REQUIREMENTS FOR VACUUM CIRCUIT-BREAKERS UNDER CAPACITIVE SWITCHING DUTY

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ABSTRACT

Capacitive current switching means a specific operating condition for vacuum circuit-breakers. It combines high inrush-currents at connection of a capacitive load with considerable low breaking currents at its disconnection. Though the event of a restrike under recovery voltage stress can cause voltage escalation a reliable dielectric performance is essential. This leads to a reconsideration of the vacuum circuit-breaker design for capacitive switching duties. The behavior of various contact materials and designs are studied during series of tests, representing complete switching cycles at 24 kV system voltage comprising making operation and current interruption followed by the subsequent capacitive recovery voltage.

The pre-arcing behavior and the occurrence of restrikes are observed as indication for the alteration of the dielectric condition of the contact system during the test series. In comparison of both kinds of breakdowns a significant difference in the breakdown field strength appeared. Considering the occurrence of restrikes these events can be observed as late as several hundreds of milliseconds after current interruption. In view of the reconsideration of an appropriate contact design the choice of contact material takes centre stage since the tested contact types of various materials show a different behavior in their pre-arcing and restrike performance. The relevant material properties affecting the deterioration of the contact surface during a number of capacitive switching operations and the probability of a breakdown must be taken into account accurately.

INTRODUCTION

Switching of capacitive currents represents a specific operating condition for circuit-breakers with a high demand on the dielectric performance of the breaker. While the dielectric behavior after high-current interruption results from the arcing period and the significantly melted contact surfaces, capacitive current switching means a particular impact on the dielectric condition of the contact system. The test specifications given by the relevant IEC standards [1] comply with these conditions.

The connection of a capacitive load to the system may involve inrush-currents of some kiloamperes at a multiple of the power frequency [2]. Inevitably this connection is associated by a pre-breakdown at the circuit-breaker at a certain moment during contact closing. The pre-arcing heats the contact surface locally and can cause contact welding. At the following breaking operation this welding is ruptured and tips are left on the contact surfaces. Some of these tips may be removed in consequence of an arc during breaking operation. But at the interruption of capacitive loads currents are significantly lower then short-circuit currents, e.g. in the range of hundreds of amperes. Hence the smoothing effect of the circuit-breaking arc is reduced distinctly. Furthermore the combination of contact welding and rupture can produce a severe deterioration of the contact surface structure in the macroscopic and the microscopic scale. Subsequently under capacitive switching conditions the circuit-breaker is stressed by a recovery voltage of up to twice the system voltage. In the event of a restrikes a voltage escalation can be caused due to the trapped charge on the capacitor [3]. Consequently a reliable dielectric performance of the breaker is essential.

For the capacitive switching performance the occurrence and the probability of a breakdown of the contact gap is an important factor. Firstly the breakdown at pre-arcing determines the duration of the heat input into the contacts due to arcing. Hence the breakdown behavior affects the subsequent alteration of the contact surface condition. Secondly the occurrence of a breakdown in terms of a restrike after current interruption is the limiting factor in view of the capacitive switching capacity of the circuit-breaker [1].

This paper covers a combined examination of the breakdown behavior in the shape of a pre-arcing and a restrike. This leads to a closer inspection of the contact system design with a reconsideration of the choice of contact material for capacitive switching duty.

TEST PROCEDURE

The capacitive switching tests comprise both making and breaking operations. The test currents and the capacitive recovery voltage are supplied by a synthetic test circuit. At making operation the contact gap is stressed by 20 kV d.c. voltage and an inrush-current of 4.5 kA and 250 Hz frequency is applied to the circuit-breaker. The breaking operation is associated by 500 A (50 Hz) breaking current and subsequently the contact gap is stressed by a capacitive recovery voltage of 50 kV (50 Hz). The configuration and the operation of the synthetic test circuit are described in detail in [4].

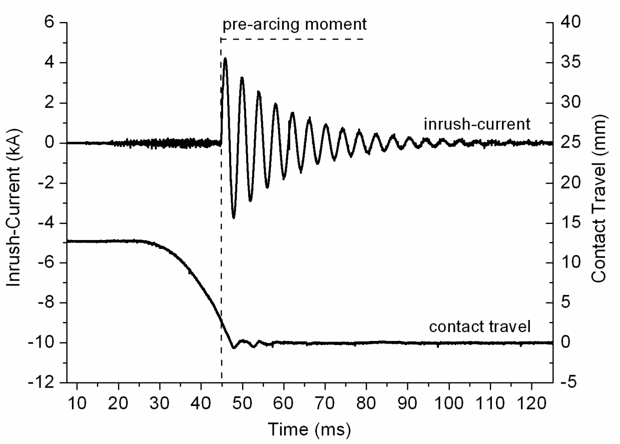

Figure 1. Making operation oscillogramm.

For all the tests a test switch is used which comprises a vacuum test vessel and an electro-magnetic drive. The drive provides the appropriate contact closing and opening speed, the test vessel permits the installation and investigation of various contact types. All tested contacts are 45 mm in diameter. The contact gap is adjusted to 12 mm, the contacts are surrounded by a vapor shield mounted insulated from either contact.

To evaluate the dielectric behavior of the circuit-breaker under capacitive switching duty for each of the contact types a series of 100 making and breaking operations is executed. During making operation the moment of pre-arcing and the present remaining contact gap are detected. Figure 1 shows a typical oscillogram of a making operation. The residual contact gap at pre-arcing corresponds to a pre-arcing field strength which is observed in the course of the test series. The pre-arcing field strength distribution gives evidence of the dielectric condition of the contact system and its development during the tests.

Again the observation of restrikes occurring after breaking operation under capacitive recovery voltage stress reveals the dielectric strength of the contact gap, always in consideration of its statistical distribution. The current and voltage curves of an exemplary breaking operation are plotted in figure 2.

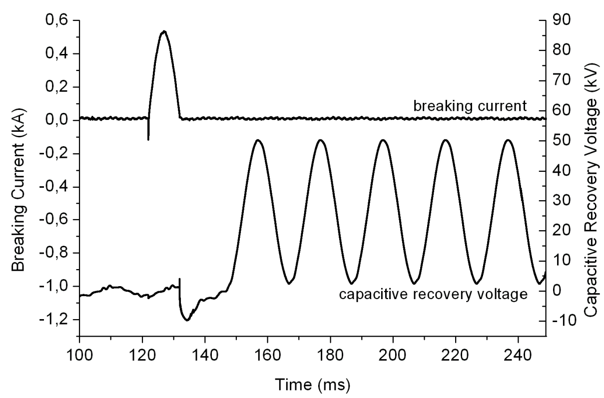

Figure 2. Breaking operation oscillogramm.

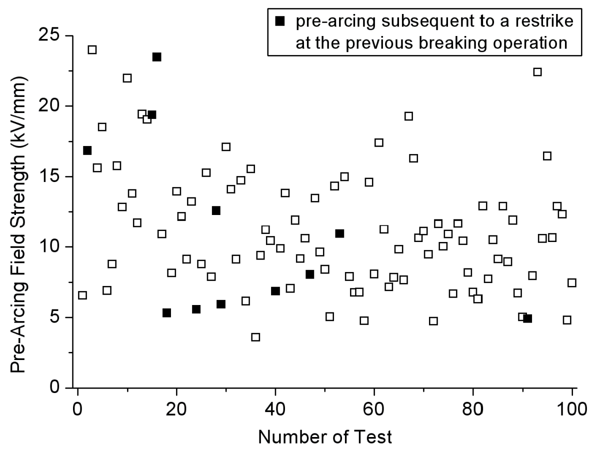

Figure 3. Pre-arcing field strength distribution (type A).

EXPERIMENTAL RESULTS

The test series are carried out using various types of contacts. These types include different contact materials and manufacturing methods. In this paper they are designated by capital letters.

The distribution of the pre-arcing field strength in the course of the tests using contact type A is stated in figure 3. The field strength values are plotted in the original order of the switching tests. In this example the distribution is considerably uniform with no obvious conditioning or deconditioning effect, especially under consideration of the lower edge of the scatter band. These lower pre-arcing field strength values correspond to early pre-arcing events and comparatively large remaining contact gaps at the moment of breakdown. During this test series the number of restrikes occurring after breaking operation total to 11, being struck with a time delay between 4 ms and 267 ms after the first rise of the recovery voltage.

Considering the events of a restrike and the pre-arcing behavior together, restrikes are not followed by a notably early pre-arcing at the subsequent making operation. In figure 3 the filled squares mark the pre-arcing field strength at making operations following a restrike.

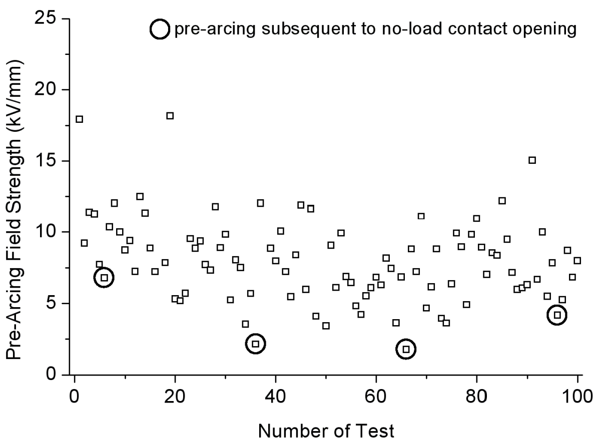

Figure 4. Pre-arcing field strength distribution (type M).

It becomes clear that the restrikes are not necessarily accompanied by a remarkably low pre-arcing field strength. On the other hand there is no coincidence of restrikes with exceptionally low pre-arcing field strength values at the previous making operation. Hence an early pre-arcing with a long pre-arcing time does not involve the occurrence of a restrike at the following breaking operation.

The breaking current value emerges as a significant factor on the pre-arcing behavior. In the course of a test series comprising 100 switching operations four no-load opening operations at different stages of the series are implemented. This reveals an immediate reduction in the pre-arcing field strength subsequent to a single no-load contact opening. Figure 4 illustrates the pre-arcing behavior of the contact type M with the field strength values adjacent to the random no-load openings being marked. In figure 5 the pre-arcing field strength distribution already shown in figure 3 is opposed to the breakdown field strength that can be determined at the moment of a restrike. Whereas the pre-arcing field strengths amount to values between some 3.6 kV/mm and 24 kV/mm the restrikes occur at field strength in the range of 2.1 kV/mm to 4.3 kV/mm.

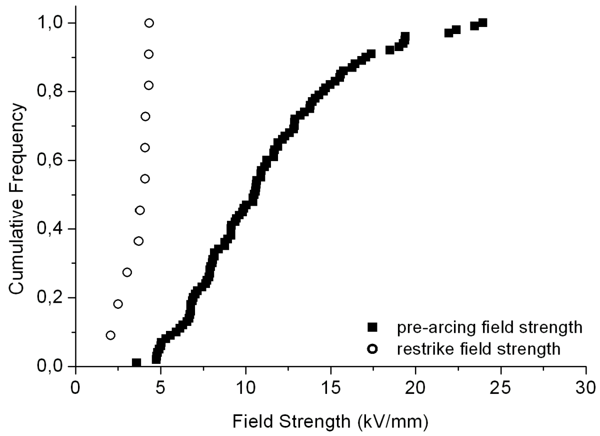

Figure 5. Breakdown field strength at pre-arcing and restrike events (type A).

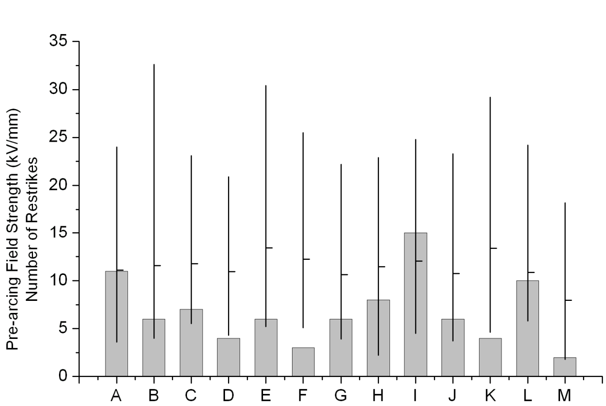

Figure 6. Range of pre-arcing field strength and number of restrikes at test series using various contact types.

Besides the differing breakdown field strengths at pre-arcing and restrike the number of restrikes in the course of a test series shows no correlation with the pre-arcing field strength distribution. Figure 6 illustrates the pre-arcing and the restrike behavior of different contact types during the designated test series. While the bars represent the number of restrikes, the lines mark the range of pre-arcing field strength with the crossline as its mean value. The number of restrikes varies from 2 to 15 and the pre-arcing field strength mean values from 7.9 kV/mm to 13.4 kV/mm, whereas the overall spread amounts from 1.8 kV/mm up to 32.6 kV/mm.

The occurrence of restrikes can be observed up to hundreds of milliseconds after applying the capacitive recovery voltage. Figure 7 summarizes the restrikes in the course of several test series. More than 40 % of the restrikes in the course of the test series are recorded during the first voltage cycle and predominantly at rising voltage slope. An other large percentage of restrikes occurs during a second time segment up to 150 ms after the first rise of the recovery voltage. Furthermore most of the restrikes are recorded at rising than at falling voltage slope.

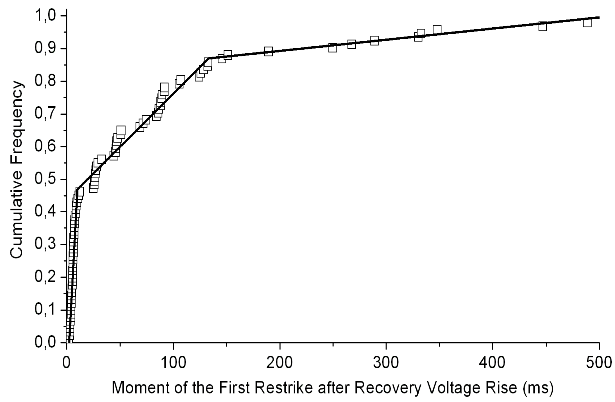

Figure 7. Restrike moment distribution.

DISCUSSION

For the certification of a vacuum circuit-breaker for capacitive switching duty according to standards the occurrence of restrikes represents the key factor [1]. Furthermore the pre-arcing behavior determines the resulting alteration and the damage of the contact surface and influences the dielectric condition of the contact system. The combined consideration of both kinds of breakdowns introduced in this paper discovers no consistent trend of the probability of the breakdowns at a certain field strength taking various contact types into account. Moreover the breakdown field strength at the restrikes fall well below the pre-arcing field strength values as shown in figure 5.

During making operation the field strength at the contact gap increases steadily as the moving contact approaches the fixed contact. Furthermore the deposition of contact material as a result of the previous switching operations may have reduced the contact gap in the macroscopic scale

seriously [4]. Besides the decreasing contact gap the local field enhancement due to microprotrusions is crucial for the moment of breakdown. The restrike event after breaking operation requires an even more detailed view. Assuming a completely opened contact gap at the moment of recovery voltage application (figure 2) the field strength at the gap develops according to the voltage shape. A large proportion of the restrikes occurs in consequence of the increasing field strength during the first voltage cycle (figure 7). Additionally the circuit-breaker faces some decaying vibration resulting from the opening operation and the following bouncing of the breaker and the drive. These vibrations can provoke the release of particles from the contacts or from the surroundings and finally cause a restrike [5, 6, 7]. Since the vibrations decay after some tens of milliseconds after the circuit-breaker reaches its final position their influence on possible particle releases causing breakdowns is temporary. This implicates the break at the end of the second time segment visible in figure 7. Finally these breakdown initiating effects are superposed by the statistical probability of a breakdown due to the ongoing voltage stress on the circuit-breaker.
Consequently the statistical distribution of restrike occurrences is supposed to be subject to more complex conditions than the pre-arcing events. The absence of an apparent correlation between the pre-arcing and restrike behavior in view of the relevant breakdown field strength, the breakdown probability and the present contact surface condition taking various contact types and materials into account corresponds to this.

At rating of contact materials for vacuum circuit-breakers diverse criteria are of main interest, most of them with regard to the high current interruption capability and the dielectric strength of the contact gap after high current interruption [8, 9]. The contact material qualification for capacitive switching duty in particular requires material properties such as a high melting point, low welding tendency, low material chunking and deposition, high work function and a smooth surface structure. These properties impact the dielectric behavior of the contact gap under recovery voltage stress, especially after a number of switching operations. Firstly they determine the contact surface damage due to the materials behavior in terms of welding, rupture and the subsequent material transfer and surface formation. Secondly for the mechanisms leading to a breakdown the properties of the individual materials and their composite used as contact material must be considered in detail. This implicates extensive tests of the eligible contact materials under capacitive switching conditions [8].

CONCLUSION

Capacitive switching duty has a significant impact on the contact surfaces of vacuum circuit-breakers. This results from the severe stress on the contact surfaces in consequence of the capacitive current switching operations. In the course of numerous operations a serious material transfer between the contacts develops. This macroscopic surface deterioration and the microstructure determine the dielectric condition of the contact system. During the combined making and breaking test series a differing breakdown behavior in terms of pre-arcing and restrikes becomes obvious. Besides the absence of a correlation between the pre-arcing behavior and the frequency of restrikes the breakdown field strength at pre-arcing and restrikes differ considerably. This reveals the differentiated responsible origins of both kinds of breakdowns.
The significantly varying pre-arcing and restrike behavior of the various types of contacts tested clarify the relevance of the appropriate choice of contact material for capacitive switching duty. In this regard the material properties affecting the contact welding, surface formation after its rupture take centre stage. Additionally the properties determining the probability of a breakdown under voltage stress such as the work function and the tendency of particle detachment are of particular relevance.

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