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ORIGINAL RESEARCH PAPER

# Online non-invasive evaluation of arcing time for condition assessment of high-voltage gas circuit breakers

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**Abstract**

Online non-invasive methods to assess circuit breaker condition have been under consideration in recent years. The combination of the arcing time and the short-circuit current recorded by protective relays can be utilized to assess the degrading impact of current interruption on arcing contacts. In many previous investigations, an integral over arcing time of different functions of current and voltage has been proposed to predict the erosion rate of arcing contacts. Although the arcing time is a crucial parameter for these indices, no easily adaptable method to online condition assessment is available. This paper proposes a method for online determination of arcing time based on the measurement of the switching time of the auxiliary contacts. Several experiments have been performed under no-load conditions as well as during short-circuit current interruption, on two circuit breakers with different trip coil excitations (AC and DC). The results show that the delay time between the contact separation instant of the arcing contacts and the switching time of the auxiliary contacts has a very low jitter. This enables precise determination of the arcing time by measurement of the switching time of the auxiliary contacts, which is accessible during the online operation of circuit breakers.

## 1 | INTRODUCTION

The condition monitoring of power equipment has been increasingly taken into account in recent years. The growing tendency of utilities to have the most reliable performance of circuit breakers at the lowest possible price, which is responsible for the move toward economic approaches determining the condition of subcomponents in circuit breakers. Among different methods of condition monitoring, non-invasive online procedures having the opportunity to become integrated into power the system operations, take the highest priority to estimate circuit breaker remaining life and to monitor its ageing. Those methods are able to provide the data required for making the decision of when and how the circuit breaker is supposed to be maintained in condition-based maintenance (CBM) and reliability-centred maintenance (RCM) methods [1–3].

The monitoring of interruption chamber as the most vital subcomponent of a circuit breaker is of the highest priority among the other parts of the circuit breaker because any deviation from normal function can lead to a failed current interruption [4, 5]. Contacts, nozzle and the interrupting medium (e.g. $SF_6$ gas) absorb the arc energy dissipated during every current interruption. The energy absorbed by contacts causes their temperature to rise to the melting and boiling points, resulting in contact erosion [6, 7]. In this regard, the question of how healthy the condition of contacts is, could be an indicator of interruption chamber health and a criterion to assess the electrical endurance of a circuit breaker [8, 9]. Furthermore, taking into account, the 14% share of interruption chamber in major faults adds on the importance of interruption chamber monitoring [10].

There have been different methods proposed in the relevant literature to perform some condition monitoring based on measuring a parameter and analysing the obtained data to assess contacts health, such as vibration analysis and dynamic contact resistance measurement. Under vibration analysis approach, the vibration patterns from operating mechanism recorded during opening/closing operations [11–15], or acoustic signals emitted by arc and main contacts at the instant of contact touch are analysed [16]. To perform dynamic contact resistance measurement, contact resistance of the circuit breaker is measured while the contacts move; this provides some information on the state of the main and arcing contacts [17–21].

Some other methods monitor contacts ageing and assess the remaining lifetime by considering the cumulative thermal stress imposed on contacts during every single current interruption. In this regard, the determination of an easy-to-measure parameter indicating the mass loss after every interruption has been under consideration in the existing literature. The number of interruptions, the current amplitude [1], transferred electric charge [22], and arc energy [23] have been proposed as thermal stress indices to evaluate contact mass loss. The proposed methods using current instantaneous amplitude take advantage of simple availability of measured current by protective relays. Nevertheless, assessing mass loss based on arc energy requires to measure arc voltage across the terminals of circuit breakers. It requires a measuring system that withstands very large transient voltages, but at the same time is able to measure the arc voltage in the range of a few kilovolts with good resolution, which is very difficult from the implementation point of view [24]. Therefore, it sounds to be more practical to consider the integral of a specific function of instantaneous current over arcing time as the thermal stress index [25]. This cannot be accomplished without an accurate measurement of the arcing time, which is a very complicated task [18], especially under online conditions. This paper is intended to propose an online easy-to-implement method to evaluate the arcing time by measuring the timing of auxiliary switches in the drive mechanism of the circuit breaker. To verify this idea, many experiments under no-load and short-circuit conditions have been conducted on two types of medium voltage gas circuit breakers. Based on the results, it is shown that the auxiliary contact timing can give an accurate indication of arcing time. It is worth mentioning that the auxiliary contacts are at ground potential and easily accessible, which makes the proposed method adaptable to online condition monitoring schemes.

## 2 | BASIC THEORY

As schematically shown in Figure 1, a circuit breaker can be subdivided into three major subcomponents [7, 26].

1. Operating mechanism: In this subcomponent, the stored energy, in a spring, or a hydraulic or pneumatic system, is transferred to the moving contact causing it to move with the appropriate speed.
2. Control and auxiliary system: The operation of a circuit breaker is triggered when a command signal is applied to a coil providing required electromechanical force to move a latch or open a valve. To monitor the closed/open state of the main contacts, this subcomponent includes auxiliary contacts. These contacts are actuated by the main shaft, used for the operation of moving contact, through an intermediate linkage.
3. Interruption chamber: This subcomponent in which the current is interrupted consists of the main and arcing contacts, nozzle, quenching gas, an insulator rod (linking the moving part to the main shaft), and the outer insulation.

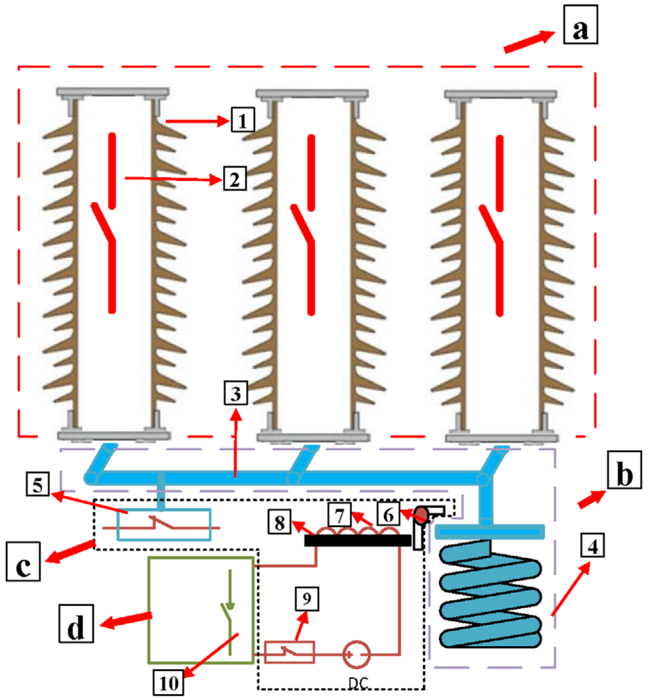

**FIGURE 1** The schematic of a circuit breaker and relay: (a) interruption chamber: (1) external insulator, (2) main and arcing contacts; (b) operating mechanism: (3) connecting rod (main shaft), (4) opening spring; (c) control and auxiliary system: (5) normally closed auxiliary contact, (6) latch, (7) trip coil, (8) armature, (9) normally closed auxiliary contact; (d) protective relay: (10) trip contact of relay

The opening time is the time interval between the instant of energizing the trip coil and the instant of separation of the arcing contacts. The opening time of a circuit breaker is not a constant parameter, as the operational delay times of different mechanical parts in the operating mechanism vary depending on different operational conditions, such as temperature, coil current, stored energy and idle time of the circuit breaker. Therefore, the nominal opening time of a circuit breaker cannot be used to determine the arcing time. The auxiliary contacts are, however, linked to the main shaft, and therefore any variation in operating time of the mechanical parts, e.g. the latch and energy storage system, influences the operating time of auxiliary contacts in the operating mechanism and main contacts in the interruption chamber, in the same way. In other words, because the time variation in the operation of the mechanical parts of the operating system is the same for the main contacts and the auxiliary contacts, the time difference between operating of auxiliary contacts and main contacts remains constant. Therefore, using the timing of the auxiliary contacts may enable an accurate determination of the arcing time. In this regard, many experiments under no-load

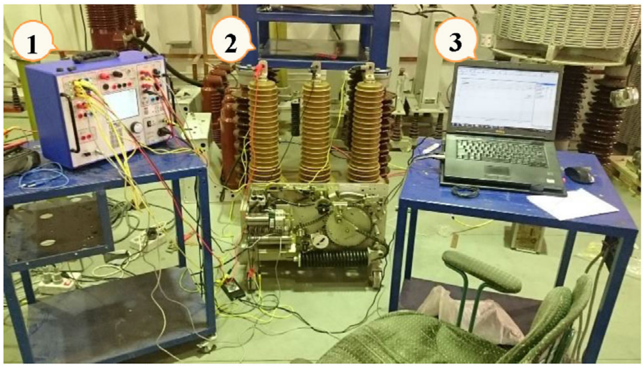

**FIGURE 2** Experimental Setup including: (1) circuit breaker analyser, (2) test circuit breaker, (3) laptop

and short circuit conditions have been performed, in order to examine the concept of using the auxiliary contact timing as a reliable and accurate indicator of the arcing time.

## 3 | EXPERIMENTAL SETUP

### 3.1 | No-load test

The no-load opening test setup, including a 24-kV puffer type $SF_6$ circuit breaker and a circuit breaker analyser (CBA), is shown in Figure 2. A laptop is used to control the CBA to implement the tests, as well as, to record and to analyse the data.

The main target of this test is to investigate the correlation between the instant of the main contact separation (i.e. start of the arcing in the circuit breaker) and the instant of change in the status of two types of auxiliary contacts, normally closed (NC) and normally open (NO). To ensure that the correlation exists independent of the type of the trip coil current, whether it is AC or DC, the tests have been performed on two circuit breakers having different type of trip coil currents. The trip coil current along with the status of main and auxiliary contacts during the opening operation of the two circuit breakers are recorded in the CBA. To make sure that the results are reproducible, 10 experiments have been done on each circuit breaker. Furthermore, the same number of experiments have been executed in different trip coil voltages to evaluate the validity of the results in the range of variation of trip coil voltages.

### 3.2 | Short-circuit interruption test

In puffer circuit breakers, the net acting force on the moving contact is resulted from the interaction between spring force as the driving force and gas pressure force as the retarding force. As a consequence, the maximum pressure inside the compression volume becomes nearly twice the filling pressure under no-load operation [26].

During the process of current interruption, first, the gas flow is almost stopped by the fixed arcing contact, which is still inside the nozzle throat (Figure 3). Then, it is blocked by the electrical arc burning between electrodes at high instantaneous amplitudes of current, which is referred to as the nozzle clogging [26]. The confined gas absorbs part of the arc energy causing its temperature and pressure to rise. Moreover, the ablation of nozzle adds some vapor to the compression volume leading to a further increase of the gas pressure. Because of a fixed driving force provided by the operating mechanism and increased retarding force imposed by the increased gas pressure during current interruption, the contact travel characteristic becomes dependent on the current amplitude [27]. This characteristic may put the coordination between the main contact opening time and the auxiliary contact switching time (acquired during no-load tests) under question. Therefore, several interruptions with different current amplitudes and arcing times have been conducted.

In order to generate high currents, a charged high-voltage capacitor bank is discharged through a high-current reactor.

Figure 4 shows schematically the test circuit including capacitor bank, 114 mF, 2.6 kV; high-current reactor, 110 μH, 100 kA; making switch; and test circuit breaker (TCB). The test current starts to flow by closing the Making switch and the electric arc is established after TCB arcing contacts separate.

In order to check the accuracy of the proposed method for measuring the arcing time using auxiliary contact timing, the arcing time is also measured by direct measurement of the arcing voltage. For this purpose, a capacitor divider with a ratio of 1000:1 is used. The arc current is measured using a 10 $\mu\Omega$-shunt resistor.

## 4 | RESULTS AND DISCUSSION

### 4.1 | No-load test

The results including trip coil current, as well as the timings of the main and auxiliary contacts, are shown in Figure 5.

After 50 ms delay time of the current relay, a DC current starts to flow through the trip coil and reaches its first peak at $t_1$. At this instant, the electromagnetic force becomes sufficient to move the armature and to release the latch. Afterward, the charged spring starts opening the main contacts. At $t_2$, the armature has reached the end position and the current is at its minimum value. Therefore, the time interval between $t_1$ and $t_2$ can provide some information about the speed of the armature and probable excessive friction of the latch subcomponent [28, 29]. Depending on the ratio of inductance and resistance of the trip coil, coil current reaches its second maximum at $t_3$. Because of the DC excitation of the trip coil, the maximum value is solely dependent on the magnitude of the coil resistance [15]. At $t_4$, the main contacts A1, B1, and C1 are opened almost simultaneously (with a time difference, i.e. pole discrepancy, of less than 0.2 ms), and after a short delay, at $t_5$ and $t_6$, the status of auxiliary NC contact (AUXC3) and normally-open contact (AUXC1) is changed.

The time difference between the main contact separation ($t_4$) and the auxiliary contact status change ($t_5$ or $t_6$) is of importance for the proposed method. Figures 6 and 7 show the results

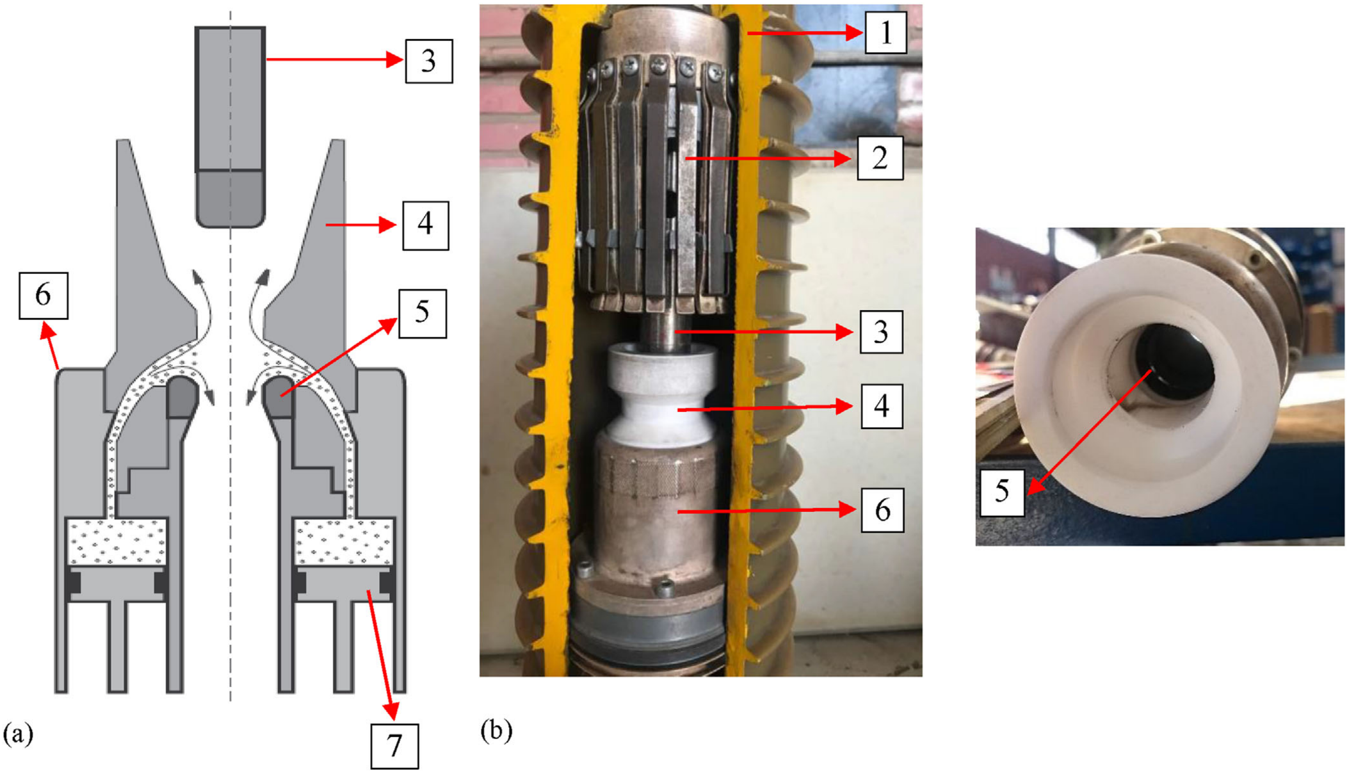

**FIGURE 3** Interruption chamber (a) schematically [26], (b) the test circuit breaker: (1) external insulator, (2) fixed main contact, (3) moving main contact, (4) nozzle, (5) moving arcing contact, (6) moving main contact, (7) fixed piston

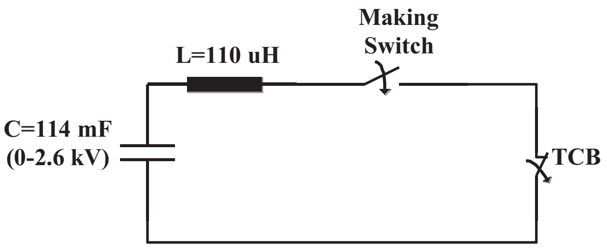

**FIGURE 4** The schematic of the test circuit

of 10 opening tests. The main contact opening time changes in the interval between 38.6 ms and 40.6 ms, and 33.2 ms to 38.4 ms for two circuit breakers with different trip coil excitation types.

The opening time of the main contacts cannot be used to calculate the arcing time because of the large opening time variations for DC and AC excitation, i.e. 2 ms and 5.2 ms, which result in significant errors in estimated arcing time. On the contrary, Figures 6 and 7 indicate that the time difference between the main and auxiliary contacts remains nearly unaltered for all no-load tests. In order to obtain a better understanding of the variation of data shown in Figures 6 and 7, Table 1 provides some statistical parameters such as mean value ($\mu$) and standard deviation ($\sigma$). A low standard deviation shows that the data are close to their mean value and, therefore, it boosts the likelihood of occurrence of the average value.

The data shown in the Table 1 confirm the use of auxiliary contact timing as an index to calculate the arcing time. Furthermore, it is noteworthy that the NC auxiliary contact has a better agreement with the main contact opening for both trip coil types. For the circuit breaker I, subtracting 1.64 ms from the opening instant of the NC contact results in the instant of the main contact opening instant. The time interval between the main contact opening instant and the current interruption instant (current-zero crossing) equals the arcing time. To investigate the validity of the results for different supply voltages of the trip coil, similar experiments have been executed and the results are presented in Tables 2 and 3.

The data shown in Tables 2 and 3 show that the variation of trip coil voltage within the ±10% range of the rated trip coil voltage does not undermine the validity of the results on the use of the auxiliary contact timing as for calculation of the arcing time.

## 4.2 | Short-circuit interruption test

Several experiments with different current amplitudes and arcing times have been conducted on the two above-mentioned circuit breakers with different AC or DC trip coil current. Figure 8 shows the recorded rated short-circuit current and the arc voltage waveforms by one of the short-circuit current interruption tests. Based on the arc voltage, the arcing time is evaluated to be 8.77 ms in this case.

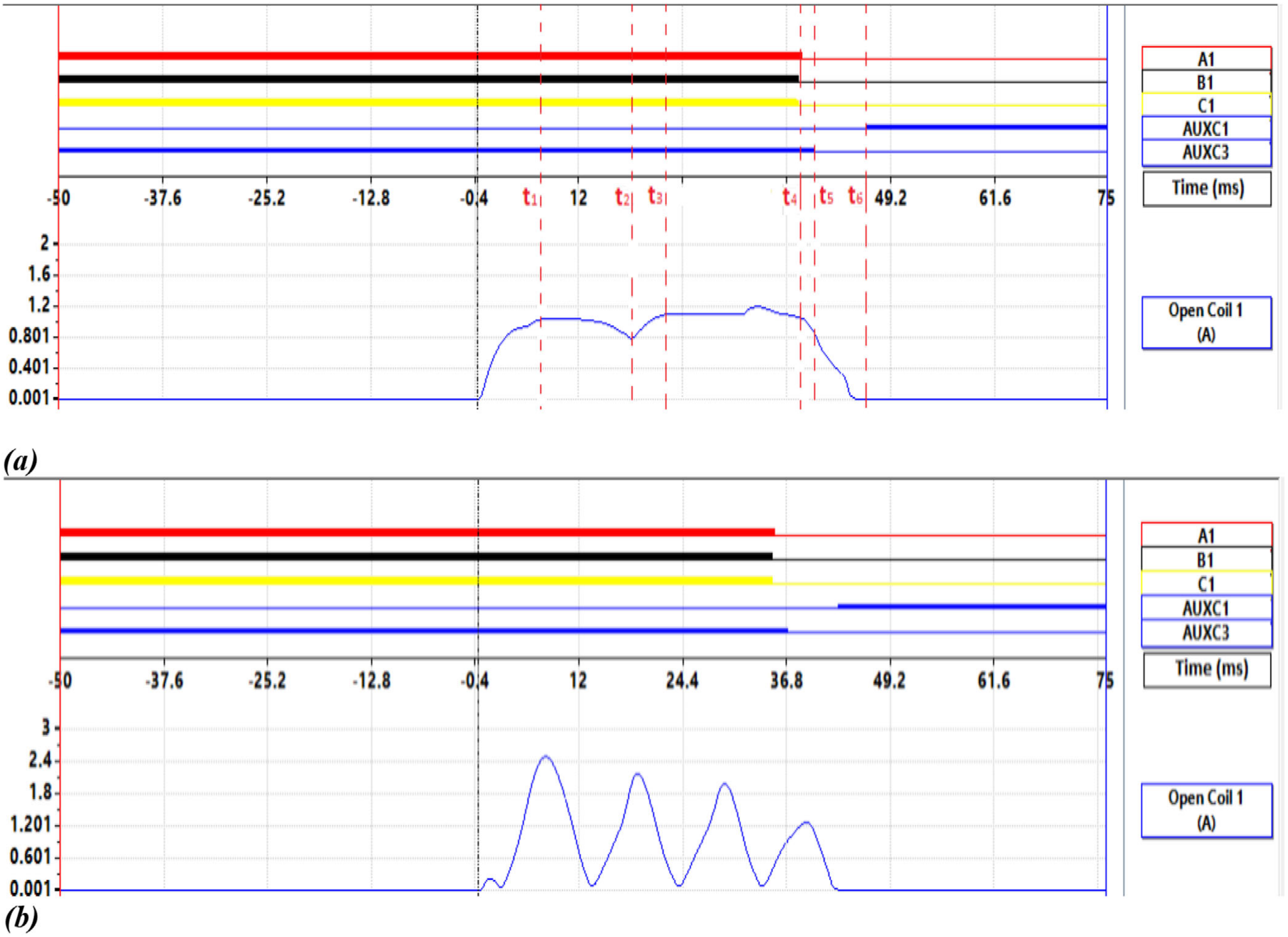

**FIGURE 5** Opening operation in two circuit breakers having different types of trip coil excitation, (a) DC and (b) AC (The explanation of $t_1$–$t_6$ are given in the text)

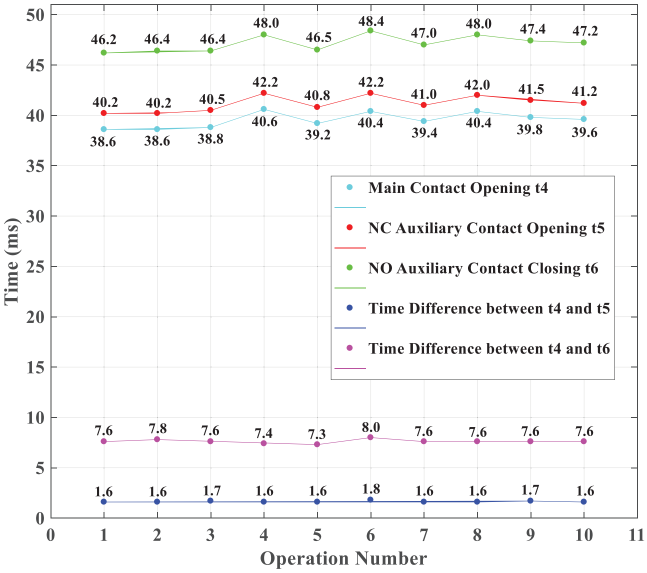

**FIGURE 6** Opening timing test results of the circuit breaker with DC-trip coil excitation

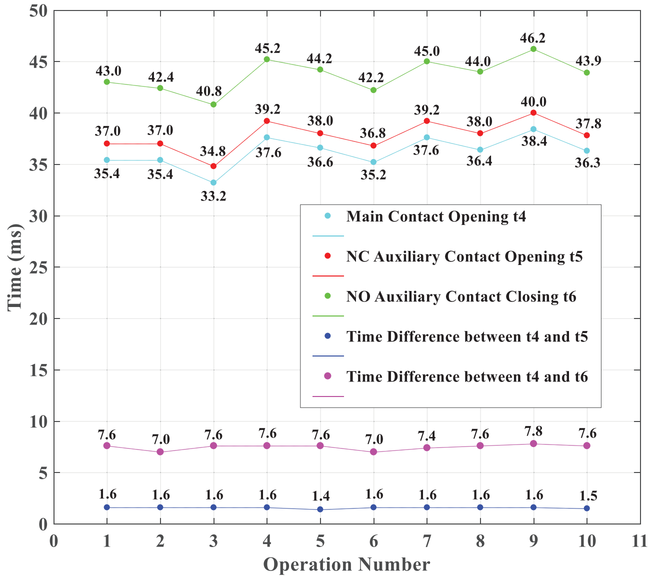

**FIGURE 7** Opening timing test results of the circuit breaker with AC-trip coil excitation

**TABLE 1** Mean value and standard deviation of main contact opening time and difference between main and auxiliary contacts timing with the rated trip coil voltage

| Circuit breaker type \ Statistical parameters | $t_4(\mu, \sigma)$ | $t_4–t_5(\mu, \sigma)$ | $t_4–t_6(\mu, \sigma)$ |
|---|---|---|---|
| I: DC excitation | **(39.5, 0.71)** | **(1.64, 0.07)** | **(7.61, 0.18)** |
| II: AC excitation | **(36.2, 1.42)** | **(1.57, 0.06)** | **(7.48, 0.25)** |

**TABLE 2** Mean value and standard deviation of main contact opening time and difference between main and auxiliary contacts timing with 90% of the rated trip coil voltage

| Circuit breaker type \ Statistical parameters | $t_4(\mu, \sigma)$ | $t_4–t_5(\mu, \sigma)$ | $t_4–t_6(\mu, \sigma)$ |
|---|---|---|---|
| I: DC excitation | (41.1, 0.91) | (1.84, 0.09) | (7.91, 0.24) |
| II: AC excitation | (37.8, 1.71) | (1.68, 0.10) | (7.62, 0.29) |

**TABLE 3** Mean value and standard deviation of main contact opening time and difference between main and auxiliary contacts timing with 110% of the rated trip coil voltage

| Circuit breaker type \ Statistical parameters | $t_4(\mu, \sigma)$ | $t_4–t_5(\mu, \sigma)$ | $t_4–t_6(\mu, \sigma)$ |
|---|---|---|---|
| I: DC excitation | (36.7, 0.76) | (1.67, 0.08) | (7.75, 0.21) |
| II: AC excitation | (36.5, 1.45) | (1.64, 0.09) | (7.53, 0.27) |

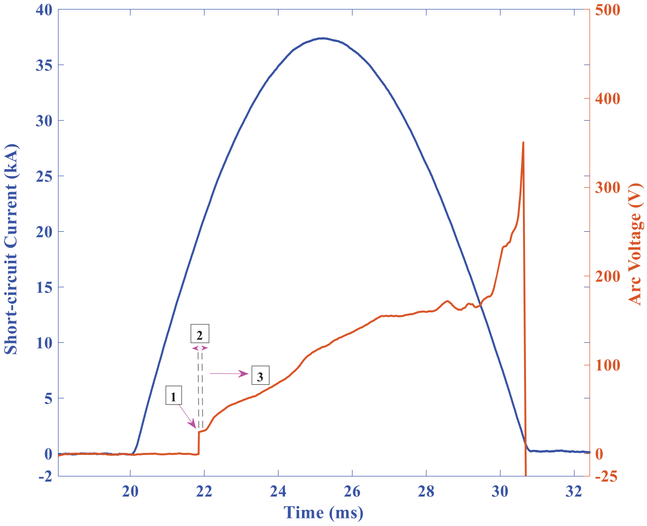

**FIGURE 8** The recorded short-circuit current and arc voltage waveforms: (1) contact part, (2) metallic phase, (3) gaseous phase

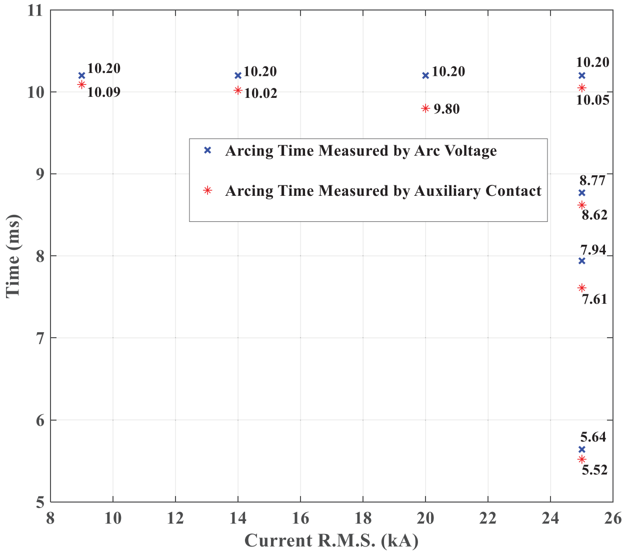

**FIGURE 9** Comparison between arcing time observed by arc voltage and calculated by auxiliary contact switching with DC-excitation-type trip coil

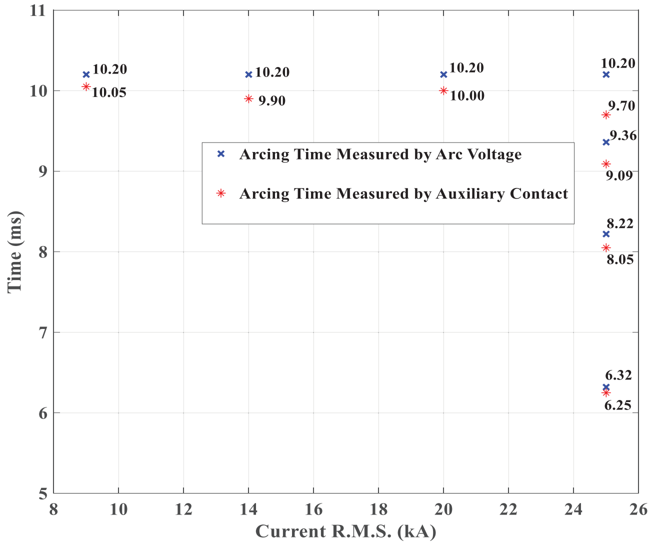

**FIGURE 10** Comparison between arcing time observed by arc voltage and calculated by auxiliary contact switching with AC-excitation-type trip coil

After arcing contacts are separated, the increasing current density in remaining contact spots causes the metal bridge built in the distance between contacts to soften, to melt, and to vaporize. The transition from liquid metal to vapor leads to a sudden increase of the arc voltage (instant 1 in Figure 8).

Subsequently, the surrounding gas is involved in the arc and a transition from the metallic phase to the gaseous phase occurs (Figure 8), and the arc voltage continues to rise [30]. Therefore, the visible indicator of contact separation in arc voltage is the abrupt voltage rise at the beginning of the metallic phase.

Figures 9 and 10 present the arcing time measured by the recorded arc voltage and calculated by auxiliary NC contact timing. According to no-load experimental data, in circuit breaker I and II, there is a 1.64 ms and 1.57 ms delay time between auxiliary contact opening time and arcing contact part, respectively. Taking those delay times into account, the arcing times in Figures 9 and 10 are calculated. The data show a highly acceptable agreement between the arcing time specified by arc voltage and arcing time specified by auxiliary contact opening time. The maximum deviation between the arcing times measured by the arc voltage and measured by the auxiliary contacts for the circuit breaker with DC-excitation-trip coil is 0.4 ms and for the circuit breaker with AC-excitation-trip coil is 0.5 ms.

It is noteworthy that experiments have been performed on two 24-kV $SF_6$ puffer-type circuit breakers with AC or DC excitation type. For puffer-type circuit breakers, the driving force necessary for the generation of the gas flow is provided solely by the operating mechanism, however, for self-blast circuit breakers, part of the arc energy is utilized to generate or to enhance the gas flow. Therefore, for self-blast circuit breakers, not only the retarding force is dependent upon the short-circuit current amplitude, like puffer-type circuit breakers, but also the driving force depends on the current amplitude. Thus, further investigations are required to prove the validity of the proposed method for arcing time determination in the case of self-blast circuit breakers.

Although the proposed method has been experimentally validated for only one type of circuit breaker in this paper, the method would work for many other gas circuit breaker types, as far as the parts/subcomponents of operating mechanism exposed to variations due to different influencing factors are placed before the linkage between auxiliary and main contacts. The FSA1 spring operating mechanism used in ABB high-voltage gas circuit breakers [31], and 3AP-Type operating mechanism utilized in Siemens high-voltage gas circuit breakers own this feature [32]. For these operating mechanism types, the time delay between auxiliary and main contacts would be more or less constant. There are, however, timing tests required to be performed in the factory to evaluate the time difference between the operation of auxiliary and main contacts for each circuit breaker type.

In addition, the contacts are shortened by the arc energy received during every current interruption. The impact of contact erosion on the precision of the proposed method could be a matter of discussion.

The pole discrepancy in the tested circuit breakers is not considerable, therefore, the main contacts opening time is assumed to be simultaneous. However, this assumption might be not valid for other circuit breakers. This matter should be taken into consideration about other circuit breakers.

It is also worth mentioning that in this investigation the NC auxiliary contact showed more agreement than NO auxiliary contact with the main contact opening time. Nevertheless, this result cannot be generalized for other circuit breaker types. Therefore, a series of no-load tests need to be performed on every circuit breaker to specify the appropriate auxiliary contact for determining the arcing time.

The other matter of discussion could be the type of operating mechanism. The spring-type circuit breaker was under study in this paper. Investigations on other types of operating mechanisms, like hydraulic or pneumatic, are required to ensure the agreement between arcing contacts separation and auxiliary contacts as an index for determination of arcing time. It is emphasized that the method proposed in this paper can be easily integrated into power system operations. In this way, it is possible to determine the arcing time in an online manner, which along with short-circuit current can be utilized to precisely predict the mass loss of arcing contacts and the remaining lifetime of the interruption chamber of high-voltage circuit breakers.

## 5 | CONCLUSION

In order to monitor the ageing of the interruption chamber as a critical subcomponent of circuit breakers, it is required to know the arcing time of current interruption. The method proposed in this paper is to use the auxiliary contact timing for the evaluation of the arcing time. Several no-load experiments have been conducted on two circuit breakers with different AC or DC trip coil current. The results indicate that there is a reliable correlation between the instant of the contact separation and the auxiliary contact switching. Furthermore, many experiments with different current amplitudes and arcing times have been performed on two circuit breakers with AC and DC trip coil current types.

The results indicate that the delay times found in no-load tests are reliably applicable to accurately determine the arcing times during current interruption operations. The measured arcing time along with current waveform recorded by protective relay can be employed to define an index for the thermal stress imposed on arc contacts during the current interruption. The noteworthy advantage of this method is the possibility of integration into power system operations, as the auxiliary switch is at the ground potential and thereby easily accessible even when the interruption chamber of the circuit breaker is at high voltage.

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