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RESEARCH ARTICLE

Suppression of Swirl Arc Re-Strike Under Magnetic Blowing for DC High-Power Application

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ABSTRACT Probability of arc re-strike increases with the increment of break voltage, especially in an arc chamber of DC bridge-type contacts equipped with permanent magnets. Among all types of arc re-strikes, the most dangerous one is that part of the arc re-enters the contact gap, which is defined as swirl re-strike in this paper. In this paper, the arc images and arc voltage waveforms were analyzed, and the typical features of arc re-strike were identified. In addition, the probability of arc swirl re-strike when the supply voltages range from 270 V to 730 V and the magnetic flux densities ranges from 30 mT to 70 mT were revealed. Mechanism of the swirl re-strike is explained and it is due to the randomness of positions of both the arc igniting and the arc-root transferring on stationary contacts, as well as the non-uniformly distributed magnetic field in the arcing region. Finally, measures to prevent arc re-strike were proposed, and their effectiveness on eliminating re-strike were verified at the voltage range of up to 730V and magnetic flux. Occurrence probability of arc re-strike drops from unity to 13% at 730 V.

INDEX TERMS Arc swirl re-strike, re-strike prevention, arc-root transferring, magnetic blowing arc chamber.

I. INTRODUCTION

Arc erosion on contacts during the breaking process shortens electrical life span of all types of electro-mechanical switches [1]. Compared with a normal breaking process with a short arc duration, breaking process with repeated arc re-strike always has a longer arc duration or even a failure open, which are more destructive to the contactors [2], [3], [4]. It is of great importance to suppress the arc re-strike, and reduce both occurrence probability and cycles of re-strike.

In order to increase the life-span of switches, researchers have analyzed arc behaviors and erosion characteristics, and revealed that breaking ability can be improved by using external magnetic field [7], [8]. Permanent magnets are an effective solution to shorten the arc duration because they can accelerate the arc root shift and bend the arc column [9], [10], as well as removing power from the arc column by generating convective flow under the electromagnetic pump effect [11]. Therefore, they are widely equipped in arc chamber for high-power contactors since they can provide intensive magnetic field with a compacted size and a lightweight.

The arc root position, column shape as well as the distribution of electric breakdown strength of the hot and ionized gas in the arc chamber have great uncertainties. Various factors, such as arc root with randomly distributed initial position, the Lorentz's force with great uncertainty under the non-uniform magnetic field, as well as the conductor structure with eroded surfaces, might lead to the uncertainties. Therefore, arc re-strike occurs in different positions including between contacts, between contact and arc column, and even between different parts of arc column. These phenomena are clearly observed by taking high-speed videos of arcing processes and by analyzing the waveform of arc current and arc voltage.

Among many types of arc re-strike [12], [13], the most dangerous one is that part of the arc column returns to the contact gap when it is fully lengthened and overly bent under magnetic field [14], [15], which is defined as swirl re- strike. This type of re-strike always happens in high-power bridge-type DC contactors equipped with permanent magnet for

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blowing arc, especially on the condition of opening a higher voltage and current. The arc column has to be lengthened enough so that the arc voltage becomes higher than the source voltage and then the arc is possible to extinguish [16]. However, limited by the dimensions of the arc chamber, the arc column is severely constrained and re-entering the contact gap where is still hot and not fully de-ionized. Therefore, possibility of arc re-strike significantly increases. The swirl re-strike is similar but not the same with the back-commutation since they have similar characteristics on arc voltage waveform. Researchers have pay more attention to the back-commutation in circuit breakers and contactors with arc extinguishing devices such as splitters in the arc chamber [17], [18], but not much research is reported on the swirl re-strike since it only happens when opening a dc circuit on a relatively high voltage in a compacted chamber and it is also hard to be clarified only through analyzing the arc voltage and current in a contactor. This phenomenon was found under the condition of DC 450V/10A [19] and higher than DC600V in our previous researches [15].

The suppression of the arc re-strike then becomes a very important topic in the field of electro-mechanical switches. Gauster and Rieder proposed that changing the gap clearance between contacts and changing contact materials can reduce probability of arc re-strike and arc back commutation [20]. Appropriate gap distance between 1.5mm and 7mm can effectively reduce the breakdown voltage. The factors those affect arc motion will also have important influence on arc re-strike were verified by means of experiments, and the increasing of breaking current is also an important factor [21]. McBride et al. studied on arc commutation on the cathode and movable contact, the key factors affect arc re-strike and arc commutation are the structure of arc chamber and the insulated wall of arc chamber, as well as the size of gas outlets at the top of the chamber, which also became the basis for subsequent studies [22]. In [23], the arc re-strike process was re-produced by using MHD modelling, and the importance of gas outlets of arc chamber was further verified. Furthermore, many scholars proposed effective methods to reduce arc re-strike and re-ignition. Chen et al. studied the phenomenon of arc re-strike in arc chamber and a new prototype of arc chamber is proposed to reduce arc breakdown [24]. Park and Choi [25] reduced the arc generation time by induction needle and magnet, that electric field value is improved up to 20.5% by changing the shape and position of needle. To avoid re-strike inside the switch, Lee and Ko [26] improved the manifold inside switch and the improvement of new structure was verified by dielectric recovery voltage. To some extent, optimization on the contact structure and arc chamber can effectively reduce possibility of arc re-strike.

The motivation of this paper is firstly to identify typical features of the swirl arc re-strike and to reveal its mechanism in the situation of bridge-type contactors with permanent magnets equipped for blowing arc. Then to find out the probability of arc swirl re-strike in a wide range of supply voltages and magnetic flux densities. And finally to propose measures to prevent arc re-strike, and to verify their effectiveness on reducing re-strike probability. The results are helpful for designing DC high-power bridge-type contactors with magnetically blowing structures.

II. EXPERIMENTAL SETUP

A. EXPERIMENTAL PROTOTYPE

An experimental mechanism with the same structure of a real commercial DC high-power bridge-type contactor is designed and its schematic is shown in Fig. 1, a two-state solenoid (noted by 5) is used to drive the movable contact (noted by 3). The contact system is shown in Fig. 2, when the mechanism is closed, the movable contact is contacted with stationary contacts by a compressed spring. The spring is compressed by a push rod, the push rod is connected to the solenoid through a PTEE insulating connector. The coordinate system is defined as shown in Fig. 2. When the solenoid is powered on in the opposite direction, the push rod and the screw, as well as the chock will move along the x axis. The chock collides with the movable contact, both of them move along the x axis. Then the contacts separate and the arc is generated. The Lorentz's force on the arc provided by the magnetic field generated by the permanent magnet (P.M.), the arc will be blown, lengthened and bent. The rectangular permanent magnet with dimensions of 40 mm×18 mm×5 mm is arranged on one side of two stationary contacts (S.C.), as shown in Fig.2 and Fig. 3. Distance between the permanent magnet and the axis of the stationary contacts is adjusted to obtain a magnetic field with flux densities of 30 mT, 50 mT and 70 mT (z-component in the coordinate system defined in Fig.2) in the center of contact surface of the stationary contact. The stationary contact is a cylinder whose diameter is 12 mm, and the distance between axes of the two stationary contacts is 25 mm. The movable contact (M.C.) is a cuboid whose length is 25 mm, thickness is 3.2 mm and the width is 12 mm. The final contact gap is set to be 5.5 mm, which is a large gap comparing with normal contactors. All contacts are made of pure copper, named TU1 in China (C10200 in the US), the copper is oxygen-free copper with a rated purity of 99.97%.

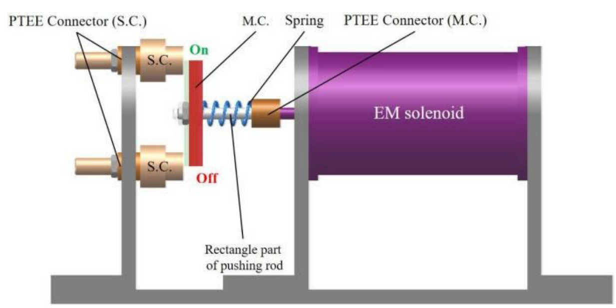


FIGURE 1. Schematic of the experimental mechanism.

B. PREVENTIVE MEASUREMENTS

To prevent swirl motion, two ceramic half tubes (a ceramic tube cut along its axis) made from Al_2O_3 are installed outside

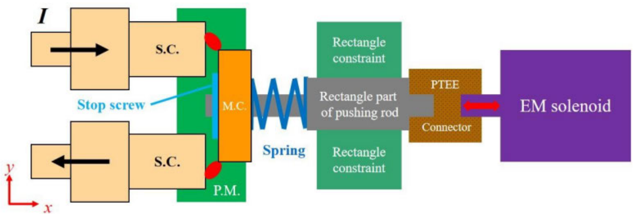
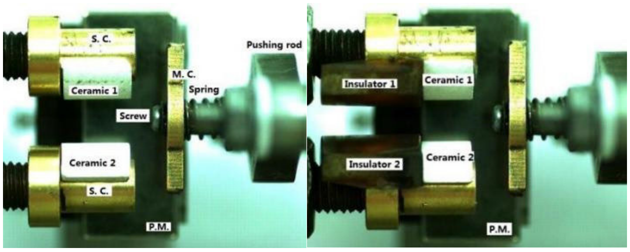


FIGURE 2. Schematic of the contact system.

stationary contacts as shown by ceramic 1 and ceramic 2 shown in Fig.3. These ceramic half tubes are used to constrain the motion region of the arc spot, namely, to cover the two side surfaces of the cylindrical stationary contacts and prevent the arc roots transferred there.



(a) (b)

FIGURE 3. Prevention methods: (a) Stationary contacts covered with ceramic half tubes. (b) Stationary contacts covered with ceramic tubes and insulators.

In addition, two polyimide insulators were used as a supplementary, as shown in Fig.3 (b). This has an advantage of preventing the arc root transferring to the bottom of two stationary contacts, which might well lead to continuous arcing between two stationary contacts on the condition of opening a higher voltage. Once an arc burning between two stationary contacts occurs, it will be merely extinguishing, as shown in [14].

C. EXPERIMENTAL CIRCUIT

The experimental circuit is shown in Fig. 4. The power supply is DC switch-type power source, and the range of voltage E could be set to in the range of from 0 to 900V. The R_L is used as the resistive load, and it is also adjustable. E and R_L are adjusted independently, for maintaining a constant current of 50 A. A voltage sensor, a 2.5 MHz AD card with 4- channel and an oscilloscope are used to record the arc voltage and arc current.

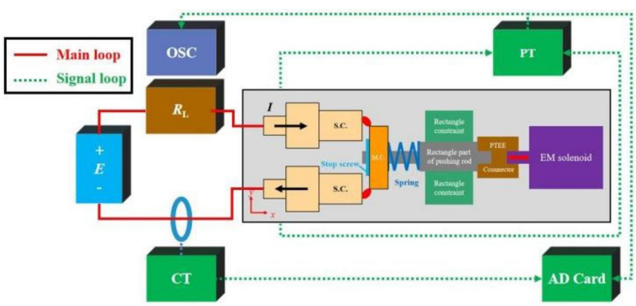


FIGURE 4. Experimental circuit.

TABLE 1. Experimental conditions.

Parameters	Value
Current (A)	50
Voltage (V)	280, 350, 400, 470, 530, 660, 730
B (mT)	30,50,70 (by $Nd_2Fe_{14}B$)
Opening velocity (m/s)	1.1(mean value during the first 2 ms)
Experiment cycles	15 times
Contact force (N)	38
Frame interval (μs)	63
Contact gap (mm)	5.5

D. EXPERIMENTAL CONDITIONS

Experimental parameters are shown in Table 1. 15 experiments under each condition were carried out in order to avoid the randomness of the experiments. For avoiding the inconsistency of the mechanism caused by changing contacts, a set of same contacts are used for all experiments under different voltages for the same flux density. Moreover, it can provide maximum comparability in the effect of preventive methods, which is the most important significance of this paper. Therefore, for the three magnetic flux densities, three sets of contacts are used in this paper. In addition, changes in contact surface during repeated arcing may affect the results, especially when the copper is oxidized. However, the influence of the oxidation on arc duration is proved to be insignificant for this research. The opening velocity is a constant of 1.1 m/s which is the mean velocity during the first 2 ms. The contact force between each stationary contact and the movable one is approximately 38 N. In each operation, the arcing process is recorded by using a high-speed camera (Phantom V7.3) whose frame interval is set to be 63 μs.

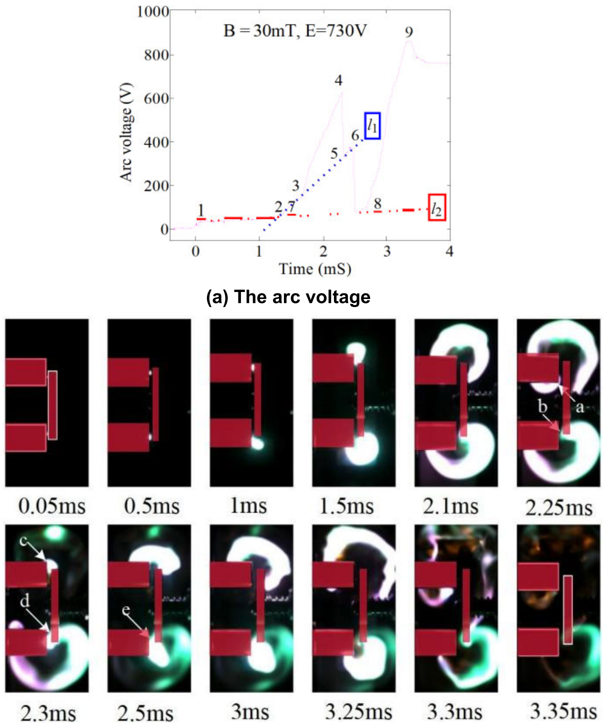
III. RESULTS

A. ARC BEHAVIOR WITH NO PREVENTION

A typical arcing process with the swirl re-strike is shown in Fig. 5. Fig. 5(a) shows the arc voltage, and Fig. 5(b) shows time evolution of the arc images corresponding to Fig. 5(a). The process of arcing and re-strike with no prevention is as follows:

The stage from point 1 to point 2 in Fig. 5(a) is the lengthening stage, during which the arc is transferred along the Lorentz's force and lengthened with the gap increasing but it is still in the contacts gaps as shown by the arc shape before nearly 1ms in Fig. 5(b). At after 1ms, the arc in between the lower contact gap (denoted by the lower arc) is transferred out, and its arc root is transferred to the edge part of the stationary contact surface. After this point, the arc voltage increases as fast as 250 V/ms, as shown by the curve from point 2 to point 3 in Fig. 5(a).

As the contact gap is lengthening, the arc in the upper gap is also transferred out and deformed under the magnetic field at approximately 1.5 ms as shown by point 3 in Fig. 5(a). After 1.5 ms, the lower arc and the upper arc are lengthened and deformed and it is obvious that the arc voltage increases sharply (higher than 500 V/ms) as shown by from point 3 to



(a) The arc voltage

(b) Arc behaviors by high-speed camera

FIGURE 5. A typical process of swirl arc re-strike.

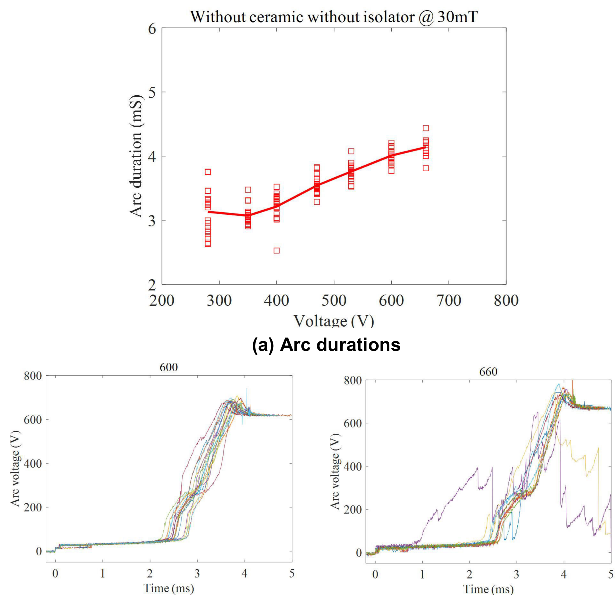
point 4 in Fig. 5(a). This process lasts approximately until 2.25 ms.

(3) A swirl re-strike occurs at about 2.25 ms as shown by the arc figures and point 4 in Fig.5. The arc in the upper gap forms a huge circle and part of it returns into the upper gap again as shown by an arrow 'a' in Fig.5 (b). Consequently, current flowing through the longer and bent arc is commuted to the new formed short one inside the gap for its lower resistance as shown by the arrow 'c', and the arc voltage drops to half of its original value. It drops from higher than 600 V at point 4 to nearly 300 V at point 5. This process is a typical arc re-strike, and it is named as swirl re-strike for it is occurred owing to the swirl motion of the arc. Another swirl re-strike occurs in the same way at approximately 2.5 ms, whose voltage drops from higher than 300V to less than 50 V as shown by point 6 to 7.

(4) After those two re-strikes happen, an entire and almost same arc-blowing process has to be endured again during this break process after 2.5 ms. Fortunately, the arc extinguishes finally without further re-strike at about 3.35 ms at point 9, and the arc voltage returns to the source voltage.

During the above process, two lines could be figured out on ratio of only less than 10 V/ms. It stands for that two arcs remain inside the contact gap and none of them are transferred out, so that the voltage increasing is only due to the lengthening of contact gap. It can be concluded that the arc voltage would drop to approximately half of its original one once the swirl re-strike happens in one contact gap, the voltage will drop to the line l_1, and that the arc voltage would drop to several tens of volts if the swirl re-strike happens in both of the two contact gaps, and the voltage will drop to line l_2. This result could be used as a criterion for judge whether the swirl re-strike happens or not by using only arc voltage waveform during the arcing processes if one has no high-speed video recorder or the videos of the arcing process is not available like in a sealed arc chamber of a contactor. There are two patterns on the arc voltages: 1) arc voltage drops largely and 2) the arc voltage drops to the extend lines including l_1 and l_2. These two patterns are helpful to reveal the type of arc re-strike by using only arc voltage fluctuation mode.

Fig. 6 shows the arc duration at the supply voltage range from 280 V to 660 V when the flux density is 30 mT. At 730V, the arc cannot be extinguished for the first five times, an external protection circuit breaker connected in the experimental circuit is tripped and break the circuit in order to protect the whole experimental system. The experiment was terminated to protect the contacts from being burnt out. Therefore, arc duration cannot be preciously obtained at 730 V. Of all these arc duration, Fig.6 (a) excludes those arcs that cannot be extinguished by the contact system itself and that out of the sampling range of the oscilloscope. These arc duration is in tens or hundreds of milliseconds which may increase the average arc duration in order of magnitude if included, and they are of no meaning not only for comparing the effectiveness of adding ceramic tubes and insulators, but also for analyzing the by-function (slightly increasing the mean arc duration) of introducing the ceramic tubes and the insulators as we will talk in Section IV-B.



(a) Arc durations

(b) 600 V

(c) 660 V

FIGURE 6. Arc duration time at 30 mT with no prevention:(a) Arc duration. (b) Arc voltages at 600 V. (c) Arc voltages at 660 V.

The arc voltage waveform at 600 V and 660 V at the magnetic flux of 30 mT are also shown in Fig. 6, since 600 V is a critical source voltage for whether swirl re-strikes happen or not. When the voltage is lower than or equal to 600 V, there is merely swirl re-strike. Swirl re-strike only occurs at 660 V and 730 V, and the occurrence are 3 times out of 15 tries at 660 V and 5 times out of 5 tries at 730 V. The above two patterns can be easily identified by analyzing arc voltage fluctuations.

B. ARC CHARACTERISTICS WITH CERAMIC SEMITUBES

As mentioned above, when a blown and curved arc outside a gap returns into the contact gap again, the swirl arc re-ignition will occur. Therefore, it is directly to realize that constraining the region of the transferring arc spots and keeping it far away from the contact gap is a potential method to prevent the swirl re-strike.

Two ceramic semi-tubes (made from Al2O3) whose diameters are exactly the same as those of the stationary contact is used to cover their inner face-to-face surfaces, as shown in Fig. 3. The purpose is to prevent the arc roots transferring to the internal area and force the arc roots to transfer along the axis direction of the stationary contact, which may well lead the arc to move away from the contact gaps. Ceramic tubes were chosen to constrain arc spots because of their high temperature endurance.

The distribution and the mean arc duration under different supply voltages is shown in Fig. 7(a). 15 arc voltage waveform at the power voltage of 600 V, 660 V, and 730 V are shown in from Fig. 7 (b) to (d) as examples. According to the arc voltage, when the voltage was lower than or equal to 600 V, there was no such kind of swirl re-strike. When the voltage is at 660 V, one swirl re-strike occurs among the total 15 experiments, and the arc cannot be extinguished by the arc chamber for this experiment. When the voltage is 730 V, 13 out of 15 experiments are successfully switched off, only two experiments are failed. The average arc duration at 730 V is approximately 4.3 ms.

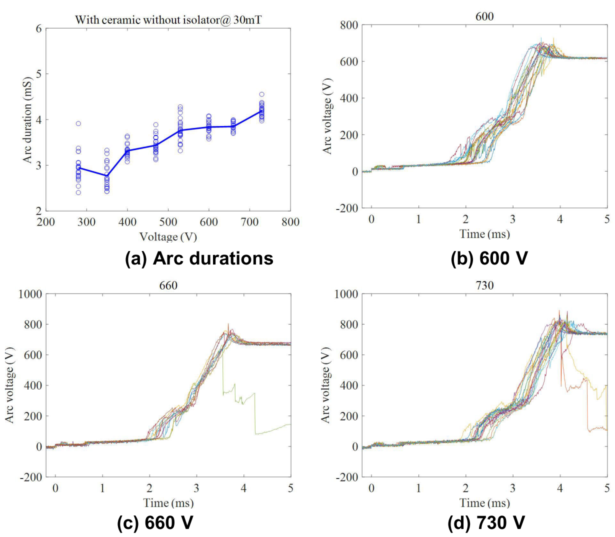


FIGURE 7. Arc behaviors at 30 mT with ceramic tubes.

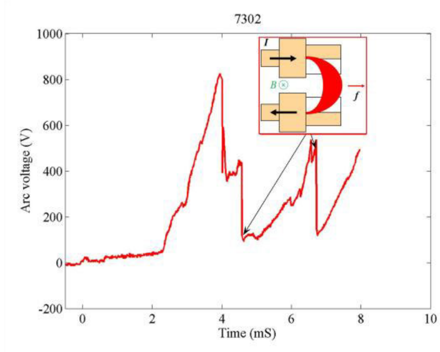
Waveform of arc voltage of one of the failed opening at 730 V is shown in Fig. 8(a), time evolution of arc images of this failed opening is shown in Fig. 8(b). By analyzing the arc voltage, it can be seen that its voltage fluctuation is very similar to the swirl arc re-ignition described in Fig.5 (a) in the first 5 ms of the arcing process, but great difference appears after 5 ms. However, by carefully analyzing the arc images, we see now such kind of swirl re-strike, and the ceramic semi-tubes do prevent the swirl arc re-ignition from re-entering the two gaps. Unfortunately, the ceramic tubes as shown in Fig. 3(a) covers only the front of the two static contacts, two circular arcs appear at the end of the area between 3.97 ms and 4.16ms. These two arcs touch and are connected, creating a new current path (namely, a new arc) between the two stationary contacts, which can be seen in the images from 4.16 ms to 5.23 ms. As shown in Fig. 8(b), a new arc occurs between two stationary contacts, and it is usually difficult to extinguish. The new arc in circular shape can be driven by the Lorentz force, which is provided by both the inductive magnetic field and the permanent magnet field (represented by B), the Lorentz's force is represented by f in the sub-graph of Fig. 8 (a). As the new arc approaches the movable contact and the two contact gaps, it touches the movable contact again and is split into two short arcs at about 6.5 ms. The process of magnetic blowing and bending is repeated again until 9.3 ms. At about 9.32 ms (out of the oscilloscope screen), the swirl arc re-strike occurs again, because the arc spot on the movable contact moves to the edge and re-entering into two gaps. Even if ceramic tubes at static contacts cannot prevent the swirl arc from re-striking, this pattern of swirl arc re-ignition is fortunately rare.

The use of ceramic semi-tubes can prevent the phenomenon of swirl arc re-strike to certain degree, but it can probably make the arc burn between stationary contacts, which might also lead to fail open and severe contact erosion. To eliminating this disadvantage of ceramic tubes, an insulator made from polyimide is inserted in the area between the static contacts to prevent the arc, as shown in Fig. 3(b). The results are shown in the next section.

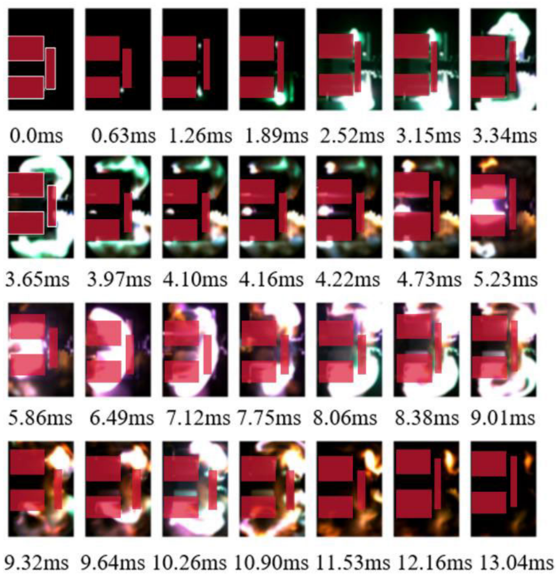
C. ARC CHARACTERISTICS WITH CERAMIC TUBES AND INSULATORS

For the probability of arcing between stationary contacts, further measures are inevitable. A straightforward measurement is to insert insulators between the static contacts. In consideration of convenient preventive methods, two circular insulators made of polyimide are attached to the end part of the stationary contacts, as shown in Fig. 3(b).

The arc duration under different supply voltages, as well as the arc voltage waveform with supply voltage of 600 V, 660 V and 730 V is shown in Fig. 9. If both the ceramic semi-tubes and the polyimide insulators are added at the same time, swirl arc re-strike will never occur again at any voltage. In addition, there is no other type of re-strike or continuous arcing phenomena, and the arcs extinguish within 4 milliseconds in all experiments. In summary, ceramic semi-tubes combined with polyimide insulators can effectively prevent the swirl arc re-strike at the magnetic flux density of 30 mT.

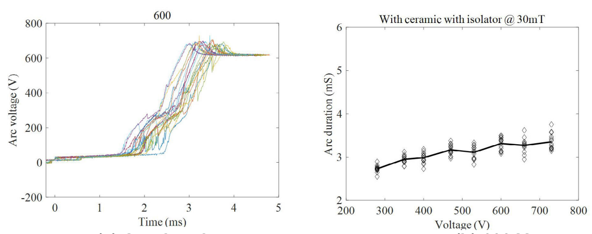


(a) Arc voltage

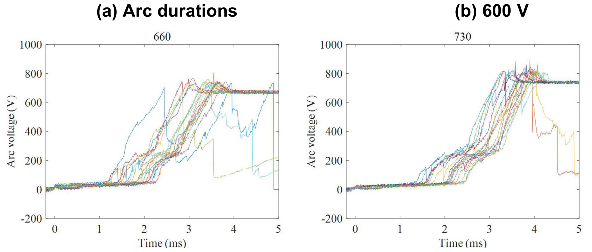


(b) Time-evolution of arc images

FIGURE 8. **Arc voltage and images corresponding to a failed opening at 730 V.**



(a) Arc durations (b) 600 V



(c) 660 V (d) 730 V

FIGURE 9. **Arc duration time at 30 mT with both ceramic tubes and insulators.**

IV. DISCUSSIONS

A. MECHANISM OF THE SWIRL ARC RE-STRIKE

Mechanism of the swirl arc motion during the opening process of a bridge-type contact system equipped with permanent magnet is shown in Fig. 10. Figure 10 (a) and (b) are top views whereas (c), (d) and (e) are side views. In the very beginning, the movable contact starts to move and separate from the stationary ones, two short arcs are generated in the gaps as shown in Fig.10 (a).

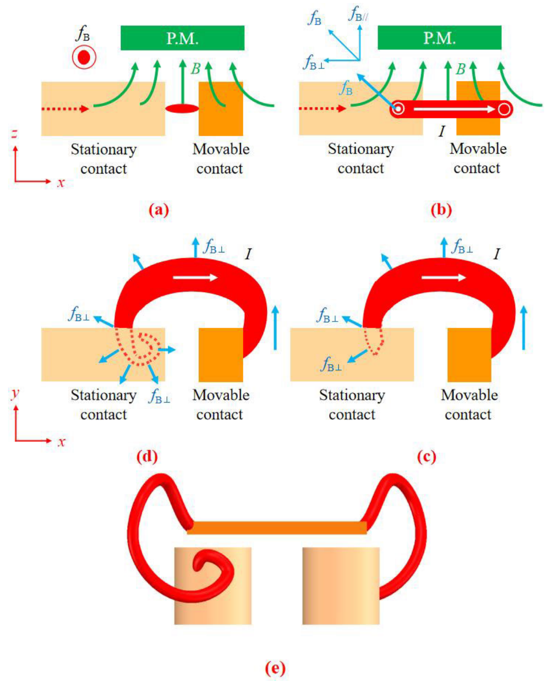


FIGURE 10. **Mechanism of the swirl arc motion and re-strike.**

The arc starts to be blown under the Lorentz's force (noted by f_B) provided by the permanent magnet (P.M.). The direction of Lorentz's force, which is also the direction of arc blowing, can be determined by magnetic field direction and current direction. Under the magnetic field, the arc is blown out by Lorentz's force and gradually transferring outwards, as shown in Fig.10 (b) and (c). The Lorentz's force is decomposed into parallel and vertical directions with respect to the arc column. They are denoted by $f_{B//}$ and $f_{B\perp}$, respectively. The Lorentz's force in the parallel direction $f_{B//}$ is the force component generated on the arc current by the parallel component of the P.M, which drives the arc root moves tangentially on the side surface of the cylindrical contacts. This force component is the unwanted one but have to exist because of the distribution of magnetic field. Whereas, the Lorentz's force in the vertical direction $f_{B\perp}$ is the Lorentz's force generated by the vertical component of the P.M, which is the major one to blow the arc. Subsequently, both the two arcs are elongated and bent, forming an arc-shape between the movable and static contacts as shown in Fig. 10 (c). At each point of the arc, the arc is subjected to a perpendicular Lorentz's force which is direction of arc motion.

During the process of the arc motion, it is worth noting that the velocity of arc root is far slower than that of arc column, the movement of arc column and arc root cannot be synchronized. Therefore, the radius of the arc-shaped arc column will be enlarged but the arc root transfers at a relatively lower velocity, which leads to a small circle forming in part section of the whole arc column as shown by the dashed part in Fig.10 (d). A clear arc column is shown in Fig.10 (e).

The small circular arc part is also going to enlarge in radius because of the vertical force $f_{B\perp}$. This radius enlarging process might well lead to that the arc sweeps into the contact gap region, or we can say it reenters the contact gap. As a result, the phenomenon of ''swirl'' arc appears in the arc motion and the swirl arc re-strike occurs. The mechanism shows that the major factor causing the swirl arc re-strike should be the position of arc igniting, the length of arc column and the velocity difference between the arc column and arc roots.

Position of arc igniting will decide the total time that the arc root transfers from the ignition point to the edge of the top surface and transfers on the side surface. In Fig.10 (a), if the arc starts near the PM, it will take the shortest time to arrive the re-strike moment illustrated by Fig.10 (e). Whereas, if the arc starts far from the PM, it will take the longest time to arrive the re-strike moment.

The length of the arc column is the most direct factor leading to the swirl re-strike. If the arc is shorter than a certain value, the arc will extinguish before the little circle formation as shown in Fig.10 (e). This will be proven in Section IV-D. The criteria for the load condition in this paper will be approximately 100 mm.

The moving velocity difference between the arc root and the arc column is also an important fact according to our mechanism. If the velocity difference is larger enough, the arc column will be lengthened quickly and be longer enough to extinguish whereas the arc root is still on the top surface, then the swirl re-strike cannot happen.

B. COMPARISONS BETWEEN THE EFFECTIVENESS OF CERAMIC AND INSULATOR

Comparison on mean arc duration and their distribution with and without prevention measurements are shown in Fig. 11. It can be observed that the mean arc duration with no insulator and no ceramic is, generally, longer than those of with ceramic tubes and no insulator. Shorter arc duration under no prevention measurements can only be found at the voltage of 400 V. The mean arc duration without any measures is longer than the other two conditions, and the shortest arc duration is under the condition of adding both ceramic semi-tubes and polyimide insulators. It can be seen that the combination of ceramic tubes and insulators can reduce the arc duration obviously. In addition, slightly long arc duration with both ceramic tubes and insulators comparing with that of with ceramic tubes but no insulators can only be seen at the voltage of 350 V. At all other voltage levels, the reduction in arc duration of ceramic tubes and insulators is much more than that of the other two. Generally, as voltage levels increase, the advantages of adding ceramic tubes and insulators become more obvious, especially when the voltage is higher than 500V. Slightly increment on mean arc duration could also be found occasionally when the voltage is relatively low. This might be a by-function of adding the ceramic tubes and the insulators. However, elimination of the swirl re-striking and continuous arcing is worth this sacrifice of slight increment on arc duration.

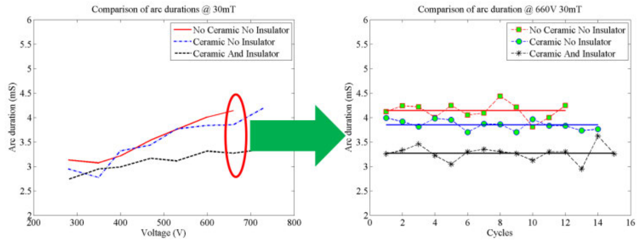


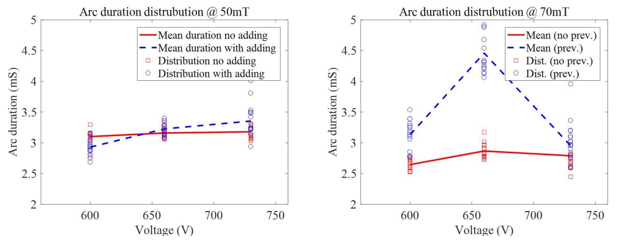
FIGURE 11. **Comparison on durations and their distribution with and without preventions. (Results are obtained under 30 mT, and distributions at only 660 V are shown and others can be compared in Figs. 6, 7 and 9).**

Furthermore, take the distribution of arc duration at voltage of 660 V as an example. The arc duration of all 15 experiments under the three conditions is shown in the upper left of Fig. 11. The advantages of adding ceramic tubes and insulators are obvious. In the 13th experiment, the shortest arc duration of ceramic tubes and insulators was found, and the shortest arc duration was 2.9 ms. However, the breaking without any prevention measures has failed at this time, and the arc duration with ceramic tubes but no insulator is nearly 3.9ms, the difference is nearly 1ms. The middle line in the figure shows the average arc duration of the 15 experiments. The average arc duration of the experiments with no ceramic tubes and no insulators is about 4.3 ms, the average arc duration of the experiments with ceramic tubes but no insulator is about 3.8 ms, while the average arc duration of the experiments with both ceramic tubes and insulators is only 3.25ms. At the voltage of 660V, the mean arc duration of adding ceramic tubes but no insulator is reduced by 11.63% compared with that of neither ceramic nor insulator. The mean arc duration of adding both ceramic tubes and insulators is reduced by 11.47% compared with that of with ceramic tubes but no insulator. Apparently, the comparison between adding both and neither of them is the most obvious, and the arc duration is reduced by 24.42%.

On the occurrence probability of arc re-strike, it is about 20% at 660V and 100% at 730V when no additional measurement is added, as shown in Fig.6. The probability of re-strike drops to 7% at 660 V and 13% at 730 V when only ceramic half-tubes are added as shown in Fig.7, whereas, no re-strike occurred even at 730V if both ceramic half-tubes and polyimide insulators are used as shown in Fig.9. Therefore, the protection measures proposed in this paper can effectively reduce the probability of re-strike.

C. EFFECTIVENESS OF SUPPRESSIONS UNDER OTHER CONDITIONS

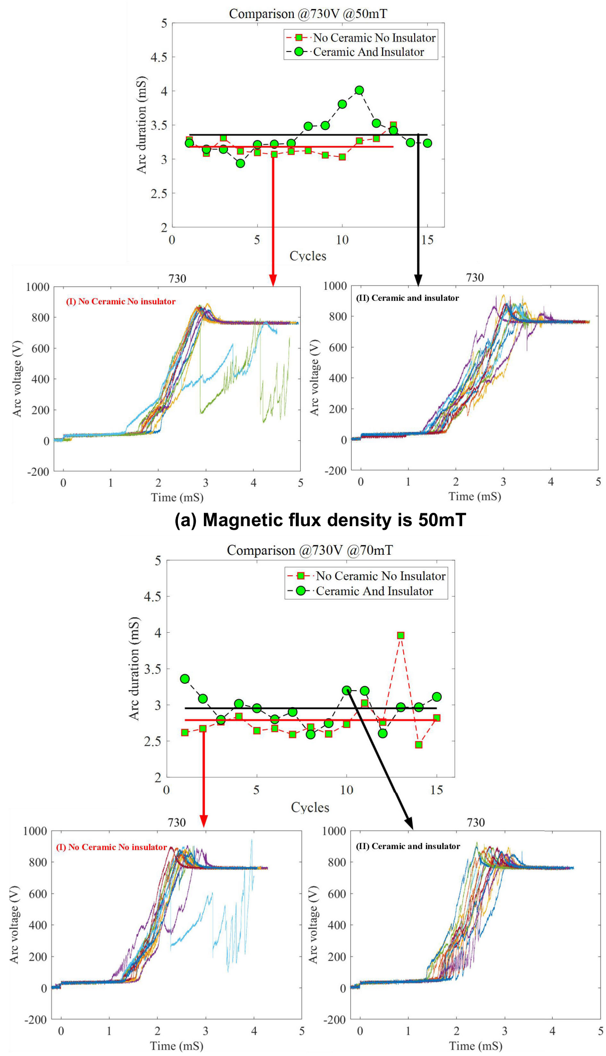
In order to further understand whether this preventive method has the universality of reducing arc duration, same experiments were performed at 50 mT and 70 mT magnetic flux densities, respectively, and at 600 V, 660 V and 730 V voltage levels. In addition, in order to avoid the randomness of experiments as much as possible, each experiment was performed for 15 tries. Figure 12 shows the comparison of arc duration and their distributions with or without prevention measurements. When the magnetic flux density is 50mT, the arc duration does not change obviously after adding ceramic tubes and insulators as shown in Fig.12 (a). At 600 V, the arc duration did not increase, but at 660 V and 730 V, the arc duration increased to vary degrees, although the arc duration does not change obviously. When the magnetic field intensity is 70 mT, the arc duration increases at different voltage levels with the addition of ceramic tubes and insulators, as shown in Fig.12 (b). It is most obvious at 660 V, the average arc duration without preventions is only 2.8 ms, but the average arc duration after installations reaches 4.4 ms. The difference of mean arc duration at 600 V is about 0.5 ms, and that of at 730V is about 0.13ms. It can be seen that with the increase of magnetic flux density, the mean arc duration with ceramic tubes and insulators will increase, but it is within acceptable limits on the whole.



(a) 50mT (b) 70mT

FIGURE 12. Comparisons of arc duration and their distribution with or without preventions at different voltage levels.

Even so, the advantages of adding ceramic tubes and insulators to the device are clear. Figure 13 compare the arc duration and their distribution with or without preventions at different voltage levels when the magnetic flux density is 50 mT and 70 mT. Although adding ceramic tubes and insulators makes the arc duration increased slightly (the difference of the average arc duration at 50 mT is about 0.18 ms, and that of 70mT is about 0.17 ms) according to each arc waveforms in the figures, the increase rate of arc voltage increases after installing the preventions. The phenomenon is particularly obvious when the magnetic flux density is 70 mT (the main reason is that the higher the magnetic flux density is, the larger Lorentz's force the arc is subjected to, and the faster the arc voltage rises). It is further verified that the arc motion between contacts is limited by preventions, and the arc "swirl" is effectively avoided by these methods. On the other hand, before the preventive methods are applied, the device sometimes takes a long time to break or does not break, especially after too many experiments. This phenomenon is also effectively avoided after the installation of preventions, as well as the arc voltage rise rate and arc duration are relatively stable. Therefore, adding insulators and ceramic tubes can effectively avoid the phenomenon of arc "swirl" ignition, which can prolong the life of electrical appliances, but also ensure the stability of devices.



(a) Magnetic flux density is 50mT

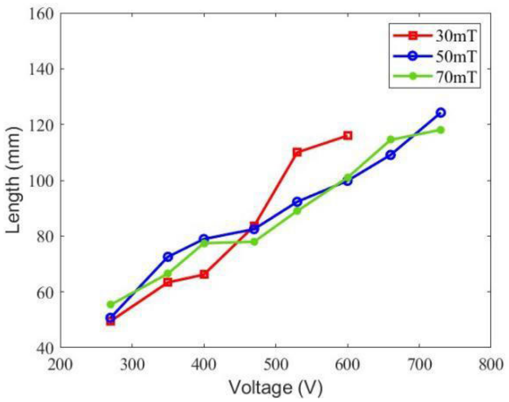
(b) Magnetic flux density is 70mT

FIGURE 13. Comparisons of arc parameters at 730 V with or without preventions.

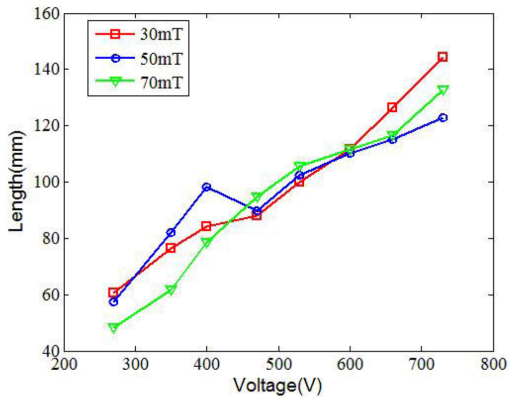
D. ARC LENGTH WITH AND WITHOUT PREVENTIONS

Magnetic field provides Lorentz's force on arc column and arc roots, and makes the arc moving and being lengthened and curved. Therefore, a longer length as well as a better heat exchanging between hot arc and cool air help increasing the arc voltage and reducing the arc duration.

Ceramic tubes and insulator have uncertain influence on arc duration as shown in Figs. 11 and 12, and it may also have influence on arc length. Arc images of experiments with or without ceramic tubes at all voltages under different magnetic field are manually processed to get arc lengths. Five different arc images at the instant of arc clearing in the same condition are picked, and their corresponding arc lengths are calculated through counting the pixels of the center line of arc columns. Average arc length is calculated and shown in Fig. 14.



(a) Without ceramic tubes and insulator



(b) With ceramic tubes and insulator

FIGURE 14. Comparison of arc length with or without preventions.

The arc length becomes longer as voltage increases, and the lines seem to be linear. Comparing with the influence of ceramic tubes and insulators on arc duration as shown in Figs.11 and 12, the ceramic and insulator has only tiny influence on the arc length at each voltage and flux density. For example, arc duration at 660 V and 70 mT with preventions is almost twice as that of without previsions, but the arc length is almost the same (which is approximately 120 mm). When compared with arc lengths at 30mT, the one with ceramic tubes are a little shorter with voltage under 470V. When voltage goes up to 530V and 600V, the result goes to the contrary. The reason is mainly lay on that ceramic tubes can restrict the arc moving path. When voltage is at a lower stage, arc is just lengthened by magnetic field instead of being curved. And the ceramic tubes prevent arc moves along the shortest path. When voltage increases over 470V, arc is not only lengthened but also curved, and the rotation is more apparent when there are no ceramic tubes. So that the arc with ceramic tubes can move more directly, thus the arc length is shorter than the other condition. Average electrical field strength inside the arc column can also be roughly estimated through dividing the voltage by the arc length, and the result is ranging from 4.5V/mm to 6 V/mm. Generally speaking, ceramic tubes and insulators have no influence on the mechanism of magnetically blow-out.

Arc re-ignition starts at the broken circuit voltage is 600V, and the corresponding arc length is about 100mm as shown in Fig 14(a), which is consistent with the mechanism analysis discussed in section IV-A, and the arc length must also reach a certain threshold for re-strike occurring. From this point of view, suppression measures are only necessary in products with high voltage, but not necessary for the low voltage.

E. FURTHER WORKS

Experiments are carried out under a single condition of copper contact, opening speed, 50A current, as well as resistive load in this study, those parameters do have influence on effectiveness of the suppression on swirl re-strike. According to the mechanism mentioned in Section IV-A, the contact material may affect transfer speed of arc root which is much slower than that of arc column, and it should have less influence. The opening speed multiplying the instantaneous of re-striking will determine the gap when arc re-entering and therefore determine how much the arc voltage drops, which will have a little influence on the arc duration. With a large time-constant load, voltage in final stage of arcing should be the total voltage of power source and electrical motive force of inductance, which usually is times of source voltage and lead to a longer arc length, and may add difficulty on suppressing re-strike. Higher current might also make it hard to suppress the swirl re-strike. It needs further study to make it clear how effectiveness the insulator will be under different current level and load type.

V. CONCLUSION

Behavior and mechanism of swirl arc re-restrike in high power bridge-type DC contactors was studied and preventive methods are proposed. Information on 4 aspects are given for switch designers, they are: mechanism and factors of the swirl re-strike, judgement of the swirl re-strike from only arc voltage waveform, potential suppression method as well as possible by-functions of the suppression method. The following conclusions are obtained.

(1) Swirl arc re-strike occurs once the magnetically blown-out arc is long enough to re-enter contact gap when the arc voltage is high and magnetic field is non-uniform. And it can be figured out by the pattern of voltage dropping to half appearing on arc voltage if no high-speed video is available.

(2) The mechanism of the swirl re-strike is clarified, and the random arc starts position, the perpendicular Lorentz's force to the circular-shape arc, as well as the different transferring velocity of arc column and arc roots are major reasons.

(3) Covering the inner faced part of the two stationary contacts with ceramic half-tubes and inserting insulators between them can perfectly eliminate the swirl re-strike occurred at voltage high to 730 V and magnetic flux density of from 30 mT to 70 mT. Adding ceramic half-tubes and insulators has no influence on arc length and mechanism of magnetically blow-out, but has possible by-function of slight increasing of the arc duration.

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