/m) and the copper chromium contact plates (75 wt-% copper, 25 wt-% chromium, CuCr 75/25, $\sigma = 32 \cdot 10^6$ S/m). The assumption of a homogeneous conductivity of the vacuum arc resulting in a nearly even current distribution within the plasma does not exactly describe the physical properties of the plasma. The experimental results presented within the next chapter, however, show that this assumption is a good basis during the design phase. The simulations are carried out transiently taking into consideration the non-linear magnetising curve of the ferromagnetic material. The initial permeability is assumed to $\mu_{ra} \approx 300$, the saturation polarisation to $J_s = 2.05$ T.

Fig. 2 displays a typical magnetic flux-density distribution of the quadrupolar contact system in the middle of the contact gap. Here and in all following simulation results a contact diameter of 100 mm is assumed. Additionally, the results are related to a gap distance between the electrodes of 10 mm and a thickness of the contact plate of 4 mm. These values are typical for a 12 kV/63 kA application. The thickness of the contact plate plays an important role in dimensioning the contact design. On the one hand an increased thickness results in a weakening of the AMF, since a bigger part of the magnetic flux does not penetrate the electrodes and the inter-electrode gap but will flow through the gap between the two ferromagnetic materials behind one electrode. On the other hand an increased thickness provides a bigger warm capacity during, after, and in between the short-circuit current operations.

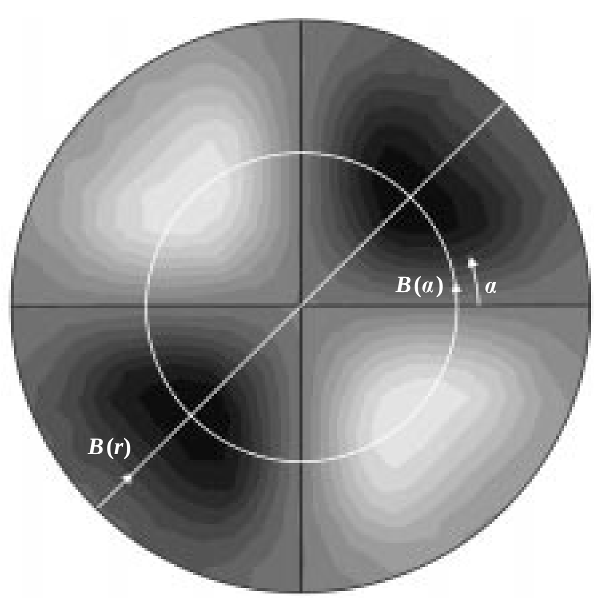

Fig. 2. Typical distribution of the axial magnetic field in the middle of the contact gap

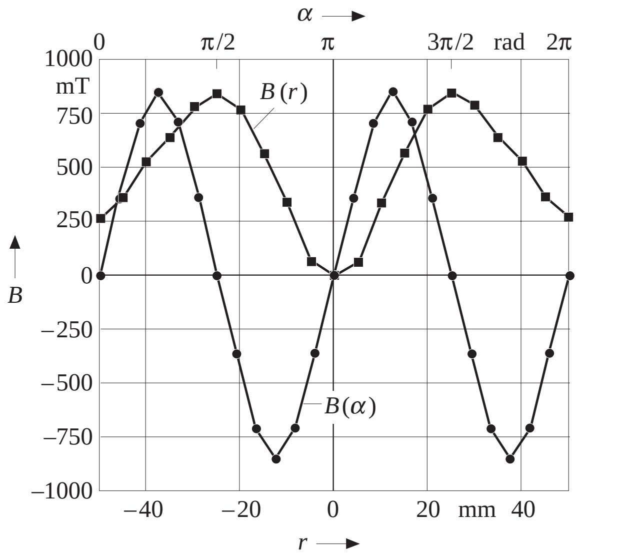

Fig. 3. Axial magnetic flux density in the middle plain of the contact gap dependent on radius and azimuthal angle at current peak; the values displayed are taken along the lines as defined in Fig. 2; gap distance: 10 mm; current: 63 kA (rms), 50 Hz, symmetrical

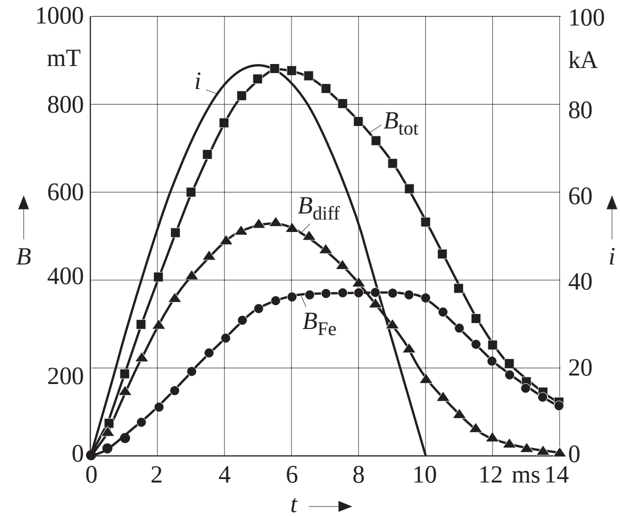

Fig. 4. Maximum value of the axial component of the magnetic flux density in the middle plain of the contact gap; gap distance: 10 mm; current: 63 kA (rms), 50 Hz, symmetrical

There are four areas with the same AMF distribution (by amount), i. e. four areas with equal conditions are given. In the cross symmetrically dividing the four areas an axial magnetic field does not exist. At the contact edge, however, a comparatively high axial magnetic field exists, i. e. the percentage of the area where the axial magnetic flux density is bigger than a certain amount is relatively high.

Fig. 3 displays the distribution of the axial component of the magnetic flux density in radial and azimuthal direction at current maximum of a 63-kA (rms)/50-Hz sine half cycle. The values displayed are taken along the lines as defined in Fig. 2. The result underlines that four areas with equal conditions are given by the investigated contact system. The maximum value of the magnetic flux density is about 850 mT. At the contact edge the axial magnetic flux density has still a value of about 270 mT. One can recognise that the value of the axial component of the magnetic flux density rises quickly after crossing the lines with a magnetic flux density of zero.

Beside the amount of the axial magnetic flux density and its local distribution, the shape of the axial magnetic flux density dependent on time is of major interest. During the high-current phase eddy currents mainly flowing within the contact plates and the ferromagnetic pieces cause both a reduction of the maximum axial magnetic flux density and a phase shift between current and axial magnetic flux density. After current zero, when the transient recovery voltage appears over the contacts, the residual magnetic field may confine charge-carriers inside the gap and therefore delays their diffusion processes. The maximum value of the axial component of the magnetic flux density in the middle plain of the gap during one 63-kA (rms)/50-Hz sine half cycle is shown in **Fig. 4**. It is assumed that the vacuum interrupter clears the current at current zero. The magnetic flux density is also shown within the first 4 ms after current zero in order to investigate the decay of the magnetic flux density mainly influenced by the eddy currents. In addition to the axial component of the magnetic flux density B_{tot} generated by the complete hybrid contact system as displayed in Fig. 1e, the axial magnetic flux density B_{Fe} provided by the contact system without slots in the contact plate according to Fig. 1c is presented. The curve denoted B_{diff} shows the axial magnetic flux density due to the implemented slots which is given by the difference of the axial magnetic field flux density with and without slots.

In the vicinity of the current peak the phase shift between the current and the axial magnetic flux density B_{tot} is about 0.7 ms. In the second part of the sine half wave, however, the phase shift increases. At current zero there is still a maximum residual axial magnetic flux density of about 530 mT. After current zero this magnetic flux density decays with an initial time constant of about 3.5 ms. The rise of the phase shift in the second half of the current sine half cycle is mainly influenced by the ferromagnetic circuit. One can clearly recognise that the part of the axial magnetic flux density introduced by the slots is nearly in phase with the current. This results from the fact that the slots reduce also the eddy currents within the contact plate as discussed later. The part of the axial magnetic flux density generated by the ferromagnetic circuit, however, provides a stronger phase shift due to the deeply saturated ferromagnetic material in the vicinity of the current peak and the eddy currents within the ferromagnetic pieces and the contact plates. After about 8 ms this part becomes dominant and therefore the phase shift generated by the complete hybrid contact system rises. A reduction of the eddy currents and therefore a reduction of the phase shift and residual AMF after current zero can be easily achieved by laminating the ferromagnetic pieces. Since in this case the junctions between the plates are not well defined this lamination has not been a subject of the theoretical investigations.

The current density in the contact plate at current maximum is shown in **Fig. 5**. The current coming from the copper stem behind the contact plate equally divides into the two directions given by the slots. The magnetic field generated by this component is responsible for the

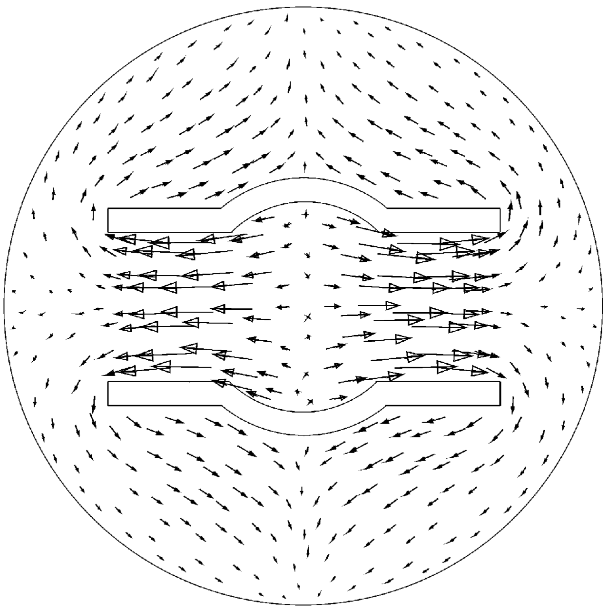

Fig. 5. Current distribution within the contact plate at current peak

increase of the magnetic flux density resulting from the magnetic circuit. Due to the high value of the current and the small derivation of the magnetic flux density in the surroundings of current peak the current density within the contact plate does not show strong indications of eddy currents. The current flows through the contact plate in order to provide the vacuum arc with a nearly even current density.

Fig. 6 displays the current density within the contact surface at current zero. The eddy currents try to reinforce the magnetic flux density and therefore initiate the residual magnetic flux density after current zero (Fig. 4). Compared to Fig. 5 the maximum of the current density within the contact plate is reduced by more than 70 % (different scale of the arrows between Fig. 5 and Fig. 6).

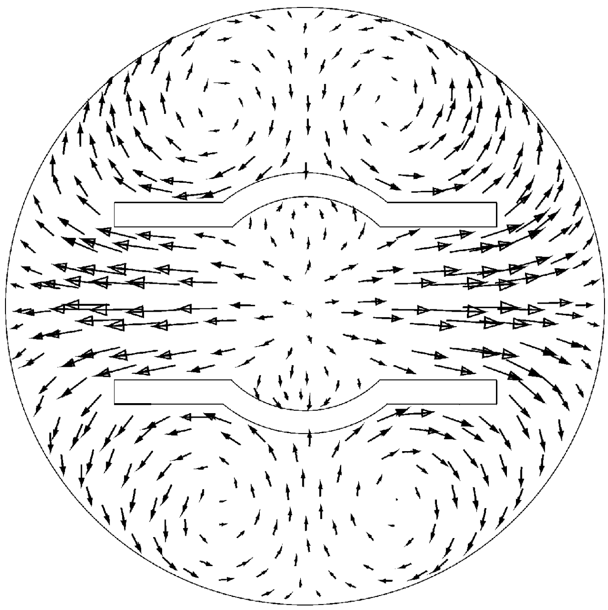

Fig. 6. Current distribution within the contact plate at current zero

Unlike Fig. 5 one can recognise four centres of eddy currents evoked by the four poles of the magnetic flux density. This phenomenon is responsible for the reduction of eddy currents by the quadrupolar principle itself, since compared to single-pole AMF contact systems the area surrounded by the eddy currents is divided into four areas which strongly reduces the losses. Additionally, due to the slots within the contact plate the four areas surrounded by the eddy currents are much smaller compared to one fourth of the contact surface in case of a non-slotted contact plate. Hence, the impact of the slots on the axial magnetic flux density is twofold: the reinforcing of the AMF by the forced current loop and the reduction of eddy currents within the contact plate. Nearby the four eddy current centres the most significant eddy currents flow between the slots into the outer direction. Most parts of these eddy currents surround the magnetic flux guided within the ferromagnetic pieces behind the contact plate (Fig. 1c).

4 Short-Circuit Tests, High-Speed Films, and Investigation of Contact Surfaces after Arcing

The interruption capability of the quadrupolar contact design has been tested at the high-power laboratory. The three-phase, direct short-circuit tests prove the interruption capability of the new hybrid contact system up to 12 kV/63 kA. The dimensions of the contact system are similar to the above discussed one. The tests were performed with symmetrical and asymmetrical (incl. 40 % DC component) currents according to IEC 60056, TD4 and TD5 [10]. In all short-circuit tests the recorded arcing voltage showed a smooth and stable behaviour with values in the range of 60 V. This behaviour indicates that the vacuum arc is forced to stay in a diffuse mode even in the surroundings of the current peak.

A picture of a vacuum arc in the vicinity of the current peak of a 31.5-kA (rms) / 50-Hz sine half wave is shown in **Fig. 7**. The picture reveals that the diameter of the vacuum arc becomes smaller in the vicinity of the anode. This phenomenon is typical for an AMF contact and indicates the beginning of the arc constriction at the anode limiting the interruption performance of the contact system. Nevertheless, the vacuum arc uses a big part of the contact surface. In many film-sequences it has been observed that the vacuum arc starts at different positions with the initial arcing depending on the last mechanical contact. After 1 ms to 3 ms the arc evenly

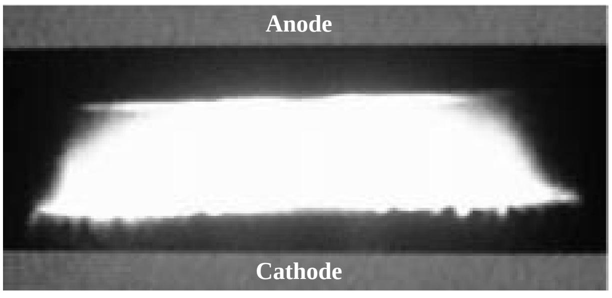

Fig. 7. Picture of a 31.5-kA (rms) vacuum arc during the influence of a quadrupolar axial magnetic field at current peak

Fig. 8. Contact surface after arcing up to 63 kA (rms)

spreads on the complete contact surface. At that time every pole of the quadrupolar contact system is filled with plasma.

This is also underlined by the investigation of the stress contours of contact plates after arcing. **Fig. 8** shows the surface of quadrupolar contact plate after 20 times 12 kV/63 kA three-phase short-circuit operations. The quite smooth melted thin layer of the contact surface indicates that the contact system has not yet reached its life-time. A comparison of the stress contours with the distribution of the axial magnetic flux density as displayed in Fig. 2 reveals that the vacuum arc follows the axial magnetic flux density. The stress contours after arcing allow to estimate a relative value of the axial magnetic flux density related to the contact area intensely used by the diffuse arc. This contact area is called the "effective area" which can be estimated as part of the contact surface where the relative magnetic flux density is higher than 4 mT/kA. This value is important during the design phase of a contact system and allows to reduce the number of short-circuit tests drastically. For the quadrupolar contact design as investigated in Fig. 3 the part of the effective area is in range of about 70 % of the whole contact surface. This value is quite similar to the bipolar design introduced in former publications [9].

5 Conclusions

A new hybrid contact design with a quadrupolar AMF arrangement has been introduced and discussed. The contact design provides four areas with the same axial magnetic flux density distribution (by amount), i. e. four areas with equal conditions are given. High-speed pictures showed that after the initial arc the vacuum arc adopts a diffuse mode during the whole high-current phase, indicating an appropriate amount and distribution of the magnetic flux density. The investigation of the stress contours on the electrodes after arcing reveals an effective area intensely used by the vacuum arc of about 70 % of the electrode surface which is related to a magnetic flux density higher than 4 mT/kA. The interruption performance of the contact system has been validated up to 12 kV/63 kA.

Due to the application of a magnetic circuit, which is reinforced by slots within the contact plate, this quadrupolar contact provides nearly the advantages of an AMF contact design regarding short-circuit interruption performance and a continuous current performance comparable to RMF spiral contacts.

6 List of Symbols and Abbreviations

6.1 Symbols

B_{diff}	part of axial magnetic flux density resulting from slots
B_{Fe}	axial magnetic flux density resulting from magnetic circuit
B_{tot}	total axial magnetic flux density
J_s	magnetic saturation polarisation
μ_{ra}	initial permeability
σ	conductivity

6.2 Abbreviations

AMF	axial magnetic field
DC	direct current
FEM	Finite-Element method
IEC	International Electrotechnical Commission
RMF	radial magnetic field
rms	root mean square
TD4	test duty 4
TD5	test duty 5
wt	weight
3D	three-dimensional

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