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INFLUENCE OF A PULSED AXIAL MAGNETIC FIELD ON A HIGH-CURRENT ARC OF A VACUUM CIRCUIT BREAKER

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The effect of a relatively short external axial magnetic field on the characteristics of a vacuum arc discharge in a vacuum circuit breaker is studied. A pulsed magnetic field is generated by external coils. The shape of the magnetic field pulse is one harmonic half-cycle with duration of 1.5, 2.8, or 4.5 ms. The magnetic field induction is regulated independently of the main discharge current. The use of a delay generator makes it possible to apply the magnetic field at different points of time relative to the main discharge current in the gap. It is assumed that the use of a pulsed magnetic field would provide a control over the burning regime of a high-current vacuum arc, i.e. realize the reverse mode with a transition from the active anode spot to the diffuse mode of discharge.

Keywords: axial magnetic field, vacuum circuit breaker, high-current vacuum arc.

INTRODUCTION

At present vacuum circuit breakers are extensively used in midrange-voltage applications [1]. A self-magnetic field in nearly all of them is formed due to the discharge current passing through specially shaped contacts. These contacts form either an axial or a radial magnetic field in the discharge gap [2]. The use of such contacts with a transverse magnetic field causes the arc channel to rotate across the electrode surface without attaching to a certain site, which reduces the heat stress on the electrodes [2, 3]. However, more preference is given to the contacts generating an axial magnetic field, since they demonstrate a better breaking capacity [4].

When the current is interrupted by a vacuum circuit breaker, an arc discharge is developed in the interelectrode gap. At relatively low currents (up to 6 kA) the arc burns in a diffuse mode [5]. Note that it is the cathode spots evenly distributed across the cathode surface which play the roles of emission and act as plasma sources, while the anode is only a passive collector of charged particles. As the current increases under the action of its self-magnetic field, the discharge channel is constricted. As this goes on, the anode is considerably heated and an anode spot is formed. Generally, an anode spot is a powerful source of the vapor phase and plasma. Melting of the electrodes causes their more intensive wear, and the presence of dense vapors in the gap during the voltage increase detrimentally affects the breaking capacity of the vacuum circuit breaker.

All these limitations are primarily typical for the butt contacts, being simple to manufacture, which do not generate any (but azimuthal) magnetic fields. Therefore they are utilized in the vacuum circuit breakers designed to interrupt relatively weak shock currents (up to 5–6 kA) [6].

At present, it is the electrodes generating an axial magnetic field (AMF) which show the best promise for interruption of high currents. These electrodes have a short coil under the contact pad, which generates an AMF during passage of the discharge current. The availability of an AMF in the discharge gap prevents the discharge channel from being constricted, retards the formation of an anode spot, and helps stabilize a high current vacuum arc in the diffuse

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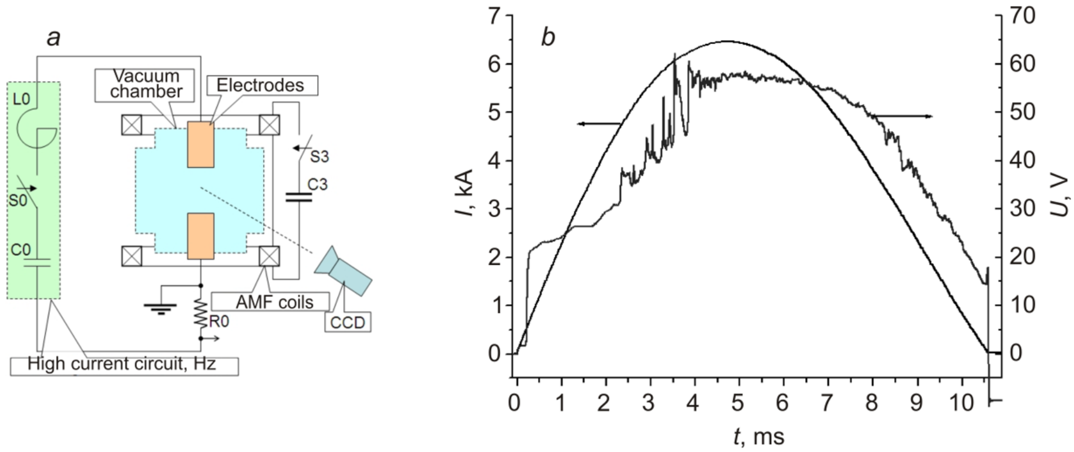

Fig. 1. Schematic circuit diagram of the experiment (*a*) and oscilloscope traces of the discharge burning current and voltage without any external magnetic field (*b*).

discharge mode [7]. As a result, the contact erosion is decreased [8], the level of interrupted currents is increased, and the breaking capacity is improved [9].

As noted above, in the AMF electrodes the field is generated by the current flowing through the electrode, i.e., simultaneously with the discharge current. Therefore, the AMF specific inductance, expressed in mT/kA (generally up to 7–8 mT/kA), remains practically constant during the entire discharge burning time and can be varied by changing the electrode design only. In this connection, of great interest are the laboratory studies with a capability of a gradual adjustment of the inductance by the AMF and by the non-synchronous magnetic field relative to the main discharge current.

In order to generate a homogeneous axial magnetic field under laboratory conditions, external coils are commonly used. In [10] such coils were powered from an external DC source. The coil current was regulated but the AMF was not synchronized with the discharge current. Another version is as follows: the external coil represents wire loops with the discharge current passing through them [11]. Such coils generate a synchronous AMF; however there is a limitation in this approach – it is impossible to gradually vary the field inductance in a wide range.

The present work studies the influence of an asynchronous magnetic field on the characteristics of a vacuum arc discharge in a vacuum circuit breaker. It should be recalled that a similar approach was implemented earlier [12]. The difference from the present work was the use of electrodes with a generation of an AMF, in other words, the resulting magnetic field was a superposition of the external field and the field from the electrodes. In the present study we use model flat electrodes (of the butt type), where no axial self-magnetic field is generated.

EXPERIMENTAL PROCEDURE

The experimental layout is given in Fig. 1*a*. The experiments were performed in a test bench designed according to a synthetic Weil–Dobke pattern [9]. The bench imitates the transition processes characteristic for short-circuit current interruption by a vacuum breaker in the electricity transmission lines. This bench generates a harmonic current pulse of an amplitude up to 15 kA with a duration of 10 ms, which corresponds to the mains frequency of 50 Hz. After the current zero, a pulse of the transient recovery voltage (TRV) is applied to the gap, with an amplitude up to 41.5 kV and a predesigned rate of pulse rise. In our experiments, however, no TRV was applied. The circuit contains calibrated gages for measuring the arc current and voltage on the gap.

The experiments were performed at a residual pressure of ~10^{-5} Pa, sustained by a Penning-type pump. The arc gap was formed by two identical electrodes 2 cm in diameter. The electrode material was a CuCr35 copper-chromium

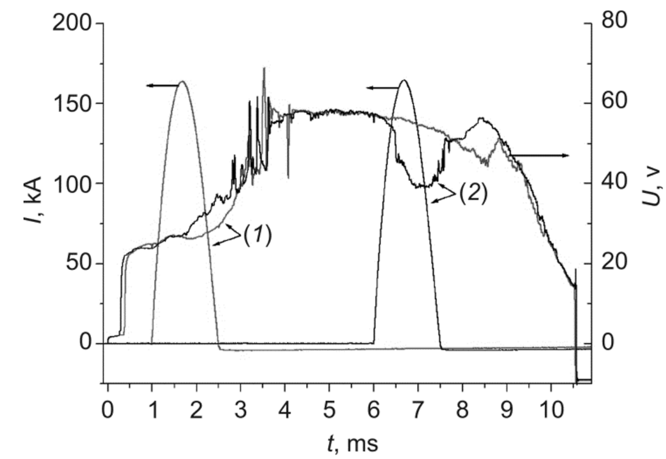

Fig. 2. Oscilloscope traces of the discharge burning voltage and short magnetic field pulse applied at different points of time (Case 1– (*1*), Case 2 – (*2*)). *I* – coil current, *t* – discharge burning time, *U* – discharge burning voltage.

composite [13]. An arc discharge was initiated by opening the contacts. The electrodes were separated at a velocity close to 1.3 m/s.

An axial magnetic field in the gap was generated by two external coils connected in parallel. Each coil consisted of 190 turns with an average diameter of 232 mm. The spacing between the turns was 205 mm. In accordance with the Biot–Savart–Laplace law, the magnetic field induction on the coil axis is 0.866 mT per 1 A of passing current. The coil current was supplied from an independent external power supply. The power supply parameters were selected so that to ensure the magnetic field durations of 1.5, 2.8 and 4.5 ms. The magnetic field duration of 10 ms was extensively discussed in [14, 15]. The current amplitude in the coils was regulated by the charging voltage.

The processes in the discharge gap were visualized using a Photron Fastcam SA1.1 high-speed video camera. The camera was actuated by an external signal synchronous with the onset of current passage through the discharge gap. The camera recording rate was 25000 frames per second at a frame resolution of 576×384. The exposure time was equal to 1 μs.

EXPERIMENTAL RESULTS AND DISCUSSION

An investigation of the influence of an external axial short magnetic field was carried out at a fixed amplitude of the main discharge current (6.5 kA). We changed only the magnetic pulse duration and the time of its switching relative to the onset of the main discharge current in the gap.

Figure 2 presents the oscilloscope traces of the discharge burning voltage and the short magnetic field pulse of 1.5 ms duration, applied at different points of time. In the first case (*1*), the magnetic field was applied practically immediately after initiation of an arc discharge in the gap. It is clear that the applied magnetic field (time interval of 1–2.5 ms) does not practically affect the initial stage of discharge burning. There is only a slight decrease in the burning voltage. Upon termination of the magnetic field action, the discharge transits into a constricted stage followed by the formation of an anode spot. In the second case (*2*), the magnetic field is applied 6 ms after the onset of current passage. It is seen that the burning voltage coincides with case (*1*) up to the point of magnetic field application. As the field increases, the voltage begins to decrease. At the point of time 6.5 ms, there is a sharp burning voltage drop. This indicates a transition of the discharge from the constricted into the diffuse mode.

In the latter case the on-peak magnetic field induction was as high as 142 mT. At the moment of magnetic field application, the discharge burning voltage decreased from 55 to 38 V. The beginning of the burning voltage decrease

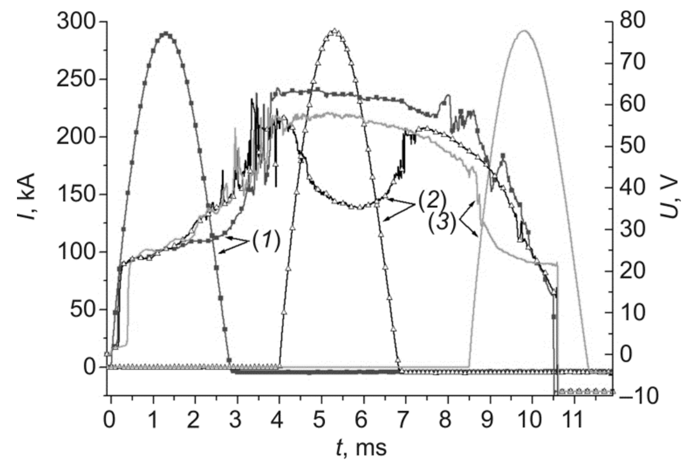

Fig. 3. Oscilloscope traces of discharge burning voltage and short magnetic field pulse of 2.8 ms, which was applied at different points of time (Case 1– (*1*), Case 2 – (*2*)). *I* – coil current, *t* – discharge burning time, *U* – discharge burning voltage.

occurs in about 250 μs after magnetic field application. This is most likely due to the magnetic field induction being very low at the initial point of time, where its value is lower than its axial self-field. The minimum voltage is achieved approximately 1 ms after the pulse beginning already in the descending section.

In the subsequent series of the experiments the magnetic field duration was increased. Figure 3 gives the oscilloscope traces of a short magnetic field with duration of 2.8 ms, applied at different points of time. Similarly to the previous case, the field applied at the initial point of time (Figure 3, Case (*1*)) did not practically affect the discharge characteristics but only slightly decreased the burning voltage. After termination of the magnetic field, the discharge transited into a constricted mode. In this experimental series, the on-peak magnetic field induction reached 253 mT.

In the final series of experiments, the magnetic field duration was increased to 4.5 ms. The application of pulse in the initial and final discharge burning stages did not practically differ from the two preceding experimental series, i.e., if a pulse was applied at the beginning of the contact opening, so after the end of the pulse the discharge transited into a stationary constricted burning mode.

Figure 4 presents the oscilloscope traces for the 4.5 ms pulse applied at 3 ms with respect to the beginning of the main discharge current. It is clear that with a magnetic pulse delay of 3 ms the discharge fails to reach the stationary mode with an anode spot (as was the case with (*1*) and (*3*) in Fig. 3). Within the time interval 2.5–3 ms, there are non-stationary processes of anode spot formation (Fig. 4*b*), which were detailed in [16]. Since at the point of time of 3 ms the magnetic field begins increasing, a stationary anode spot fails to be formed. Under the influence of the field the discharge returns to its diffuse mode. The voltage decreases to 35 V and remains constant within the time interval 3.5–7.5 ms. A series of images of the discharge gap demonstrate that within this time period the discharge functions in a diffuse mode without any anode spot (Fig. 4*b*, time point 7.00 ms).

After termination of the magnetic field action the discharge burning voltage increases, and the discharge channel under the action of self-magnetic field tends to transit into the constricted mode. Since the main discharge current is decreasing in this period, the discharge fails to reach a stationary mode with an active anode spot. However, the tendency towards the anode spot formation is supported by a photo of the discharge gap at the point of time 7.80 ms presented in Fig. 4*b*.

Figure 5 gives the oscilloscope traces of the discharge burning voltage and the coil currents for the 4.5 ms magnetic field pulse applied 4 ms after the beginning of the current passage through the discharge gap. An analysis has demonstrated that since the point of time 2 ms the discharge is functioning in the mode of an unstable anode spot [16]. This lasts until the time point 3.2 ms. Starting from 3.2 ms, the discharge transits into the mode with an anode spot

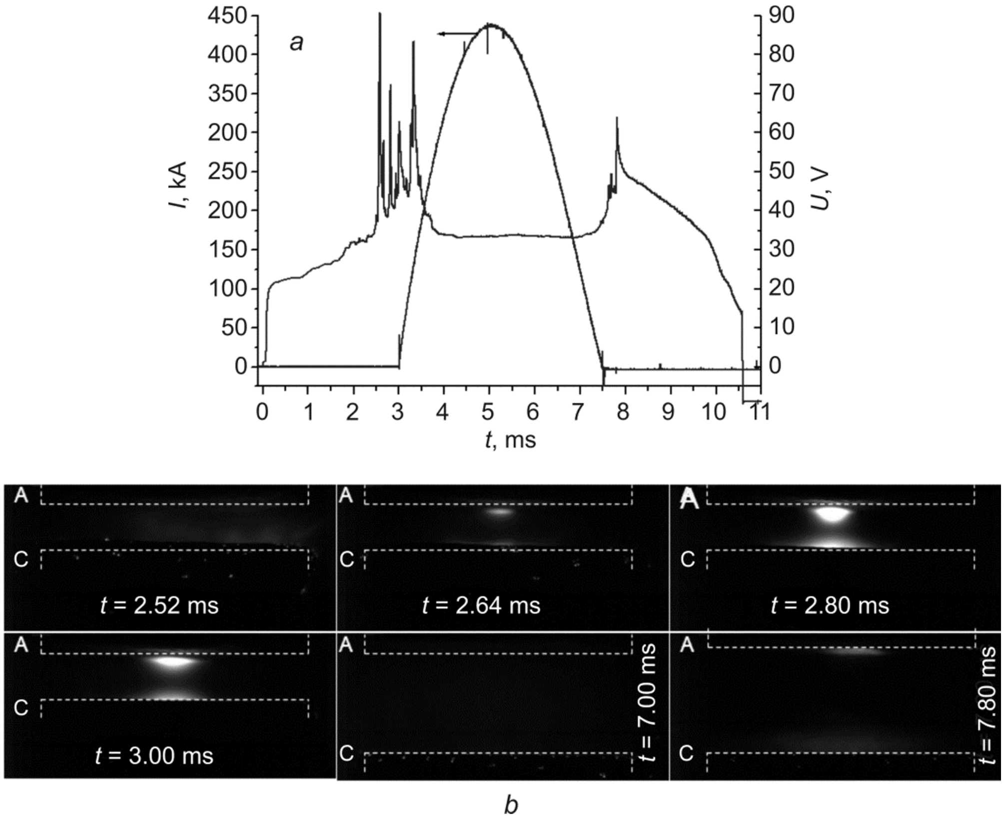

Fig. 4. Oscilloscope traces of discharge burning voltage and short magnetic field pulse of 4.5 ms. *I* – coil current, *t* – discharge burning time, *U* – discharge burning voltage (*a*) and a series of discharge gap images at different points of time (*b*).

(Fig. 5*b*), which lasts until the time point 4.2 ms. Despite the fact that at 4 ms a magnetic field was applied, its level was rather low and did not affect the discharge characteristics. From the time point 4.2 ms the role of magnetic field increases, and the burning voltage starts decreasing, though the anode spot is still functioning. The anode spot completely disintegrates by the time point 4.6 ms, but the heated region is still visible. Further on, as the magnetic field is increased, the discharge finally transits into the diffuse burning mode lasting until the current zero transition.

To sum up, the time of the active anode phase is slightly longer than 1 ms. This functioning mode alleviates the thermal stress on the electrode, which eventually reduces the erosion of the circuit breaker contact unit. This is also favorable for the breaking capacity of the circuit breaker as a whole, since prior to the voltage increase on the gap (after current zero) there is no vapor-phase and plasma source (hot anode).

CONCLUSIONS

The influence of an external axial non-synchronous magnetic field on the arc discharge behavior in a vacuum circuit breaker has been studied. The magnetic pulse duration was regulated from 1.5 to 4.4 ms. This approach is thought to be important and promising in terms of the experimental design of advanced vacuum circuit breakers.

It has been shown that comparatively short magnetic fields of 1.5 and 2.8 ms, applied at the initial time point of discharge burning, does not affect the pattern of the arc discharge burning, but slightly shortens the active anode-spot stage. The same field applied at the time of an already available anode spot causes a constricted-to-diffuse burning mode transition. However, after termination of this field the discharge returns to its constricted burning, Thus, the duration of an active anode phase (with an anode spot) shortens but very slightly.

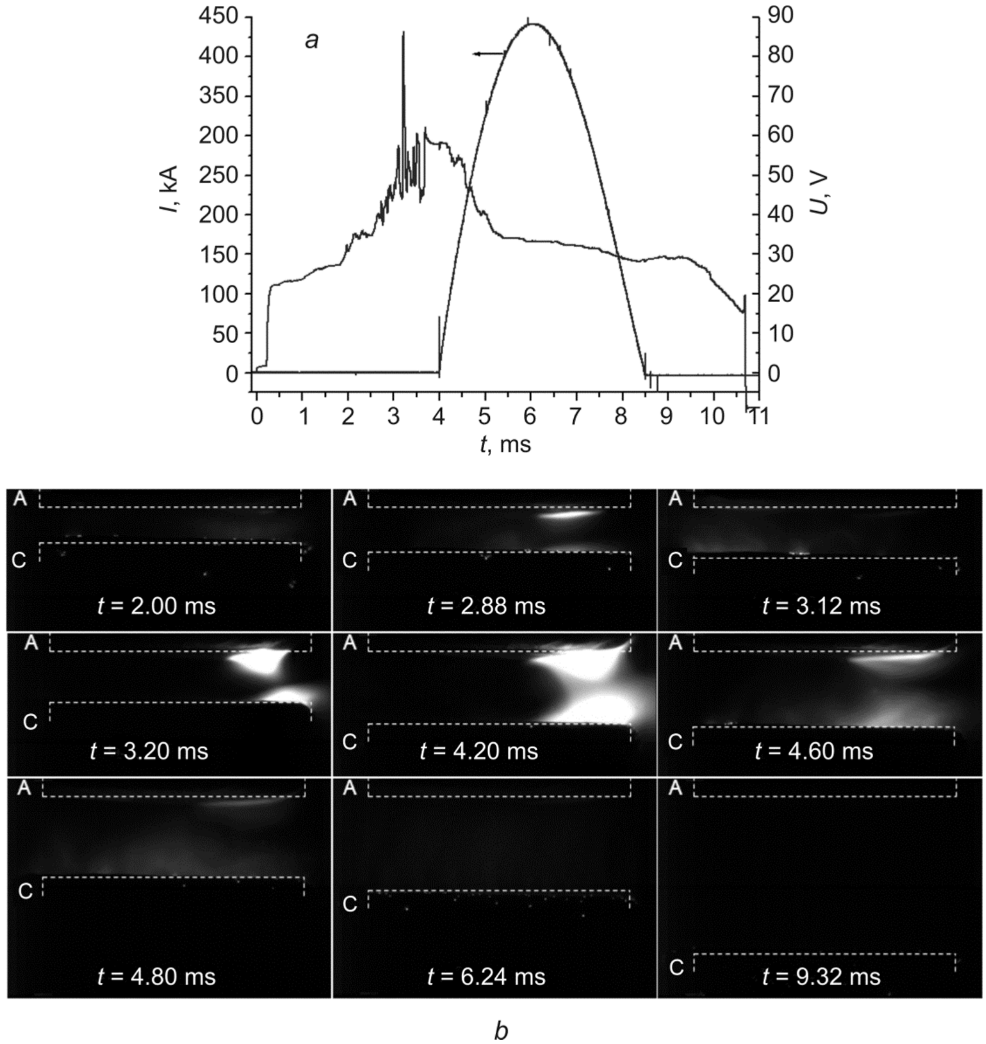

Fig. 5. Oscilloscope traces of discharge burning voltage and short magnetic field pulse of 4.5 ms. *I* – coil current, *t* – discharge burning time, *U* – discharge burning voltage (*a*) and a series of discharge gap images at different points of time (*b*).

A magnetic field of a duration of 4.5 ms, applied at the time points from 0 to 4 ms relative to the beginning of the current passage in the gap, demonstrates the same results as the fields of shorter durations (1.5, 2.8 ms). However, in the case of a 4 ms delay in its application the discharge burning character changes. Specifically, the active anode spot phase decreases to 1 ms in the initial discharge burning period. Upon termination of the magnetic field action, the discharge remains to be diffuse. This mode of the discharge functioning reduces the thermal stress on the electrode, which eventually decreases the contact unit erosion. Under these conditions, the density of the post-arc plasma decreases, its decay is faster, and the probability of a reverse breakdown is reduced.

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