Experiments on Capacitive Current Interruption with Air-break High Voltage Disconnectors

Y. Chai¹, P.A.A.F. Wouters¹, R.T.W.J. van Hoppe¹
1, Department of Electrical Engineering, Eindhoven University of Technology, the Netherlands
email: y.chai@tue.nl, p.a.a.f.wouters@tue.nl, r.t.w.j.v.hoppe@tue.nl

R.P.P. Smeets¹,², D.F.Peeo³
2, KEMA T&D Testing Services, Arnhem, the Netherlands
3, D.F. Peelo and Associates, British Columbia, Canada
email: rene.Smeets@kema.com, dfpeelo@ieee.org

Abstract—Capacitive current interruption with air-break disconnectors in a high-voltage network is an interactive event between circuit and arc with a variety of interruptions and re-ignitions. In order to investigate this transient phenomenon, a series of interruption tests was performed at KEMA High Power Laboratory. In this paper, a brief analysis of the interruption process is presented and is compared with experimental data from the test. Typical wave shapes of voltages across the capacitances, disconnecter and current through the disconnecter are given. Re-ignition voltage and energy input to the arc on re-ignition are also investigated. Comparison shows that the test data are in good agreement with simulation. It is concluded that besides higher interruption current and higher power supply level, a lower ratio between source side and load side capacitance leads to more severe interruption and longer arc duration. In the end, the actual status of IEC recommendations on testing, that has taken into account this arc-circuit interaction, will be discussed.

Keywords—Arc, capacitive current, disconnector, disconnect switches, high voltage, interruption, measurements, re-ignition, substation, standards, testing.

I. INTRODUCTION

In a power substation, disconnectors (in North America, disconnectors are called disconnect switches) are commonly used mechanical devices. The definition of a disconnector is: “A mechanical switching device which provides, in open position, an isolating distance in accordance with specific requirements” by International Electrotechnical Vocabulary (IEV) 441-14-05. That means disconnectors only have a safety function. However, in practice due to parasitic capacitances such as from unloaded bus bars, lines etc. in the networks, there is always a capacitive current that disconnectors need to interrupt. Moreover, although not designed for interrupting current, the disconnectors do have a certain current interrupting capability thanks to one or more moving contacts during switching operations. According to the IEC 62271-102 [1], this small capacitive current, which is called “negligible current”, does not exceed 0.5A for rated voltage 420kV and below. In the past, the current interrupting capability of the air-break disconnectors has therefore been taken as 0.5A or less. Nowadays, with the fast development of power networks in the world, user’s requirement for small capacitive current interruption using air-break disconnectors frequently exceeds the above stated 0.5A.

Literature related to capacitive current interruption using air-break disconnectors is quite sparse, for instance [2]-[15]. A good overview is provided in [12]. The principal work in the past is that of Andrews et al. in the 1940s. Some results from literature such as [3], [8] were collected for IEC and IEEE recommendations [11] as well. However, literature provides only a limited insight into the experiments on the capacitive current interruption by an air-break disconnector. In this contribution we will therefore present a more detailed approach to the electrical phenomena during arcing that, by the associated voltage transients, may endanger nearby network components such as instrument transformers.

Specifically, a study on experimental data obtained from tests is presented in detail. In principle, the capacitive current interruption capability of a disconnector may be affected by various factors such as air humidity, wind speed, earthing type of the system and phase spacing. In this paper, however, only effects of electrical parameters, such as capacitances, inductances, etc. are evaluated. Based on measured data, factors affecting the arc characteristics, re-ignition voltages and other phenomena such as energy input into the arc on re-ignition and recovery voltage are analyzed and results are discussed in detail. The paper concludes with suggestions for standardization.

II. BRIEF INTERRUPTION PROCESS ANALYSIS

Capacitive current interruption with a disconnector consists of a succession of interactive events between circuit and arc with a repetitive sequence of interruptions and re-ignitions. The re-ignition is characterized in terms of oscillation frequency, transients of current and voltage, etc. An arc is characterized in terms of arc duration, arc reach (perpendicular distance of outermost arc position to a line connecting the contacts), arc type (repetitive or continuous), and energy input from circuit during the re-ignition, and so forth.

The basic equivalent circuit for capacitive current interruption is shown in Fig.1. The disconnector is marked with $D$; The short-circuit inductance $L_s$ is based on the short-time current for which the disconnector is rated; $R_s$, $C_s$ and $C_l$ stand for resistance, capacitance at supply side and load side
respectively; $i_d$ is current through the disconnector to be interrupted; $u_s$ is the voltage of the power supply of the network.

![Diagram](Image)

**Figure 1.** Basic circuit diagram for capacitive current interruption with a disconnector

Before the interruption starts, the disconnector is closed. The entire circuit of Fig.1 is energized by source $u_s$. When the disconnector opens, the interruption process begins. The basic circuit in Fig.1 is separated into two parts abruptly. The left part of the circuit, consisting of $R_s$, $L_s$, $C_s$, remains energized with $u_s$. The voltage across $C_s$, denoted as $u_{cs}$, remains very close to the source voltage $u_s$. The right part of the circuit only contains $C_l$ which has no discharge path and the voltage $u_{cl}$ across $C_l$ is dc due to trapped charge. The Transient Recovery Voltage (TRV), i.e. the difference between $u_{cs}$ and $u_{cl}$ [16], and the dielectric withstand capability of the air gap between the contacts of the disconnector are denoted as $u_d$ and $u_r$ respectively. After arc temporary extinction, the TRV starts to rise and the dielectric strength starts to recover, simultaneously.

Once $u_d$ exceeds the dielectric strength of the gap $u_r$, the arc re-ignites. At sufficiently low current, the arc lasts no longer than a half power frequency cycle and extinguishes when the arc current passes through zero. When the arc extinct the circuit is separated into two parts again until the next re-ignition occurs. The interruption process may therefore be described as a periodic arc extinction and re-ignition. Finally, this sequence comes to an end and the arc extinguishes completely when the distance between the disconnector contacts becomes sufficiently large to prevent any further re-ignitions.

At each re-ignition, the voltages $u_{cs}$, $u_{cl}$, $u_d$ and current $i_d$ have oscillations at distinct frequencies. A high-frequency ($HF$, about a few MHz) component arises after re-ignition when the voltages across load and source side capacitance are equalizing. After this process, the voltages $u_{cs}$, $u_{cl}$ change and a voltage drop arises across $L_s$ which causes a medium frequency ($MF$ up to a few kHz) oscillation in the circuit. As the $HF$ and $MF$ oscillations are damped out, the power frequency ($PF$) remains. A detailed theoretical analysis is given elsewhere [17].

III. INVESTIGATION OF MEASURED DATA

A series of tests were carried out at 90kV to 173kV supply voltage at the KEMA High Power Laboratory. The basic simplified test circuit is shown in Fig.1. The test current varied from 0.23A to 2.1A, and the source side and load side capacitances were taken in the range of $C_s = 1.5nF$ - 100nF, $C_l = 4.3nF$ - 40nF respectively. Various combinations of current, $C_l$ and $C_s$ were selected. The value of $L_s$ was fixed at 480mH. The test was performed on a 300kV center-break disconnector.

During the tests, general arc behaviour such as arc duration, gap length, blade angle at arc extinction, and overvoltage across $C_l$ were recorded. Instantaneous current $i_d$ and voltages $u_{cs}$ and $u_{cl}$ were also recorded during the current interruption process. Further, high-speed video recording of the arc was made. Initial analysis of the test data was done in [12], [13] and revealed:

- Arc duration increases with interruption current magnitude (at constant $C_s$);
- Arc duration increases with decreasing value of $C_l/C_s$ and the minimum blade angle of the disconnector required for the arc extinction is about 50 degrees. The disconnector can be close to fully open for the smallest values of $C_l/C_s$ before current was finally interrupted;
- Overvoltage across load side capacitor reached maximum values when $C_l/C_s$ << 1;
- The thermal effect which affects the arc recovery behaviour becomes significant for currents greater than 1A.

Most of these conclusions can be explained from theoretical point of view [17], showing that with smaller $C_l/C_s$, transients in current and voltage are larger.

In the following section, a more detailed analysis of the test data is given. Firstly, various typical wave shapes are shown of the relevant transient phenomena during arcing. Secondly, the interruption process is analyzed, taking into account the voltage and the energy supplied to the arc during re-ignition.

A. Voltage and current wave shapes from measurements

Typical test wave forms of $u_{cs}$, $u_{cl}$, $i_d$, $u_d$ are shown in Figs.2 to 4. Parameters for these measurements are: $U_l = 173kV$, $C_l = 1.5nF$, $C_s = 40nF$.

The waveforms of Figs.2-4 confirm that capacitive current interruption with a disconnector consists of multiple re-ignitions and there is a transient in the circuit on each re-ignition. Maximum overvoltage of $u_{cs}$ is about 2.33p.u. The overvoltage became largest just before the complete arc extinction (Fig.2a). Maximum medium frequency transient currents of about 65A (Fig.3a) are observed. The voltage $u_d$ across the disconnector was not measured directly, but was determined as the difference between voltages $u_{cs}$, $u_{cl}$. Similar as in Fig.2b, Fig.3b shows the arc re-ignition and arc extinction moments clearly, Fig.4b shows arc duration and transient recovery voltage rising period during interruption as well.

An interesting feature is that values of $u_{cs}$, $i_d$ (Figs.3a, 4a) on each moment of re-ignition do not rise continuously with the increasing contacts distance, but a few “steps” are observed. This phenomenon indicates that re-ignition voltage is not only determined by the distance between two contacts of the disconnector but also depends on other influences, the most important of being probably a thermal effect: a reduction of breakdown voltage due to the heating of the air by the arc.
B. Re-ignition voltage

By analyzing the wave shape envelope of the disconnector voltage $u_d$, the re-ignition voltage $u_r$ can be obtained: for each arc re-ignition point in $u_d$ both re-ignition time and voltage are interested. In order to present the re-ignition voltage wave shapes, two different groups of test data were selected; one group with fixed $C_s$ and parameter current $i_d$, another group with fixed current $i_d$ and as parameter the ratio $C_s/C_l$. The results for the tests performed at power supply level of 173kV are given in Fig. 5.

The following observations are made:

− Re-ignition voltage level can be as high as 500kV (2.05 p.u.) at $C_s/C_l = 3.1$. It does not increase continuously but with a few “steps” at both positive and negative polarities.

− The current $i_d$ and the ratio of $C_s/C_l$ significantly influence the re-ignition voltage and arc duration. Re-ignition voltage increases with decreasing $i_d$ and increasing $C_s/C_l$. The reason is that with larger $i_d$ and smaller $C_s/C_l$ there is a higher energy input to the arc on re-ignition. The arc path needs more time to recover its dielectric strength.

− The positive and negative re-ignition voltages are not symmetrical. For example, at 2.1A in Fig.5a the negative re-ignition voltage is larger than the positive re-ignition voltage, especially near the final arc extinction point; and at $C_s/C_l = 0.08$ in Fig.5b, the positive re-ignition voltage is larger than the negative re-ignition voltage in the end.
As mentioned before, one re-ignition occurs each half power frequency period. However, because of the polarity dependency which causes an asymmetrical overvoltage across \( C_s \) and \( C_l \), a few test group data show only one re-ignition within each full power frequency cycle. Further, test results show that this phenomenon only happens at \( C_s/C_l < 0.1 \).

C. Energy input into the arc on re-ignition

The energy input into the arc on re-ignition is an important influential factor for arc duration, thermal effect and next re-ignition voltage value. Once a re-ignition occurs, the arc electrically connects two capacitances. There is a current \( i_d \) through the arc and a voltage \( u_d \) across the arc. The energy input into the arc can be calculated by integrating the product of the current \( i_d \) and voltage \( u_d \) for each cycle from the moment of re-ignition \( t_1 \) to the (temporary) arc extinction \( t_2 \): 

\[
E = \int_{t_1}^{t_2} u_d i_d \, dt .
\]

Typical energy wave shapes are shown in Figs. 6, 7. From these figures it is concluded:

- The energy input into the arc on re-ignition is about a few hundreds joules and up to a few thousands joules at lower ratio of \( C_s/C_l \). It becomes larger gradually (with occasional “steps”) when the contacts of disconnector are moving away. It reaches the largest value, just before complete arc extinction.

- \( C_s, C_l, i_d \) have significant influence on the arc energy input on the re-ignition as well. It is observed that the energy input is higher with higher interruption current and lower \( C_s \).
D. Comparison with simulation

The bandwidth of the measurements equipment in the test was too low to show the high frequency component. Only the medium frequency component therefore is compared with simulation on basis of the model in [17].

Firstly, a specific measurement with one set of parameters is compared on basis of the general voltage wave shape over the load side capacitance after re-ignition. The parameters in the simulation of Fig. 8 are chosen equal to those in the real test given in Fig. 3: \( U_r = 410 \text{kV}, \; C_s = 1.5 \text{nF}, \; C_l = 40 \text{nF}, \; L_s = 480 \text{mH}, \; R_s = 3 \text{k}\Omega, \; R_h = 25 \Omega, \; L_h = 15 \mu\text{H}, \; E_m = 173 \times 2 \text{kV}, \; \phi = 90^\circ \). Fig. 8 shows clearly the three components (HF, MF, and PF). The HF component lasts several microseconds and the MF component lasts about 4 milliseconds both in experiment (Figs. 2-4) as in simulation (Fig. 8). Medium frequency is 1.0 kHz both in simulation and in real test.

Secondly, the test and calculated overvoltages across the load side capacitance are compared. Table I shows that the calculated results are slightly larger than those obtained from measurement, probably because of differences in the damping. Actual losses occurring in the real tests at the MF and HF can only be estimated.

Data analyzed from test show that the transients during interruption are qualitatively and quantitatively in agreement with the simulations.

### Table I.

<table>
<thead>
<tr>
<th>Source(kV)</th>
<th>( C_s/C_l )</th>
<th>( u_c )(p.u.)</th>
<th>( u'_c )(p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.0</td>
<td>60/19.3</td>
<td>1.39</td>
<td>1.52</td>
</tr>
<tr>
<td>171.5</td>
<td>6/19.3</td>
<td>2.09</td>
<td>2.32</td>
</tr>
<tr>
<td>173.0</td>
<td>1.5/40</td>
<td>2.33</td>
<td>2.57</td>
</tr>
<tr>
<td>173.0</td>
<td>6/40</td>
<td>2.25</td>
<td>2.40</td>
</tr>
</tbody>
</table>

*Note: \( u_c \)(p.u.), \( u'_c \)(p.u.) is overvoltage across load side capacitance from test and theoretical calculation respectively.*

IV. IMPLICATIONS FOR STANDARDIZATION

As already pointed out in Section III, the macroscopic arc behaviour is strongly dependent on the ratio \( C_s/C_l \). This is illustrated in Figs. 9 and 10 showing the arc duration and observed overvoltages as a function of \( C_s/C_l \) for two values of current.

This observation implies that for testing of the disconnector switching capability, the circuit plays a major role (this also applies to the testing of auxiliary interrupting devices such as so-called whips). Since no test-circuit has been defined yet, one of the tasks of the IEC maintenance team, elaborating an amendment to the IEC standard 62271-102 [1] was to define a circuit. It was decided that 20 CO (close/open) tests have to be performed with \( C_s/C_l = 0.1 \), adopting a test-circuit as in Fig. 1. Alternative supply circuits, supplying much less than the short-time current, are under discussion. It was decided to give the document the status of a technical report and allow time for collecting experience. The technical report will be issued in 2009[18].
V. SUMMARY

In this paper, interruption of capacitive current with an air-break high voltage disconnector is studied through a series of measurements. The results show that capacitive current interruption with an air-break disconnector is an event with multiple re-ignitions. This can cause significant overvoltages (value up to 2.3 p.u. was observed in test) and prolong arc duration. This makes interruption more severe and might cause damage to nearby equipment.

Specifically, energy input to the arc, overvoltage, (transient) current and other arc characteristics depend on the interruption current $i_d$ and electrical circuit parameters such as $C_s, C_l$, their ratio, and source voltage $u_s$. At lower values of $C_s/C_l$, higher voltage power supply level and higher interruption current level, the arc duration and overvoltage magnitude across the load tend to increase.

The analysis shows that by a suitable choice of $C_s/C_l$ arc duration and overvoltages can be reduced, for example, making $C_s/C_l$ as large as possible. Larger $C_s/C_l$ leads to lower energy input into re-ignition and makes the dielectric strength of the air gap to recover faster.

Future work also aims to investigate the air dielectric strength and transient recovery voltage in detail. It is the final purpose of the present project to develop air break disconnectors that have increased current interruption capability.

REFERENCES