

THE INFLUENCE OF AIR FLOW ON CURRENT INTERRUPTION WITH AIR-BREAK HV DISCONNECTORS

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Abstract: The application of forced air flow is one of the possible approaches for quenching the arc during current interruption with air-break HV disconnectors. In the present paper, a series of experiments is presented to investigate the influence of the air flow on the small capacitive interruption with current up to 7.5A at 90kV phase voltage. Experimental data analysis shows that the arcing duration reduced 40%-50%, compared to interruption without air flow. This is because the re-strike voltage across the gap between the main contacts of the disconnector is increasing nearly linearly with increasing air gap distance with the assistance of the air flow. The re-strike frequency and the time derivative di/dt at current zero with air flow are much higher than that without air flow. Moreover, arc images show that there are two different arc modes: "thermal arc" and "dielectric arc". The obtained results reveal that application of air flow may convert thermal interruption mode to dielectric interruption mode, increases the dielectric strength of the air gap, and increases the interruptible di/dt with about a factor of 20. The mechanisms are discussed causing it to be an effective method to improve the interrupting capability of the air break disconnector.

1 INTRODUCTION

Disconnectors (also called disconnect switch, DS) need to interrupt small capacitive current in power substations. The principle study on interrupting small capacitive current using a DS without any aid devices was reported in [1]. The maximum current which can be interrupted successfully is limited by the speed of the moving DS blades, circuit topology, system voltage, etc. In order to allow a DS to interrupt a certain level of current, auxiliary devices such as arcing horns, vacuum interrupters, SF₆ interrupters are employed [2], [3]. A device injecting forced air flow into the arc ("air flow device") is one of the methods to improve the DS interrupting capability. This method proved to be an effective means to improve the capability of interruption [4]-[7]. For instance, it is stated that gas (air) flow has a strong effect in reducing the arc reach and arc length during the interruption process [4]; a vertical break DS with gas-flow device could interrupt 20A in a 138kV station [5]; a 135km line was dropped successfully at 345kV with the support of the gas-flow on a vertical break DS [6]; a 330kV vertical break DS with gas flow device was designed and tested in a 500kV test site showed that it was capable to interrupt a capacitive current up to 8.5A at 220kV phase voltage successfully [7]. Although the work related to DS with air flow is rather old, and exclusively based on an extra pipe applied under a vertical break DS, all test results proved this method to be effective for capacitive current interruption with a DS. However, all (but limited) literature only focuses on macroscopic test results but any

detailed analysis on mechanisms behind this method is lacking. In this paper a study is presented on the experimental data, specifically arcing time, re-strike voltage, re-strikes frequency and current derivative di/dt , etc. The simplified experimental circuit is plotted at the left side of Figure 1. R_s , L_s and U_s represent the source. C_s and C_l stand for the source- and load side capacitors bank. A picture showing the DS in the test-station is shown at the right side of Figure 1. The type of the DS is centre break. The air flow is controlled through two separated nylon air hoses ending at each tip of the main blades, directed towards the arc roots. The hose opening area is approximately 50mm², directed about 5cm from the arcing contact.

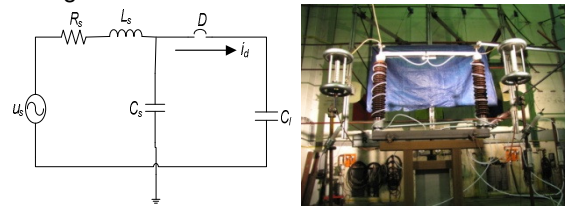


Figure 1: Basic circuit diagram (left), and photo (right) of the laboratory set-up on current interruption using a DS with assistance of air flow on both sides of main blades roots.

The experiments are conducted with the current I_d values of 0.5A, 1.4A, 2.6A, 3.9A, 5.0A, 6.3A and 7.5A at 90kV phase voltage. The value of C_s is taken 50nF and C_l ranges from 18nF to 265nF. The value of I_d depends on C_l since all other parameters in the circuit are fixed.

Two types of interruptions are performed for each applied current level: interruption without air flow (denoted as case A), interruption with air flow (325 litre per minute, denoted as case B). The air flow on each side is measured by air flow meters. Three operations are performed at each current level. The test of case A was not done at current 7.5A because the DS main blades reached the maximum position just after final arc extinction at 6.3A, which implied that interruption at 7.5A without air flow could fail. All interruptions during the experiments were successful, meaning that the arc extinguished before the main blades of the DS reached the final 90 degree angle opening position. The voltages across the source- and load side capacitors (u_{cs} , u_{cl}), and the current flowing through the DS i_d were recorded. The measuring and data acquisition system are presented in detail in reference [8].

2 EFFECT OF AIR FLOW ON ARCING

The current and voltage wave shapes for case A differ from case B. For the purpose of illustration, Figures 2-5 show the wave shapes of the voltages u_d across the DS ($u_d = u_{cs} - u_{cl}$) and the current i_d through the DS for the two different cases with current $I_f = 2.6A$. Experiments at other current levels have similar wave shapes in spite of varying arc duration. Figures 2 and 4 show wave shapes of u_d and i_d during the entire interruption in case A and case B respectively. Figures 3 and 5 are expansions of these two cases taken over the period $t = 1000 \sim 1150ms$ ($t = 0$ indicates the start of the arc). The air gap distance is approximately equal during this short time span.

For both cases: (i) by visual observation, the arcing duration lasts over 1s; (ii) the entire interruption consists of numerous interruptions- and re-strikes; (iii) electrical transient phenomena occurs at each re-strike. However, the differences between the interruptions with- and without air flow are apparent.

In case A, the arcing duration is 2.3s. Mostly, there is only a single re-strike within each half cycle of the power frequency current as shown in Figure 3. Once the re-strike occurs, the arc continues till the next current zero (the arrows in Figure 3 illustrate re-strike and the next arc extinction). Comparison of the wave shapes in Figures 2, 4 shows that the re-strikes for case A occur at lower breakdown voltage (and with lower transients) than for case B. For instance, in Figure 2 the re-strikes between 0-1000ms are not so clear; the re-strikes after 1000ms are less intensive as in case B. The arc duration, however, is 1.4s for case B, which means that with air flow the arc duration becomes shorter. Moreover there are multiple re-strikes occurring within each half cycle of the power frequency current. The re-strikes occur more frequently and have higher voltage transients. For instance, the

re-strikes at case B in Figure 5 are more numerous compared to case A.

Figure 6 shows the wave shapes of the voltage u_d between 800ms and 950ms for the two cases. Compared to case A, the re-strike voltages (the maximum values of u_d at the moment when the re-strike occurs) at case B are much larger for identical air gap distances. The reason is that the air flow cools the former arc path and removes localized patches of ionization and thus increase the dielectric strength of the same body of air in the gap.

It is also observed that the arc appears in two distinct modes. One is called "thermal arc", usually occurring in case A. It is dominated by a sequence of arc extinction at power frequency current zero and power frequency recovery voltage leading to re-strike until sufficient gap length has been reached. The other is "dielectric arc", usually occurring in cases with sufficient air flow (case B). Here, the arc is a very concentrated succession of arc interruption and re-strike. The arc is chopped at various phase angles within the power frequency current. That means the air gap dielectric recovery speed is greatly increased compared to case A, because of arc cooling body by the air flow. The thermal arc is longer and has more curls than the dielectric arc. Typical examples of these modes and their re-strike appearance are shown in Figure 7.

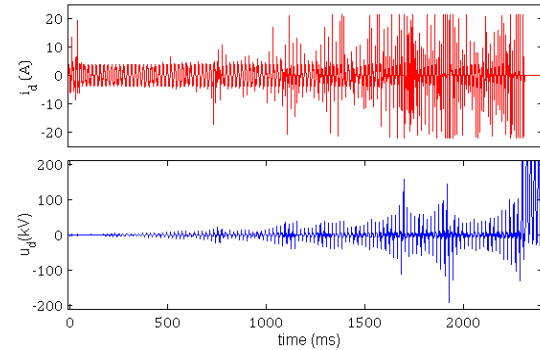


Figure 2: Wave shapes of waveforms i_d , u_d without air flow assistance (case A).

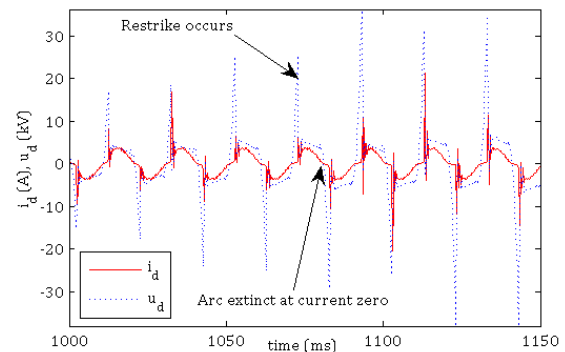


Figure 3: Expansion between 1000ms~1150ms of Figure 2.

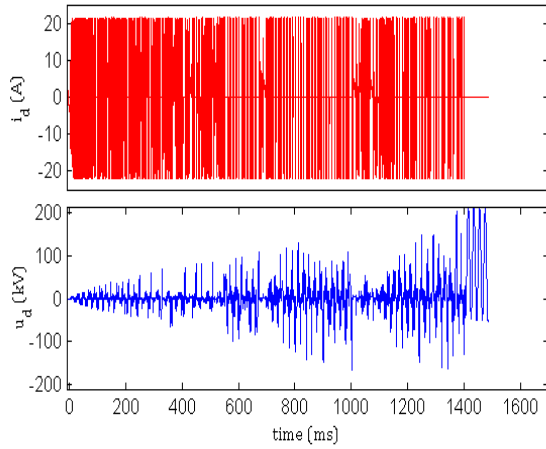


Figure 4: Wave shapes of waveforms i_d , u_d with air flow (case B).

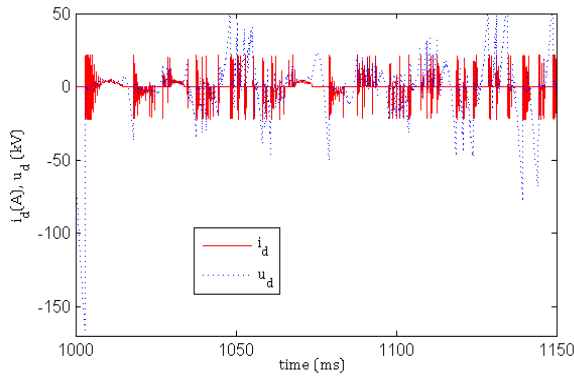


Figure 5: Expansion between 1000ms~1150ms of Figure 4.

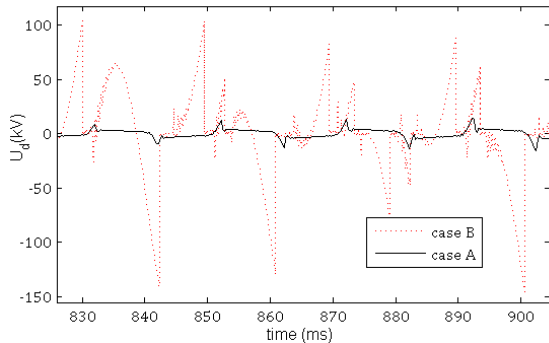


Figure 6: Expansion of u_d between 800ms and 950ms for the cases A and B.

3 ANALYSIS OF THE EXPERIMENTS

For experimental data analysis, we focus on the arc duration, which is obviously different for the cases A and B. The re-strike voltage, the number of re-strike per unit time and the current derivative di/dt are studied in order to understand the interruption mechanism with air flow.

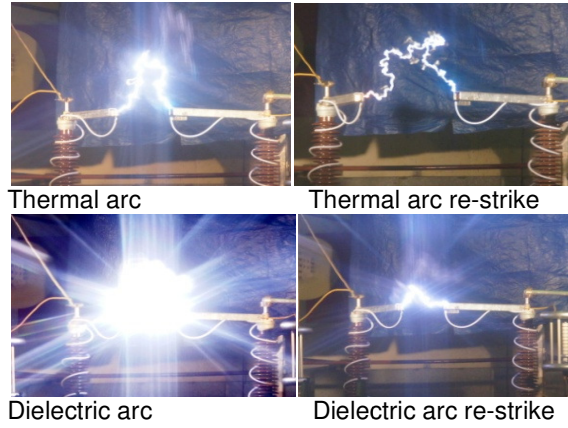


Figure 7: Arc modes and their re-strike moments.

3.1 Arc duration

The arc duration is influenced significantly by the interrupted current I_d and the air flow in the experiments. Figure 8 presents the arc duration versus the interrupted current with the air flow as a parameter for all interruption operations. Obviously, the arcing duration for case A is much longer than for cases B, the latter nearly 40-50% reduced with respect to the arc duration in case A. The trend line shows that arc duration tends to increase with increasing interruption current I_d in both cases.

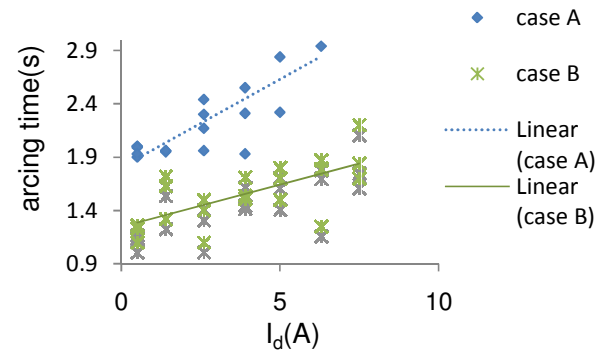


Figure 8: Arc duration versus the interruption current I_d for case A (above points) and case B (lower points).

3.2 Restrike voltage

The values of re-strike voltages are extracted from the experimental data. For the purpose of getting statistically relevant results, re-strike voltages from three repeated operations at the same current are combined. In order to find a possible trend, the obtained values of the re-strike voltages are divided into 10 bins, equally distributed over the interval from the moment when arc starts to the moment when the arc extinguishes completely. The variation of the median values of the re-strike voltage in each bin is presented in Figure 9, and 10. Because of the symmetry of re-strike value with respect to polarity, only positive re-strike voltages over time are shown. Time $t=0$ is the moment of arc initiation.

From Figures 9 and 10, the following conclusions are drawn.

The re-strike voltages in case B are much higher than in case A at each current level after identical opening time (corresponding to similar DS gap distance). The re-strike voltage is mainly determined by the interrupted current in case A. With higher current, the re-strike voltage is lower, which was also observed in [1]. However, when the air flow is high enough, the air flow becomes the dominating factor. For instance in case B, the re-strike voltage values are practically independent of current. On the other hand, at lower air flow (observed from experiments with air flow 215litre/minute, not included in this paper) the current still influences the re-strike voltage since the amount of the air flow is not large enough. It is also noticed that the re-strike voltage in cases A and B at current 0.5A approximately increases linearly with time (i.e. with the air gap distance), which suggests that the thermal influences do not play a role yet due to the small current.

It is concluded that both air flow and interrupted current play key roles during the interruption. When the current is rather small (roughly <1A), the thermal influence does not affect the re-strike voltage value significantly, and the air gap recovers mainly dielectrically. When the current is larger (roughly >2A in our test), the thermal influences start to dominate the interruption if the air flow is not large enough (roughly below 250litre/minute). If the air flow is large enough (case B, above 300litre/minute), the re-strike voltage values at different current levels are similar, which means the air flow mainly dominates the interruption process and the arc duration.

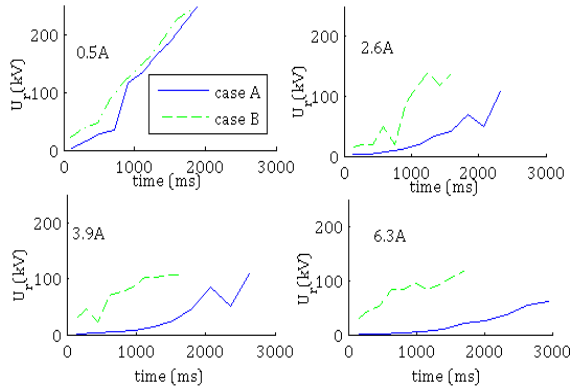


Figure 9: Restrike voltage versus time with air flow as a parameter at current range 0.5~7.5A.

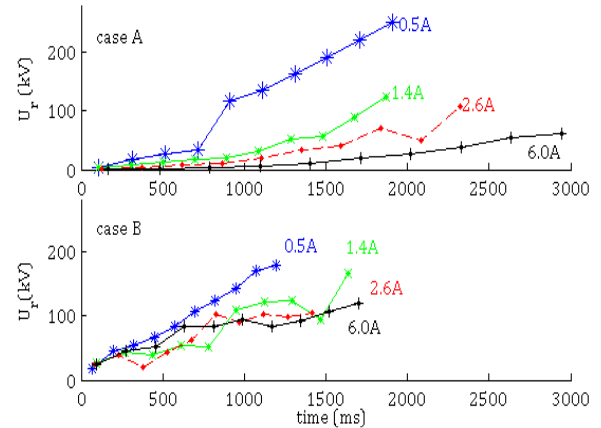


Figure 10: Restrike voltage versus time with current I_d as a parameter for cases A and B.

3.3 Re-strikes frequency

The air flow greatly influences the number of re-strikes per unit time. The number of re-strikes is different for both cases and for different current levels, see Figures 11 and 12 which show the cumulative number of the re-strikes versus time in two cases at various interrupted current levels. It can be observed: 1) Since the arc does not only extinct at current zero, but is also chopped at other power frequency phase angles due to the air flow, the number of re-strikes in cases B is much larger than in case A at each current level. 2) In case A, the number of re-strikes per unit of time is especially large at the very beginning of the interruption process. Later it increases slowly and linearly. The rate of increase is about 10 times per millisecond (one per power frequency half cycle). The initial high re-strike frequency is because the thermal influence plays no major role yet. Later on, once the re-strike occurs, the arc lasts continuously till the next current zero crossing. 3) In case B, the number of re-strikes is independent of the interrupted current level, which implies that the air flow in this case plays the major role.

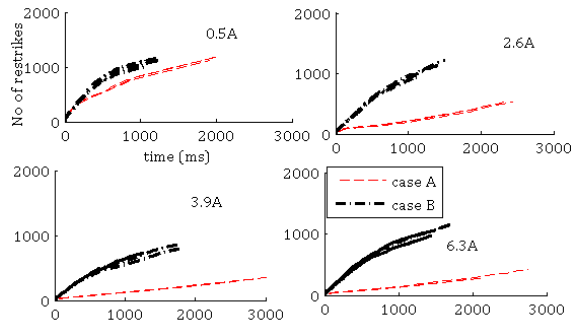


Figure 11: Number of the re-strikes versus time with the current as parameter for cases A and B.

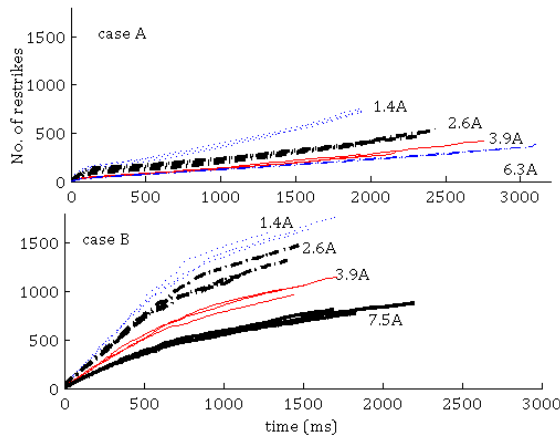


Figure 12: Number of re-strikes versus time for cases A and B at different values of I_d .

3.4 Current derivative di/dt

The current derivative di/dt at the moment of current zero is (for circuit breakers) a key factor to evaluate the interrupting performance. Since the arc extinguishes temporarily when the current crosses zero at each half cycle in case A, the derivative di/dt is calculated from the current waveform $i = \sqrt{2}I\sin(\omega t + \theta)$ where I is the rms value of the arc current; ω is the angular frequency ($2\pi * 50\text{Hz}$), and θ is the initial phase angle. The derivative di/dt at current zero is $\frac{di}{dt} = \sqrt{2}I\omega$. In case A, the current ranges from 0.5A to 6.3A, hence $di/dt = (0.2 \sim 3) * 10^{-3} \text{ A} / \mu\text{s}$. However the arc can be chopped at any moment after restrike for case B, which means it can happen at current zeros caused by the high frequency current components.

di/dt is calculated from the measurements at each arc extinction point. Calculated di/dt values are statistically distributed variables. Their properties are analyzed in Figures 13 and 14. The results are shown for different current levels and for the cases A and B. Noticeably the di/dt value at 0.5A does not make a significant distinction between case A and B, which confirms the conclusion drawn before on the thermal influences not being relevant yet at a current of 0.5A. When the current exceeds 1.4A, di/dt is higher with air flow than that without air flow at each current level.

The value of di/dt at percentile 50% in case A, is in between $0.004\text{A}/\mu\text{s}$ to $0.025\text{A}/\mu\text{s}$ (with very low current, 1.4A). This value is comparable with the estimated values before assuming only arc extinction after power frequency current zero. The values of di/dt in case B are approximately 0.1 to $0.3\text{A}/\mu\text{s}$, a few tens times higher than in case A. Obviously the interruptible di/dt with air flow is drastically larger than without air flow. This again suggests the strong influence of air flow on the interruption process. However for case B, it is hard to make difference between the test current levels.

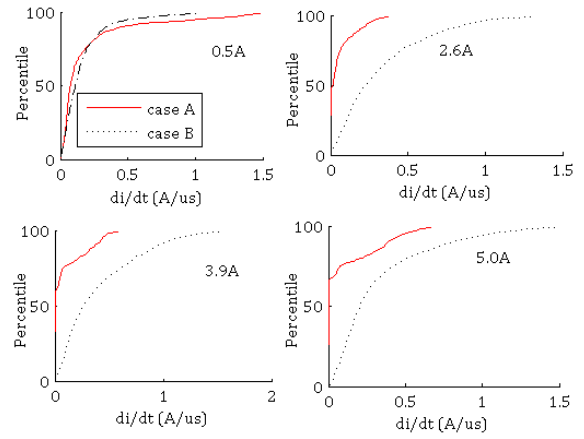


Figure 13: di/dt versus percentile in the cases A and B at different current.

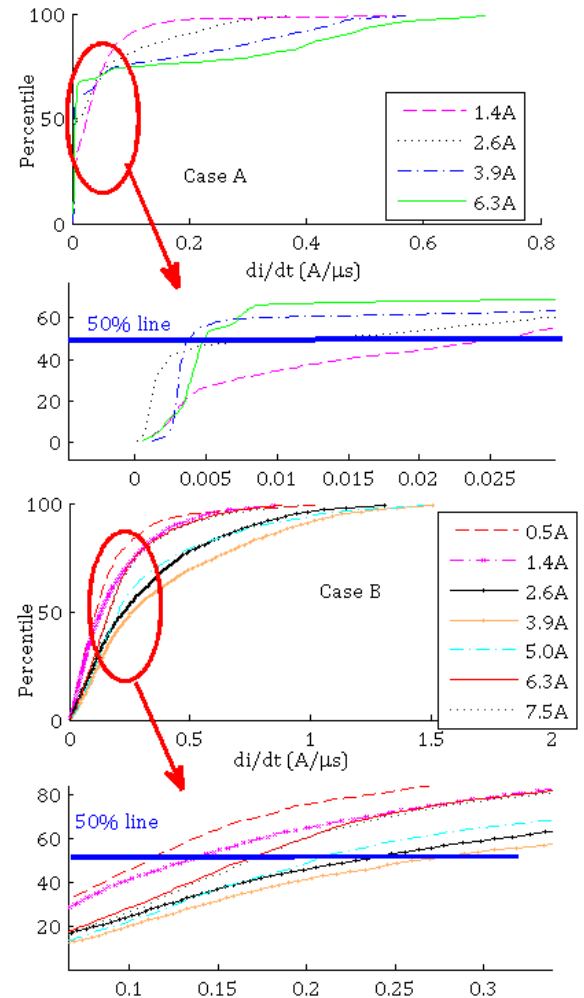


Figure 14: di/dt versus percentile for cases A and B with I_d as a parameter.

The reason is that these interruptions are unrelated to the current level.

4 DISCUSSIONS AND CONCLUSIONS

Two interruption modes are observed, dielectric and thermal mode. The dielectric mode interruption

mainly occurs in the case with an air flow of 315 litre/minute and with arc current roughly below 1A. The thermal mode occurs in the case without air flow at higher interrupted current ($>1.4A$ in our tests). The main differences between these two modes can be summarized as follows:

1) During the dielectric mode, the arc might be chopped at any moment in the power frequency cycle for the case with air flow. There can be multiple re-strikes within a half power frequency cycle and the number of the re-strikes per unit time is much higher compared with the thermal mode interruption. At the same interrupted current level the restriking voltage, mainly dominated by the air gap length, is higher than for the thermal interruptions mode, dominated by the thermal influence. Both the higher re-strike repetition frequency and the higher value of the re-strike voltage make this mode potentially more hazardous for neighbouring equipment (notably transformers). The current derivative di/dt at the current zero is much higher (about a factor 20) than for the thermal interruption mode. This implies that arc current can also be interrupted at current zero at higher frequency oscillations than power frequency, caused by the switching in the circuit.

2) During the thermal interruption mode, the arc can initially be chopped at any moment at the very beginning of interruption due to the short air gap length. However, after (1-2 half cycles), the arc extinguishes at the power frequency current zero. The current derivative di/dt increases nearly linear with the interrupted current, except in the initial arc phase. Due to thermal influence, the re-strike voltage is much lower than in the case of the dielectric interruption mode at the same air gap. This is, in principal, less hazardous for voltage transients striking neighbouring equipment.

Since air flow may change the thermal interruption to dielectric interruption, the dielectric strength of the air gap increases, as the corresponding interruptible di/dt . It is confirmed that the air flow is an effective method to improve the interrupting

capability of the air break DS to interrupt small capacitive currents. However, significant values (here 315 litre/minute) at both arc roots during the complete arcing process) have to be realized. This limits practical application.

5 REFERENCES

- [1] Y. Chai, P.A.A.F. Wouters, R.T.W.J. van Hoppe, R.P.P. Smeets, D. F. Peelo, "Capacitive current interruption with air-break high voltage disconnectors", IEEE Trans. Power Delivery, vol. 25, pp: 762-769, Apr. 2010.
- [2] D. Childress, "Disconnect switch mounted interrupting devices how to choose what to use when and where", url: www.southernstatesllc.com/pdf/MIPSYCON.pdf.
- [3] BPA Division of Laboratories: Laboratory Report ELE-89-39, "Tests to determine the interrupting capabilities of 115 kV quick break devices". Mar. 1989.
- [4] A. Foti, J. M. Lakas, "EHV switch tests and switching Surge," IEEE Transactions on power apparatus and systems, Vol. 83, pp: 266-271, Mar. 1964.
- [5] E. C. Rankin, "Experience with methods of extending the capability of high-voltage air break switches", AIEE Transaction, pp1634-1636, Feb.1960.
- [6] P. E. Richardson, A. Foti, "Gas-flow switch tests on 230-kV system", Electrical Engineering, pp.712-717, Aug.1956.
- [7] I. W. Gross. C. Killian, J. M. Sheadel, "A 330-kV Air Switch," AIEE Transactions, vol.73, pp.264-270, Apr. 1954.
- [8] Y. Chai, P.A.A.F. Wouters, R.P.P. Smeets, "Capacitive Current Interruption by HV Air-break Disconnectors with High-velocity Opening Auxiliary Contacts", accepted by IEEE Transaction on Power Delivery, 2011.