

Magnetic Control Of High Current Vacuum Arcs With The Aid Of an Axial Magnetic Field – A Review

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Abstract - This paper reviews the most important topics related to the control of HCVA with the aid of AMF: the main experimental findings, explanations and theories and the effect of AMF non-uniformity. The state of the art AMF contact systems for commercial vacuum interrupters are also presented.

I. INTRODUCTION

The application of an axial magnetic field is a well known method used to enhance the performance of gas discharge devices [1]. However, the application of AMF to a vacuum arc was first investigated only in 1967 [2]. Since then substantial progress has been achieved in both the fundamental understanding of the phenomena and the development of vacuum interrupters (VI) using AMF for arc control. This paper reviews the historical development and current state of the phenomena and related technology.

II. HIGH CURRENT VACUUM ARC UNDER UNIFORM AMF – MAIN EXPERIMENTAL RESULTS

In 1967 Ito and Okura presented the very first report related to the application of AMF for the control of a high current vacuum arc [2]. In their synthetic test they discovered a remarkable (50-100%) increase in the VI interrupting capacity.

In 1972 Kimblin published a more detailed study of the phenomena [3]. This study revealed a set of unique features that made AMF a potentially useful tool for vacuum arc control: the reduction of arc voltage and shield current by means of AMF application, arc stabilization and the hampering of the formation of an anode spot (Fig.1).

The investigators [4-8, 10] dealing with HCVA under AMF in the 70-s and early 80-s proved these features in different experimental conditions. Additionally, the coincidence of arc voltage with the voltage of a single cathode spot at high AMF [6] (Fig. 2), suppression of CS mobility by AMF [6, 10] and arc noise [7] were discovered.

Another important effect of AMF, its ability to prevent cathode spots from entering the lateral surface on relatively long arcs ($h \geq 4\text{mm}$), was discovered in 1998 [27] (Fig.4 a, b).

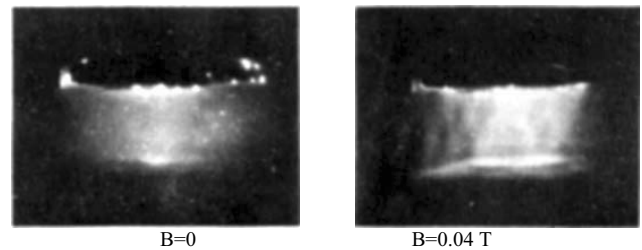
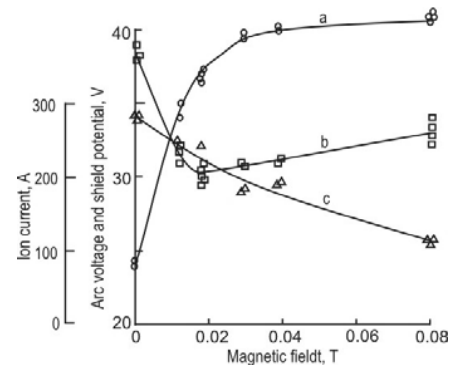


Fig.1 Pioneer U-B dependency measured by Kimblin (4.2kA DC, contact gap 1.9cm) and changing arc appearance with AMF application (at 3kA DC, contact gap 2.8cm). Electrode diameter 70mm, CuBi contacts. a – floating shield potential, b – arc voltage, c – ion current.

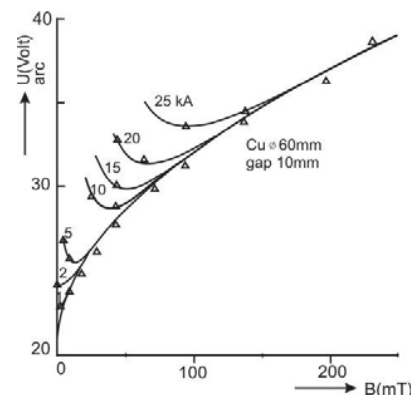


Fig.2 U-B dependencies measured by Gundlach

It is interesting to note that this assumption could be derived from earlier observations (compare for example, arc

appearance with and without AMF registered by Kimblin presented in Fig. 1), but it took quite some time to realise the importance of this effect.

Another finding of the aforementioned study was the “effect of normal current density”, i.e. the tendency of vacuum arc to occupy only a fraction of the cathode surface under strong AMF, in such a way that the average current density turns out to be dependent only on AMF induction, contact material and contact gap and not dependent on current (Fig. 4c). This result was confirmed in [35] for a wider current range.

The study [27] also revealed that in a relatively short arc ($h \leq 0.2\text{cm}$) AMF has the ability to destroy “cathode spot group formation” – a destructive effect discovered in [26]. This result was indirectly confirmed by Taylor [45] who found out that the transition time required to diffuse an arc after the initial contact separation decreases with the increase of AMF [45]. It seems that this result follows naturally from the above mentioned ability of AMF. At the initial stage after contact separation AMF is suppressed by eddy currents and cannot prevent cathode spot formation. At the same time AMF recovers faster for contact with a higher B/I ratio, providing earlier destruction of the group of the cathode spots and transition to the diffuse arc.

The observed behaviour of cathode spots was qualitatively explained in [27] on the basis of the interaction of the cathode spot with the magnetized secondary plasma.

Measurements of arc voltages versus AMF induction at higher current densities conducted in [35] revealed the presence of three sections in this dependency rather than two. Similar experimental results (that, however, had not been discussed) were obtained by Yanabu and his co-workers [22] (Fig.3).

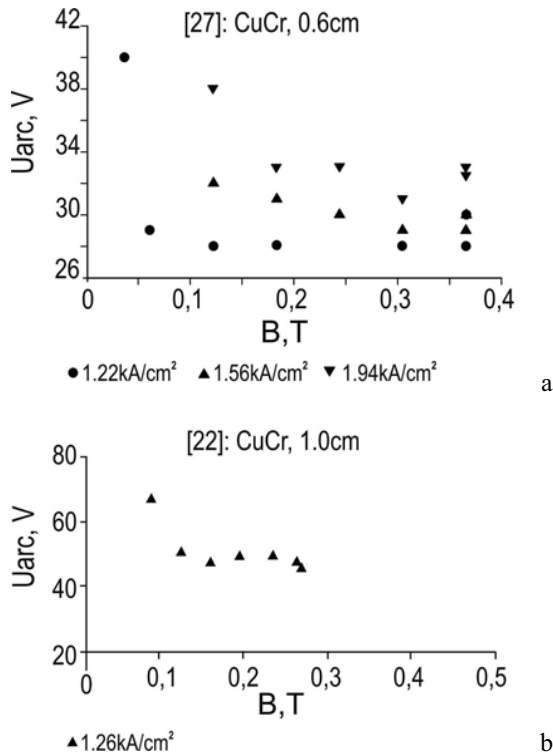


Fig.3 Independence of arc voltage from AMF induction within a wide range ($B_1 < B < B_2$) at high current densities

Each section is characterised by the particular appearance of the cathode spots and arc voltage (Fig. 4)

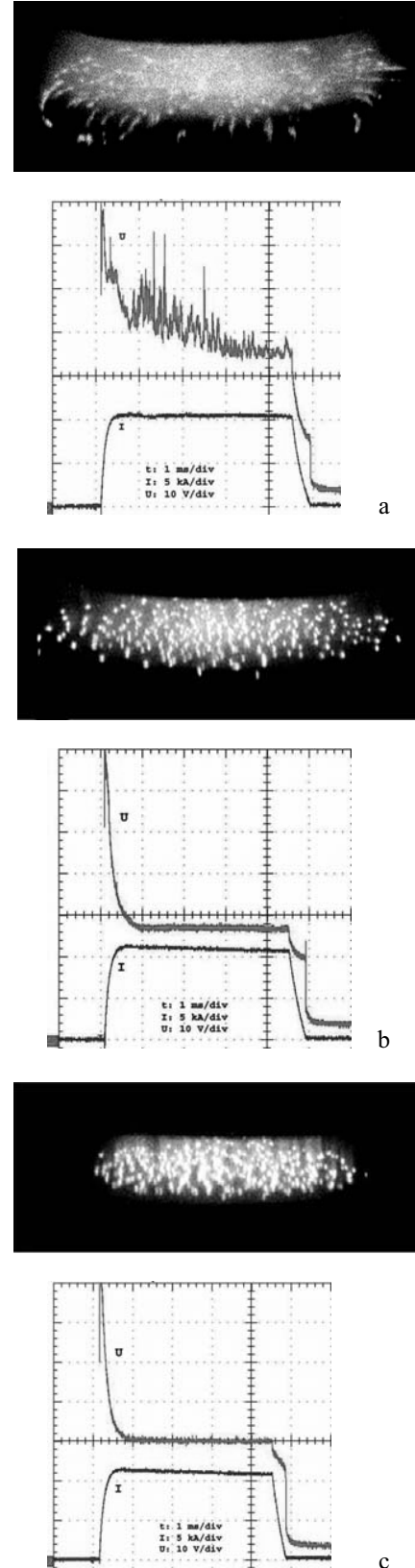


Fig.4 Cathode appearance in weak ($B < B_1$) (a), intermediate ($B_1 < B < B_2$) (b) and strong ($B > B_2$) AMF (c)

The first section occurs when AMF induction is below the characteristic value B_1 that for CuCr contacts can be approximated on the basis of experiments conducted in [35] as follows:

$$B_1 = 0.1h^{0.3} J \quad (1)$$

where J – average current density (kA/cm²), h – contact gap (cm), B_1 in T.

In case of a relatively long arc ($h \geq 0.4$ cm) this section is characterized by a high and unstable arc voltage with a lot of CS located on the lateral surface (Fig. 3a). When the contact gap is less than 2mm the arc voltage is stable, but high.

The second section appears when AMF induction B fits the equation $B_1 < B < B_2$, where B_2 – is the characteristic value at which arc voltage starts to grow. On the basis of experimental data presented in [35] one can derive the following relationship between average current density J (kA/cm²) and B_2 (T) for CuCr contacts:

$$J = \frac{U_{cs}(B_2, h) - 18.1}{12.1h} \quad (2)$$

Where $U_{cs}(B_2, h)$ is the arc voltage of a single cathode spot at a given AMF induction B and contact gap h (cm):

$$U_{cs} = 17 + (7.7\sqrt{B} + 0.47) \ln(20h) \quad (3)$$

The second section is characterized by a low and stable arc voltage. Cathode spots occupy the entire cathode surface and virtually none of them are located on the lateral surface (Fig.3b).

The third section appears when AMF induction exceeds B_2 . In this case the arc voltage is higher than for the second section and it is close to the arc voltage of a single cathode spot. Cathode spots cannot occupy the entire cathode surface (Fig.4c). The authors of [35] claim that detachment of the cathode spots from the contact edge appears when AMF induction equals B_2 (Fig.5). This means that the equation (2) defines the normal current density at a given AMF induction and contact gap.

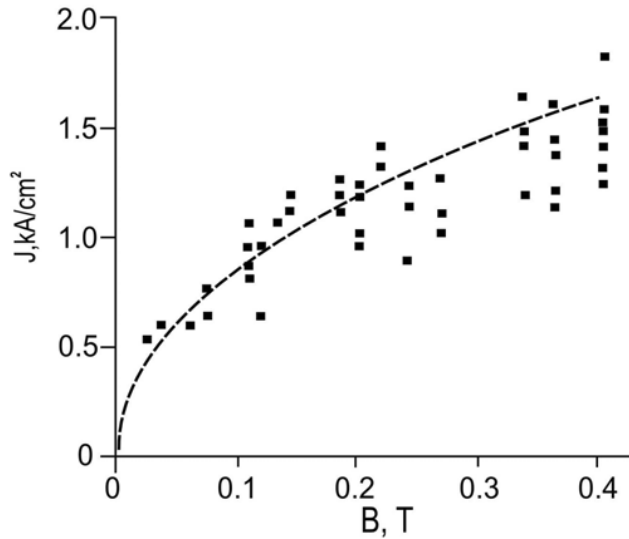


Fig.5 Comparison of induction corresponding to the detachment of the cathode spots from the electrode edge (dots) with B_2 calculated on the basis of equations (2) and (3) (dash line)

IV. HCVA UNDER UNIFORM AMF – MODELS AND THEORIES

Kimblin attributed his experimental findings (reduction of the arc voltage and shield current) to plasma confinement giving rise to an increase in ion concentration in front of the anode, following a reduction in the positive anode drop. Though the latter assumption does not fit with the modern standpoint related to voltage distribution in stable vacuum arc, all other assumptions have survived until now, contributing substantially to the modern vision on the effect of AMF.

While Kimblin's explanation of the initial decrease of arc voltage at AMF application was not disputed for some time, Gundlach [6] was the first who attributed the observed growth of arc voltage in strong AMF to the separation and constriction of arc channels initiated from individual cathode spots. This idea was later developed by Nemchinsky [16] and Keidar and Schulman [34], [40]. Though the ability of AMF to squeeze a cathode jet is not in doubt the total independence of the cathode jets in strong AMF seems doubtful. At the very least it appears to contradict the recently discovered phenomena of "normal current density".

Boxman [11], [12] offered a model of vacuum arc column, demonstrating that the application of AMF may suppress natural arc constriction. Though he did not directly attribute this result to the decrease of arc voltage, one could expect that the suppression of constriction could reduce voltage across the arc column. Keidar and Schulman [34], [40] used a similar model to explain this decrease. Nemchinsky [16] offered a different explanation attributing the initial decrease of arc voltage to the increase of plasma conductivity at AMF application. These models were based on the assumption of an even distribution of the current on the cathode within a certain area independent of AMF. At the same time recent experiments revealed a substantial dependency of the shape and size of the cathode root on AMF [35]. Though in some cases [16], [40] an excellent correspondence with the particular experimental results was reported, the application of a boundary condition independent on AMF induction for the cathode seems incorrect. Shkol'nik offered a non-stationary qualitative model to describe the behaviour of free burning HCVA in [48]. In the reviewer's opinion the model presented below, with some modifications, describes adequately the behaviour of a vacuum arc under weak AMF ($B < B_1$). Fig. 6 presents the basics of the modified model.

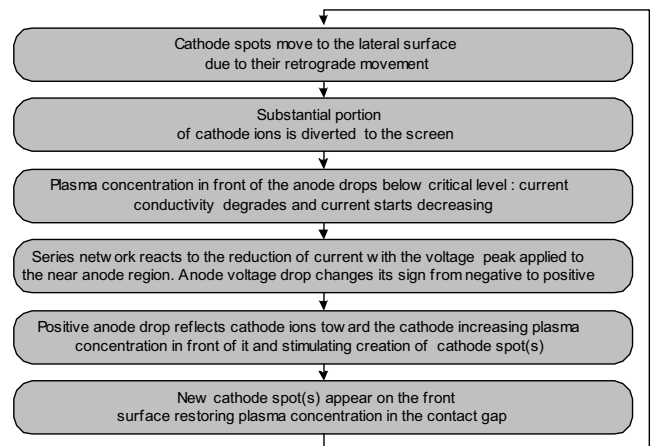


Fig. 6 Cyclic behaviour of the HCVA in weak AMF

As one can see this process describes the qualitatively well observed instability of HCVA in weak AMF including the appearance of high voltage peaks (up to a few dozen volts), followed by prolonged (by order of a hundred microseconds) sags (refer for example to Fig. 4a). On the basis of this model one could expect a steady increase in the arc voltage with the decrease of AMF (in addition to the appearance of voltage peaks) due to the reduction of negative anode voltage drop (resulting from the broken ratio between the chaotic electron current and discharge current). It seems, however, that the reduction of anode voltage drop (expected to be $\sim 1.5kTe$) cannot explain solely the observed increase in the steady arc voltage with AMF reduction. Another reason for the aforementioned increase may be associated with the decrease of conductivity in plasma with high drift velocity of the electrons [50]. Discharge constriction discussed in a number of papers [11], [40] may also play a role, though experimental observations made by Harris [51] do not support evidence of the constriction.

In the second section AMF induction is high enough ($B_1 < B$) that the combined effect of electrode edge and AMF is sufficient to hold CS on the front cathode surface. At the same time it is not high enough to prevent CS from occupying the entire cathode. As a result the most favourable regime of arc existence is established. On the one hand ion losses are negligible as virtually all CS are located on the front surface (an additional positive effect is provided due to narrowing of the cathode jets). Therefore, ion concentration in front of the anode is sufficient to ensure the chaotic electron current density is substantially above the discharge current density, providing a negative anode voltage drop and stable arc. On the other hand discharge is uniformly spread over the entire cathode surface. As a result the arc voltage is low and the electrodes are heated evenly.

In the third section ($B > B_2$) CS cannot occupy the entire cathode surface due to the effect of normal current density. Though the arc is stable due to the same reasons as given in the second section, the current density and, consequently, arc voltage are higher. Moreover, only a fraction of the electrode surface is effectively used.

On the basis of the above review one can state that we are still missing a thorough quantitative model of HCVA subjected to AMF. At the same time, it appears that the non-stationary arc model based on the CS dynamics represents a fruitful start towards understanding the phenomena.

III. HCVA UNDER NON-UNIFORM AMF

There exists a great practical interest in non-uniform AMF as contact systems of commercial VI generally generate non-uniform AMF.

Yanabu and his co-workers [7] were the first who developed commercial VI based on AMF.

However, the first report related to the effect of AMF non-uniformity on the appearance of a vacuum arc came from Kurosawa et al [9], who discovered that in multi-pole VI a vacuum arc tends to establish a number of columns corresponding to the number of poles (local AMF peaks).

Shellekens [19], [20] found out that in VI with non-uniform AMF vacuum arcs tend to concentrate in the areas with strong AMF under particular conditions. This finding was later confirmed by other investigators in different experimental conditions [28, 30, 32]. Bestel [25] discovered a correlation

between the interrupting capacity of VI and the shape of its AMF. He found out that it is preferable to have better distributed AMF. Fink et al [28] and Bestel et al [31] used the concept of “effective area” in order to judge the effectiveness of AMF configuration. At the same time their approach to the determination of AMF was different. Fink considered that an arc tends to occupy an area with AMF exceeding $4mT/kA$, while Bestel used the range $15-125mT$ as an “effective area” reference. Homma et al [32] on the basis of the Nemchinsky model [16] proposed that an ideal AMF profile is achieved through the linear growth of induction from the centre to the contact periphery. He also demonstrated that a contact system with more evenly distributed AMF produces a better interrupting performance. Glinkowski [29] offered an approach to the generation of optimum AMF distribution that, however, did not evolve into practical recommendations.

The authors of [47], [49] experimenting with different AMF shapes, reported that CS may move either into the area with strong or weak AMF depending on the particular AMF configuration and current. They explained this peculiar behaviour on the basis of the Steinbeck principle, postulating that an arc tends to arrange itself in such a way that the lowest possible arc voltage is established. On this base they found out that the optimum AMF configuration is represented with a “magnetic barrier” providing substantial AMF induction at the electrode edge and the lowest possible induction in the central region. This assumption had been experimentally proven by the measurements of the cathode current density for electrode systems utilizing a magnetic barrier (Fig.7).

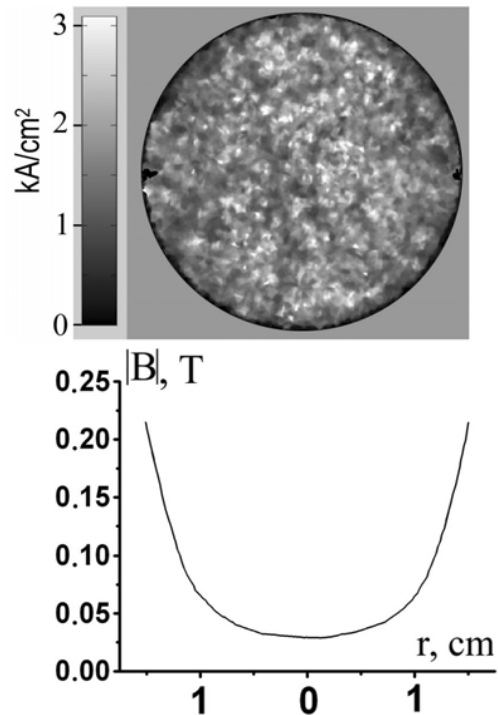


Fig.7. Finely dispersed arc surrounded with “magnetic barrier”

This experiment also proved that in the central electrode region no AMF was required for arc stabilization (as it was incorrectly considered earlier [32] and emphasised once again the important role of AMF in CS confinement within the front cathode surface.

IV. AMF BASED VI

The first commercial VI was developed by Toshiba engineers [7] who also proved the ability of AMF VI to interrupt practically unlimited currents. This VI was based on the creation of an artificial coil providing a tangential current flow under the contact plate (Fig. 8a). This design turned out to be very successful. It laid down the basis for a whole generation of Toshiba VI. Later on this design was also followed by other companies with some modifications. Another interesting development was the application of a slotted cup for the creation of AMF (Fig.8b). Engineers from Cooper Power Systems [25, 31] further improved this design by offering tubular contacts (Fig. 8d). The first attempt to create an asymmetrical multi-pole AMF was undertaken by engineers from Hitachi [9], who proposed a special contact design providing two or four local AMF peaks.

A very interesting “horse-shoe” design was offered by Schellekens and his co-workers [14]. This design used specially configured iron providing two or four pole AMF with changing polarity (Fig. 8c). This design did not require the creation of any special current path for AMF generation.

It certainly provided great advantages from the manufacturing standpoint.

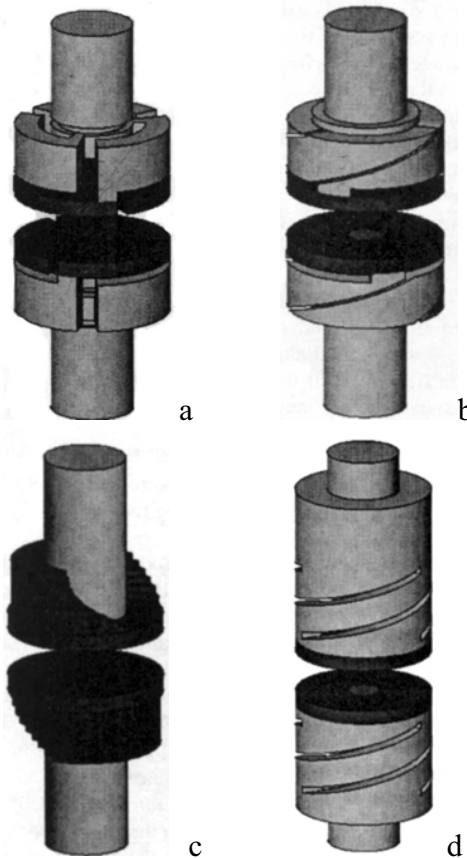


Fig.8 Designs of AMF contacts

In recent years interest in multi-pole contact designs has grown [23, 28, 30, 37, 38, 41, 46]. Some of them are equipped with iron inserts. A novel (SADE) design that provided a slower decrease of AMF induction towards the contact periphery had been offered by Toshiba in 1998 [32]. However, the reported improvement of interrupting capacity was slightly shaded by the complicated contact structure.

In 1998 Schneider electric suddenly offered AMF contacts equipped with an external coil [33]. This allowed the provision of more advantageous AMF distribution; however, complicated the design of VI and limited the applicability of VI with rated voltage $\leq 17.5\text{kV}$. An earlier similar design was offered by Jimei and his co-workers for low voltage application [15].

The reviewed design structures cover in general the population of commercial VI (though there are a lot more patented solutions that, for different reasons, did not evolve to practical use).

Fig. 9 summarises the maximum interrupting capacity expressed in kA/cm^2 , achieved for VI of different manufactures for 12kV and 36kV. This data is based on [21, 22, 24, 31, 36, 37, 41-44, 52].

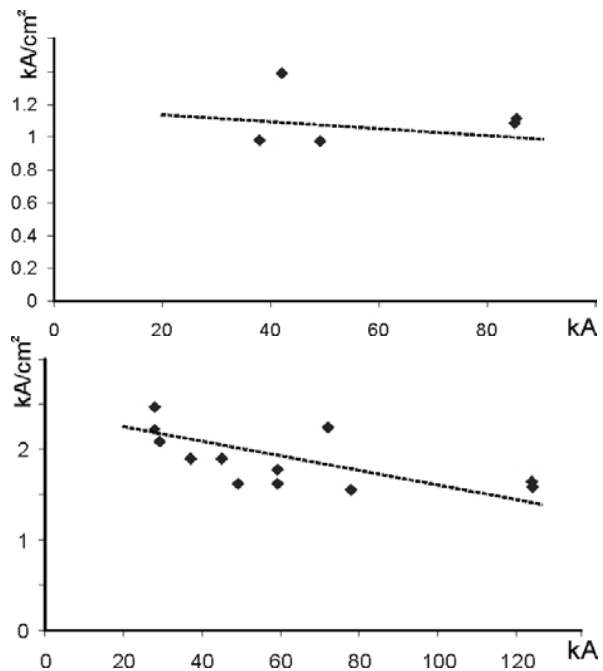


Fig.9 Maximum interrupting capacity (peak) for commercial VI for 36kV (upper curve) and 12kV (lower curve)

V. CONCLUSION

AMF appears to be a very productive tool for enhancement of the interrupting performance of VI. The majority of manufactures today use this principle for high current VI. Since its first application both our knowledge and devices have made substantial progress. At the same time a lot of open questions related to this phenomena remain. It seems that we lack the following basic knowledge:

1. Experimental data related to the movement of a single cathode spot under combined axial and radial magnetic fields, in particular with regard to contact materials applied for commercial VI
2. Experimental data related to energy distribution between the anode, cathode and screen for AMF based VI, in particular for currents close to their interrupting limit
3. A reliable model of the arcing column taking into account realistic boundary conditions, in particular on the cathode surface

4. Reliable experimental data related to plasma parameters for vacuum arcs in AMF

From a practical standpoint it is important to extend “normal current density” zones and define optimum AMF shapes for longer electrode gaps. It seems that on the basis of the above further progress in the creation of even more compact (i.e. more economical) VI, as well as an advance towards higher voltages, will be possible.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

1. W.Finkelnburg, "Hochstromkohlebogen", Berlin-Göttingen-Heidelberg, 1948
2. T. Ito, T. Okura. "High current interruption phenomena in vacuum interrupters", Mitsubishi Denki Giro, 41, 1967
3. C.W. Kimblin, R. Voshall. "Interrupting ability of vacuum interrupters subjected to axial magnetic field", IEEE Proc. Vol.119, No12, 1972
4. O. Morimiya et al. "High current vacuum arcs stabilized by axial magnetic fields", IEEE PES Winter meeting, New York, 1973
5. W. G. J. Rondeel, J. Foosnas. "The energy balance of a vacuum arc in an axial magnetic field", ISDEIV, p. 312, 1976
6. H.C.W. Gundlach. "Interaction on between a vacuum arc and an axial magnetic field", ISDEIV, p. A2, 1978
7. S. Yanabu, S. Souma, T. Tamagawa, S. Yamashita, T. Tsutsumi. "Vacuum arc under an axial magnetic field and its interruption ability", Proc. IEE, Vol.126, No.4, 1979
8. J.V. R. Heberlein, D.R. Porto. "The interaction of vacuum arc ion currents with axial magnetic fields", ISDEIV, 1982
9. Y. Kurosawa, Y. Kawakudo, H. Sugawara, T. Takasuna. "Behaviour of vacuum arcs in transverse magnetic fields and axial magnetic fields", ISDEIV, p. 261, 1982
10. M. Agarwal, R. Holmes. "Arcing voltage of the metal vacuum arc", J. Phys. D: Appl. Phys.,17 p.p. 757-767, 1984
11. R. Boxman. "Magnetic constriction effects in high current vacuum arcs prior to release of anode vapour", Journal of Applied Physics, Vol.48, p.p. 2238-2345, 1977
12. R. Boxman, S. Goldsmith. "The current distribution and the magnetic pressure profile in a vacuum arc subject to an axial magnetic field", ISDEIV, p. 125, 1986
13. S. Yanabu, E. Kaneko, M. Okawa, K. Otobe. "The investigation of vacuum interrupter contacts subjected to an axial magnetic field", ISDEIV, p. 195, 1986
14. H. Schellekens, K. Lenstra, J. Hilderink, J. Kamans, J. Hennepe. "Axial magnetic field type vacuum circuit breakers based on exterior coils and horse shoe", ISDEIV, p. 241, 1986
15. W. Jimei, S. Wenkai, Q. Zhoungou. "A new concept of vacuum interrupter with axial magnetic field", ISDEIV, p. 341, 1988
16. V. Nemchinsky. "Vacuum arc in axial magnetic field", ISDEIV, p. 263, 1990
17. F. Bestel, M. Glinkowski, S. Salon. "Magnetic field calculations in vacuum interrupter structures with eddy current effects", ISDEIV, p. 484, 1990
18. E. Kaneko, I. Ohshima. "Recent trends and activities of vacuum interrupters in Japan", ISDEIV, p. 399, 1992
19. H. Schellekens, W. Shang, J. Hilderink. "Experimental investigation of the arc properties of vacuum circuit breaker with horse shoe electrode and its applications", ISDEIV, p. 369, 1992
20. H. Schellekens, W. Shang. "The interrupting abilities of vacuum interrupters with horseshoe electrodes", ISDEIV, p. 183, 1994
21. A. Pertsev, L. Rylskaya, S. Chistyakov. "Strengthened magnetic field for vacuum interrupters", ISDEIV, p. 291, 1994
22. S. Yanabu, K. Watanabe, E. Kaneko. Technological progress of axial magnetic field vacuum interrupters", ISDEIV, p. 231, 1996
23. W. Shang, H. Fink, J. Lipperts, G. Pilsinger. "Bipolar axial magnetic field contact", ISDEIV, p. 315, 1996
24. M. Lindmayer, B. Fenski. "Vacuum interrupters with axial magnetic field contacts", ISDEIV, p. 337, 1996
25. F. Bestel, P. Stoving. "Axial magnetic field interrupters in autorecloser applications", ISDEIV, p. 1045, 1996
26. A. Chaly, A. Logachev, S. Shkol'nik. "Cathode spot dynamics on pure metals and composite materials in high-current vacuum arcs", IEEE Trans. Plasma Science, Vol. 25, p.p. 564-570, 1997
27. A. Chaly, A. Logachev, S. Shkol'nik "Cathode processes in free burning and stabilized by axial magnetic field vacuum arcs", IEEE Trans. Plasma Science, Vol. 27, p.p. 827-835, 1999
28. H. Fink, D. Gentsch, M. Heimbach, G. Pilsinger, W. Shang. "New developments of vacuum interrupters based on RMF and AMF technologies", ISDEIV, p. 463, 1998
29. M. Glinkowski. "A new principle in vacuum arc interruption using magnetic fields", ISDEIV, p. 473, 1998
30. W. Shang, B. Fenski, M. Lindmayer. "Characteristics of a vacuum switching contact based on bipolar axial magnetic field", ISDEIV, p. 459, 1998
31. F. Bestel, P. Stoving. "Finite element analyses of AMF vacuum contacts", ISDEIV, p. 522, 1998
32. M. Homma, H. Somei, Y. Niwa, K. Yokokura, I. Ohshima. "Physical and theoretical aspects of a new vacuum arc control technology", ISDEIV, p. 415, 1998
33. H. Schellekens. "Arc behaviour in axial magnetic field vacuum interrupters equipped with external coil", ISDEIV, p. 514, 1998
34. M. Keidar, B. Schulman. "Modeling of the effect of an axial magnetic field on the high current vacuum arc", ISDEIV, p. 210, 2000
35. A. Chaly, A. Logachev, S. Shkol'nik, A. Zabello. "Current density on the cathode of high current vacuum arc, stabilized by axial magnetic field", ISDEIV, p. 286, 2000
36. H. Schellekens, B. Schulman. "High current diffuse vacuum arc on axial magnetic field contacts: arc visualization and contact temperature", ISDEIV, p. 180, 2000
37. W. Jimei, L. Zhiyuan, W. Zheng, G. Shuyi, H. Guangli. "Analyses of axial magnetic field of an iron style bipolar axial magnetic field vacuum interrupters", ISDEIV, p. 455, 2000
38. W. Shang, H. Fink, M. Heimbach. "Vacuum interrupters with axial magnetic field contacts based on bipolar and Quadrupolar design", ISDEIV, p. 375, 2000
39. M. Leusenkamp, C. Bouwmeester. "Investigation of vacuum circuit breakers for high currents", ISDEIV, p. 392, 2000
40. M. Keidar, B. Schulman "Modeling of the effect of an axial magnetic field on the vacuum arc", IEEE Trans. Plasma Science, Vol. 27, p.p. 684-689, 2001
41. W. Jimei, X. Shixin, J. Shenli, J. Li. "Development and study on iron core style bipolar axial magnetic field vacuum interrupters", ISDEIV, p. 526, 2002
42. M. Lindmayer, K. Steinke. "Differences in current zero behaviour between bipolar and Quadrupolar AMF contacts", ISDEIV, p. 530, 2002
43. H. Schellekens, A. Henon, T. Altimani, P. Picot. "3D finite element simulation and synthetic tests of vacuum interrupters with axial magnetic field contacts", ISDEIV, p. 463, 2002
44. Z. Shi, S. Jia, J. Fu, M. Rong, Y. Geng. "Analyses of AMF vacuum contacts with ferromagnetic material", ISDEIV, p. 291, 2002
45. E. Taylor. "Transition to the diffuse mode for high current drawn arcs in vacuum with an axial magnetic field", ISDEIV, p. 339, 2002
46. W. Shang, E. Dullni, H. Fink. "Optical investigations of vacuum arc development with different axial magnetic field contacts", ISDEIV, p. 311, 2002
47. A. Chaly, A. Logachev, K. Zabello, S. Shkol'nik. "High current vacuum arc appearance in non-homogeneous axial magnetic field", ISDEIV, p. 380, 2002
48. S. Shkol'nik. "Secondary plasma in the gap of high current vacuum arc: origin and resulting effects", IEEE Trans. Plasma Science, vol.31, no.5, p.p. 832-846, 2003
49. A. Chaly, A. Logachev, K. Zabello, S. Shkol'nik "High current vacuum arc appearance in non-homogeneous axial magnetic field", IEEE Trans. Plasma Science., vol.31, no.5, p.p. 884-889, 2003
50. B.B. Kadomtsev, "Collective Phenomena in Plasma", Moscow, Nauka", 1976
51. J. Harris. Journal of Applied Physics, Vol.50, No. 2, 1979
52. Tavrida electric laboratory test reports