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

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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, disconnector and current through the disconnector 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.

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_{cl} , u_{cs} 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 $C_s = 1.5\text{nF} - 100\text{nF}$, $C_l = 4.3\text{nF} - 40\text{nF}$ respectively. Various combinations of current,

C_s and C_l 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_s/C_l 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_s/C_l before current was finally interrupted;
- Overvoltage across load side capacitor reached maximum values when $C_s/C_l \ll 1$;
- 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_s/C_l , 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: $U_s = 173\text{kV}$, $C_s = 1.5\text{nF}$, $C_l = 40\text{nF}$.

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_{cl} 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_d , 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.

Figure2. Typical test voltage wave shape for u_{cs} , u_{cl} (a) and its expansion (b)

Figure4. Typical disconnector voltage u_d wave shape from measurement (a) and its expansion (b)

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.

Figure3. Typical current i_d wave shape from measurement (a) and its expansion (b)

Figure5. Re-ignition voltage versus time with parameter i_d ($C_s = 1.5\text{nF}$) (a) and C_s/C_l ($i_d = 2.1\text{A}$) (b)

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 :

$$E = \int_{t_1}^{t_2} u_d i_d dt . \text{ Typical energy wave shapes are shown in}$$

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

Figure6. Energy input into arc on re-ignition versus time with parameters C_s/C_l ($i_d = 2.1\text{A}$) (a), i_d ($C_s = 1.5\text{nF}$) (b)

Figure7. Expansion at $t = 900-1260\text{ms}$ and at $t = 1011-1016\text{ms}$ from Fig.6a with $C_s/C_l = 100\text{nF}/40\text{nF}$

on the re-ignition as well. It is observed that the energy input is higher with higher interruption current and lower C_s .

- The energy input level rises very fast after the re-ignition starts, where the higher frequencies components dominate. Then it remains almost constant during the power frequency period (Fig.7b).

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: $U_r = 410\text{kV}$, $C_s = 1.5\text{nF}$, $C_l = 40\text{nF}$, $L_s = 480\text{mH}$, $R_s = 3\text{k}\Omega$, $R_H = 25\Omega$, $L_H = 15\mu\text{H}$, $E_m = 173 \times \sqrt{2}\text{kV}$, $\phi = 90^\circ$. 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.

Figure8. Wave shape for overvoltage across load side capacitance and expansion to show the HF component

TABLE I.

COMPARED OVERVOLTAGE BETWEEN TEST AND SIMULATION CALCULATION

Source(kV)	C_s/C_l	$u_{cl}(\text{p.u.})$	$u'_{cl}(\text{p.u.})$
90.0	60/19.3	1.39	1.52
171.5	6/19.3	2.09	2.32
173.0	1.5/40	2.33	2.57
173.0	6/40	2.25	2.40

Note: $u_{cl}(\text{p.u.})$, $u'_{cl}(\text{p.u.})$ 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 circuit especially 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].

Figure9. Disconnector arc duration as a function of C_s/C_l for arc current 1.0 and 2.2 A

Figure10. Measured overvoltages (p.u.) across load as a function of C_s/C_l for arc current 1.0 and 2.2 A

V. SUMMARY

In this paper, interruption of capacitive current with an air-break high voltage disconnecter is studied through a series of measurements. The results show that capacitive current interruption with an air-break disconnecter is an event with multiple re-ignitions. This can cause significant overvoltages (value up to 2.3p.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.

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