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# DC current interruption tests with HV mechanical DC circuit breaker

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## SUMMARY

HVDC transmission has been expanding due to rapid development of power electronics technology and by the need for connection of offshore or remote wind farms and / or large hydro power generators. CIGRE Study Committee B4 established various WGs and leads the HVDC investigations especially for multi-terminal HVDC. For example, WG B4.52 published TB533 on “HVDC Grid Feasibility Study” and WG B4.46 published TB492 on “VSC HVDC for Power Transmission”. SC A3 and B4 established a JWG A3/B4.34 and published TB 683 “Technical requirements and specifications of state-of-the-art HVDC switching equipment” investigating various DC switchgears potentially applicable to future HVDC grids and summarized available technical specifications required for DC circuit breakers applied to multi-terminal HVDC.

Multi-terminal HVDC grid will be required to operate the healthy lines continuously, DC circuit breaker is required to avoid DC voltage collapse and operate the healthy lines continuously, even if a DC fault occurs. Rapid fault clearing is essential for DCCB even though the requirement varies depending on: 1) DC transmission system configurations, 2) Voltage Source Converter (VSC) design, 3) transmission capacity, 4) DC reactor connected in series with the line/cable, and 5) impedance of the line/cable.

In this paper, a prototype mechanical DC circuit breaker with active resonant current zero creation scheme was tested in a test circuit using a AC short circuit generator operating under a reduced power frequency. The mechanical DC circuit breaker can interrupt DC current up to 16 kA within several milliseconds after receiving a trip signal (command).

Since there are no international standards for HVDC circuit breakers to demonstrate the interrupting capability, an equivalent and economical testing circuits were first investigated within a certain restriction of testing facilities. Several testing circuits including a synthetic test, multi-part test, and a unit test can verified to reproduce the full stress imposed on DC circuit breakers in the networks.

## KEYWORDS

Multi-terminal HVDC, Active current injection, Synthetic test, Multi-part test, Unit test

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## 1. Introduction

HVDC circuit breakers are required to clear a DC fault as soon as possible compared with HVAC circuit breakers where the propagation speed of a fault occurred in HVAC systems due to existence of large power transformers, is relatively slower than that occurred in HVDC systems. The DC fault current tends to increase with time after a fault occurrence due to contributions of current flows from different lines at remote sides. Another singularity is a role of MOSA connected in parallel with an interrupter, which requires to disseminate the stored energy of inductance such as DC reactors after the current interruption. The energy dissipating time can change depending on system parameters and configuration. For example, in case of four-terminal HVDC network shown in [1], this value is in the range from several ms to about 20 ms.

There are no international standards on HVDC circuit breakers nor no specific recommendations on HVDC interruption test due to lack of practical field experience of HVDC circuit breakers. There are three steps of DC current interruption processes with HVDC circuit breakers. 1) DC fault current built up time from a fault occurrence to breaker operation, 2) Current zero creation period due to current injection and high frequency interruption, 3) Current suppression due to energy dissipation by MOSA.

In order to verify the interrupting performance of HVDC circuit breakers, it is essential to develop a test circuit which can reproduce the equivalent voltage and current stresses during a whole interruption process expected in a practical HVDC systems considering available testing facilities.

This paper is divided into two main sections. After introduction, chapter 2 deals with fundamental DC interruption test results with HVDC circuit breaker composing of single and multi-break vacuum interrupters. Chapter 3 propose some practical testing methods for HVDC circuit breaker economically. In this paper a mechanical HVDC breaker, with an active resonant current zero creation scheme (current injection type) were used to confirm a validity of DC interruption tests.

## 2. Development and Testing of High-voltage DC Circuit Breakers

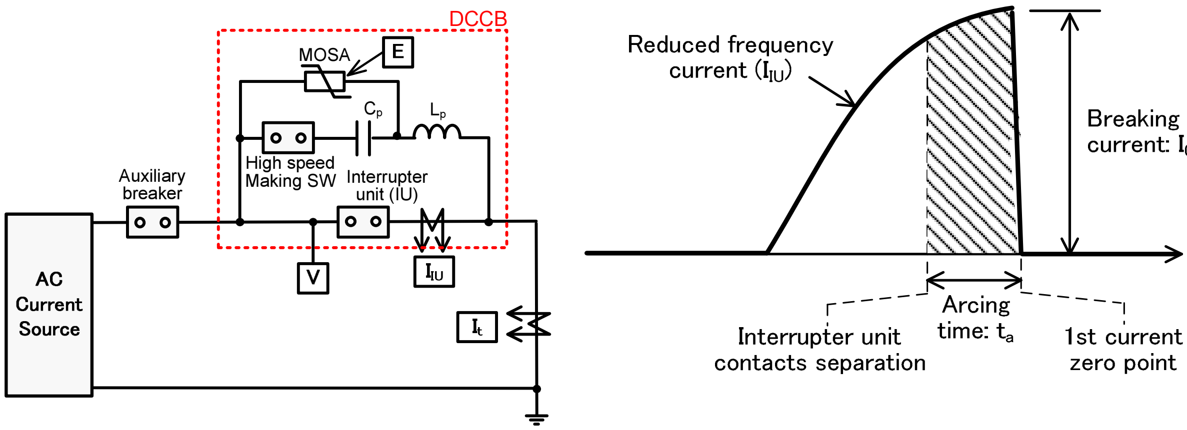
An equivalent and economical interruption test method is essential for HVDC circuit breakers development. The test circuit is required to reproduce the current and voltage stresses on HVDC circuit breakers equal to those expected in a practical HVDC networks. A direct test can reproduce the equivalent stresses but require an expensive investment similar to build a HVDC converter station. Therefore a practical interruption test method should be established using the common testing facilities applied to short-circuit tests for HVAC circuit breakers.
There are three test methods used with different HVDC power sources. 1) A charged reactor, 2) A charged capacitor, 3) AC short circuit generator operated with reduced power frequency.

The charged reactor can supply slightly decaying DC current but an expensive large capacity reactor is required to supply the DC current during the whole interruption process. Also, the auxiliary switches in the test circuit should be controlled much accurately to supply the stress to the test DCCB appropriately. The charged capacitor can potentially supply low frequency current similar to DC but an extraordinary large capacity capacitor and reactor are required to provide low frequency current into main interrupter unit and sufficient energy into energy dissipation unit.
The authors propose a practical interruption test method using AC short circuit generator operated with reduced frequency than commercial frequency. AC short circuit generator operated with lower frequency can supply current which is close to DC but the amplitude of the voltage will be reduced, which leads to current reduction. Therefore it is important to reproduce an equivalent current stress by adjusting some parameters of test circuit.

Fig. 1 (a) shows an interruption test circuit including an HVDC circuit breaker using AC short-circuit generator operated with reduced frequency. Figure 1 (b) shows a schematic of the current waveform supplied by this test method with AC short-circuit generator. HVDC circuit breaker generally opens the contact when the current waveform just before the current peak and interrupt it around the current peak.

If the time between the contacts separation and the interruption instant is short, the reduced frequency current can be considered to be a quasi-DC current. In this paper, interruption tests were conducted with the reduced frequency of 30 Hz.

The current waveform can be adjusted to be equivalent to DC current stress by controlling making phase of source voltage. The average rate-of-rise of interruption current is adjusted to be equal to that of a practical HVDC system (based on system simulations). The test current conditions are set in the range of 1.6 kA-16 kA. This range corresponds to a nominal current level and the maximum current level at about 10 ms after a fault occurrence with some redundancy.




(a) DCCB Test circuit set up (b) Schematic of test current waveform

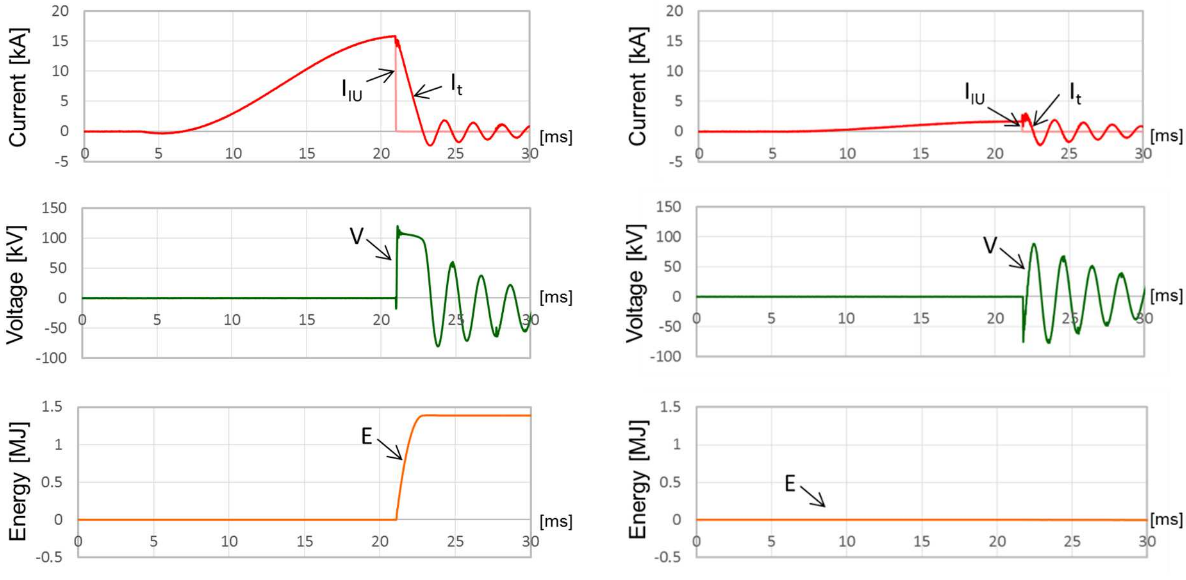
Fig. 1: DCCB interruption test method with AC short circuit generator

## 2.1 Interruption test with DC circuit breaker composing of single break interrupter

HVDC interruption test were conducted with 80 kV prototype HVDC circuit breakers composing a single breaker vacuum interrupter originally designed for HVAC 84kV 31.5 kA ratings. DC interrupting currents were set as 1.6 kA and 16 kA. A unique electromagnetic operating mechanism is applied to the HVDC circuit breaker using electromagnetic actuator fulfilling to perform both open and close operations with several milliseconds by eliminating the need for mechanical latches to keep the vacuum interrupter either in closed or open position and realizes very high speed operation.

Figures 2 (a) and (b) show typical examples of the interruption test oscillograms with 80 kV DC circuit breaker at interrupting currents of 16 kA and 1.6 kA, respectively verified by the HVDC test method with AC short circuit generator operated with reduced frequency of 30 Hz. Here $I_{IU}$ is the current through the interrupter unit and $I_t$ is the total current through the HVDC circuit breaker.

The HVDC circuit breaker with active resonant circuit (current injection type) composing of a pre-charged capacitor with a reactor and a thyristor switch /triggering gap imposes a high frequency (several kHz) inverse current on the interrupting fault and nominal current and creates a current zero instantly. The capacitor has an enough charged energy (capacitance) to create the current zero for the maximum DC fault current expected in the HVDC network. Accordingly it will create higher (di/dt) at current zero due to current injection for smaller interrupting current in case of nominal current interruption. Moreover, high residual charge voltage of $C_p$ compared with that for large current interruption causes higher voltage slope (dU/dt) and higher peak initial transient interruption voltage (ITIV) just after the interruption of IU. Therefore, smaller current interruption is more severe DC interruption duties for this type of HVDC circuit breaker.




(a) Typical waveform for 16 kA interruption (b) Typical waveform for 1.6 kA interruption

Figure 3: Examples of the interruption test oscillograms with 80 kV DC circuit breaker by the HVDC test method with AC short circuit generator operated with reduced frequency of 30 Hz. $I_{IU}$: the current through the interrupter unit; $I_t$: total current through the HVDC circuit breaker

### 2.2 Interruption test with DC circuit breaker composing of multi break interrupters

For higher HVDC systems, HVDC circuit breakers shall withstand higher voltage requirements including higher ITIV requirements in case of DC interruption. HVAC Vacuum interrupters are currently available for 72-145 kV levels and the unit voltage is mostly in the range of 72 kV. Therefore, series connected multi-break vacuum interrupter arrangement is a common configuration for EHV DC circuit breakers with active resonant current zero creation method (current injection type). It is important to distribute the voltage uniformly among each break to realize a compact design.

#### 2.2.1 Influence of the Grading and Stray Capacitance on Voltage Distribution

The uniform voltage distribution among each interrupter is essential when designing an EHV DC circuit breaker composing of multi-break vacuum interrupters. In this section, a double-break DCCB model is used to assess voltage sharing between two vacuum interrupters. Figure 3 show a combination of capacitor and resistor grading scheme in order to attain the even voltage sharing between the interrupters. The stray capacitance $C_e$ to earth (which depends on the structure of the DCCB such as dead tank or live tank type) has a significant influence on the voltage sharing, especially after DC interruption.

When the current-zero occurs in the interrupter units due to current injection, current then flows through the stray capacitances and grading capacitances across the interrupter. Figure 4 (a) show a simplified circuit to evaluate the voltage sharing after the DC current interruption through an interrupter unit. The ratio of voltage distribution at the point where a peak voltage is applied to Interrupter A as shown with a dotted line in Fig. 5(b) can be estimated by (1).

$$V_a : V_b = (C_g + C_e) : C_g \quad (1)$$

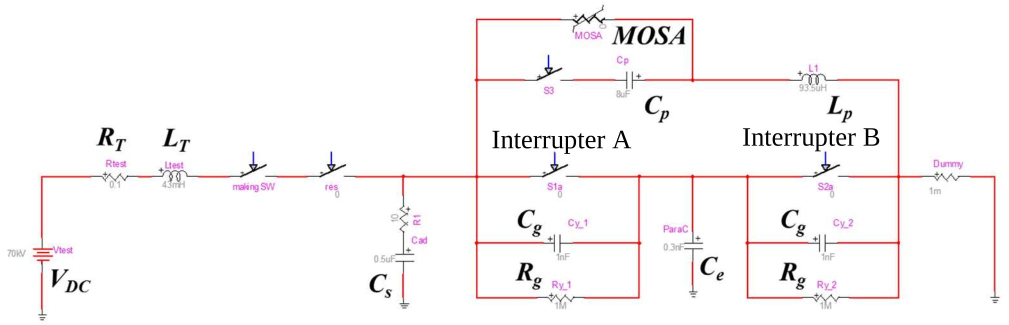
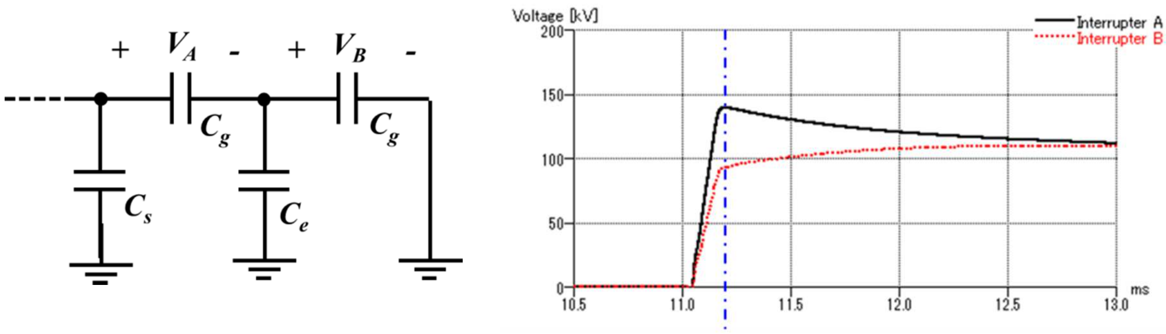



Figure 4: Simulation circuit for voltage distribution among breaks for multi-break mechanical DCCB




(a) Capacitance for multi breaks

(b) Typical results of voltage behaviors with double breaks after DC interruption

Fig. 5 Example of simulation result for voltage distribution for double break interrupter

Simulations have been performed to evaluate the effect of the grading capacitors. Grading capacitors ($C_g$) are varied and the corresponding distribution measured. In addition, the earth stray capacitance of interrupter are also varied from 50 pF to 300 pF which corresponds to the assumed range of $C_e$ of live and dead tank type. This is because this the earth stray capacitance has influence on voltage distribution. These results are then compared to the theoretical results calculated from equation (1). Figure 5 shows a comparison of simulation and theoretical results, and parameters used for the evaluation are given in Table 1.

The results show good agreement between the simulated and theoretical calculations. They can indicate that a $C_g/C_e$ ratio of approximately 10 is required to achieve a uniform voltage sharing within ~10%. The error between simulated results and analytical calculated results is due to parallel resistance $R_g$ in Figure 3. When $C_g$ is small, impedance value of $C_g$ becomes close to $R_g$ and the influence of $R_g$ can't be neglected. The result suggest that larger $C_e$ requires larger $C_g$, for the same voltage sharing.

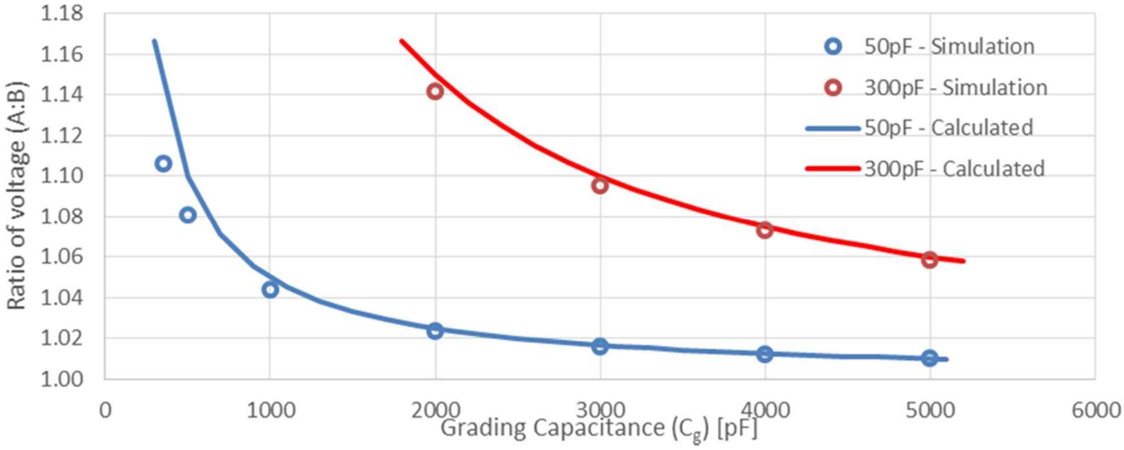



Fig. 6 Comparison of theoretical and simulated Voltage Distribution, for Live and Dead-Tank Interrupters

Table 1 Simulation Parameters for Multi-break Mechanical DCCB

| Parameter | | | Value |
|---|---|---|---|
| $C_s$ | [μF] | System Stray Capacitance | Assumed fixed |
| $C_e$ | [pF] | Stray between the interrupters to earth | 300, 50 |
| $C_g$ | [pF] | Grading capacitor | Variable: 500 → 5000 |
| $R_g$ | [MΩ] | Grading resistor | 1 |

### 2.2.2 DC Interruption Tests with single break and double breaks

The thermal interrupting performance with HVDC circuit breaker with active resonant current zero creation method (current injection type) composing a vacuum interrupter inherently show excellent high frequency interruption capability compared with a gas circuit breaker. The thermal interrupting performance depends on the current slope (di/dt) at current zero crossing due to current injection, which may affect by the arcing time (the time from contact separation to current zero). With multi-break interrupter units connected in series, arcing time may be reduced since the thermal stress is shared among the breaks and also the voltage withstand strength improved.

In this section, the interruption performance using HVDC circuit breaker with multi break interrupters is evaluated and compared to that of HVDC circuit breaker with a single break interrupter. All tests were performed with the rated voltage of 80 kV, which means the voltage stress for the double break is divided in a half. Three cases are tested: (Case 1) HVDC circuit breaker with a single break interrupter with the standard arcing time, which can secure the sufficient contact separation for DC 16 kA interruption, (Case 2) HVDC circuit breaker with a single break interrupter with shorter arcing time, which may not secure the sufficient contact separation for DC 16 kA interruption, (Case 3) HVDC circuit breaker with double break interrupters with shorter-acting time.

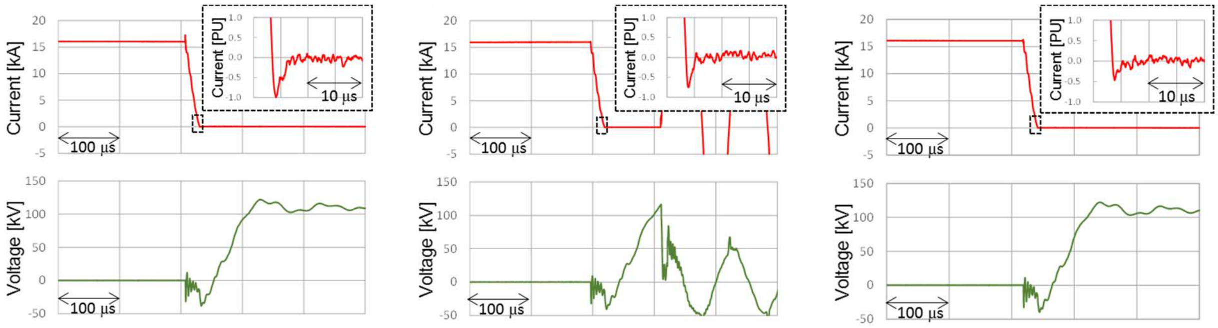
Fig. *7* shows typical oscillograms of the DC interruption tests including the current flowing through the $I_U$ and the voltage across the HVDC circuit breaker for the three cases. Table 2 summarizes the test conditions and the results. (It should be noted that $t_a$' is equal in cases 2 and 3.).

In Case 1, HVDC circuit breaker with single break tested with the standard arcing time demonstrates successful thermal and dielectric interruptions. In Case 2, HVDC circuit breaker with single break tested with the reduced arcing time shows successful thermally interruption but causes restrike (dielectric interruption failure) due to insufficient dielectric withstand recovery, because of the reduced arcing time. In Case 3, HVDC circuit breaker with double break tested with the reduced arcing time shows both successful thermal and dielectric interruptions.

Figure 6 also provides the enlarged current waveform in vicinity of current zero for each case. The results show that, for same arcing time (i.e. Case 2 and 3), the peak of post-arc current for the HVDC circuit breaker with the double-break interrupter is lower than that of the single-break interruption. This is because the TIV imposed on each unit is reduced by increasing the number of the breaks of HVDC circuit breakers and the energy injected into each interrupter unit can be reduced. Therefore, HVDC circuit breaker composing of double-break interrupters is more favorable than single break design in case that higher thermal and dielectric interruption performance with short breaking time is required for example for EHV applications.

Table 2: Test conditions and results of thermal and dielectric interruption performance

| Case No. | Test current [kA] | Number of the breaks | Arcing Time | Post arc current peak [PU] | Success or failure | |
|---|---|---|---|---|---|---|
| | | | | | Thermal | Dielectric |
| 1 | 16 | 1 | $t_a$ (standard) | 1.0 | Success | Success |
| 2 | 16 | 1 | $t_a$' (shorter) | 0.75 | Success | Failure |
| 3 | 16 | 2 | $t_a$' (shorter) | 0.47 | Success | Success |



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 7 Test results for single break and double break prototype DCCB

## 3. Proposed Practical Interruption Test Methods for HVDC circuit breakers

HVDC interruption test method using AC short circuit generators operated with reduced frequency lower than power frequency can reproduce the major stresses when a fault clearing in HVDC systems (current, voltage and energy) by adjusting the test circuit parameters. However, the method with only a single DC current source may not reproduce the current and voltage stresses during a whole interruption process from a fault occurrence to current zero through MOSA (end of energy dissipation by MOSA) in some testing conditions. In such a case, another test method with additional current or voltage sources can be applicable.

These testing methods using additional voltage or current sources such as a synthetic test, a multi-part test and a unit test methods are commonly used in testing EHV AC circuit breakers. In this section, the application of these combined test methods for HVDC circuit breaker interruption tests is studied with 320 kV DC circuit breaker composing of four series connected 80 kV DC circuit breakers as shown in the Figure 7. Figure 8 show the stresses for full pole of four break 320 kV DC circuit breaker (black line) and those for one unit of 80 kV DC circuit breaker (Gray dotted line).

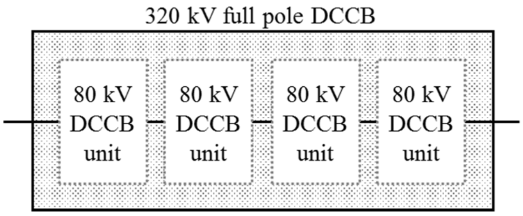



Figure 8: 320 kV DC circuit breaker (black line) composing of four series connected 80 kV DC circuit breakers (Gray dotted line)

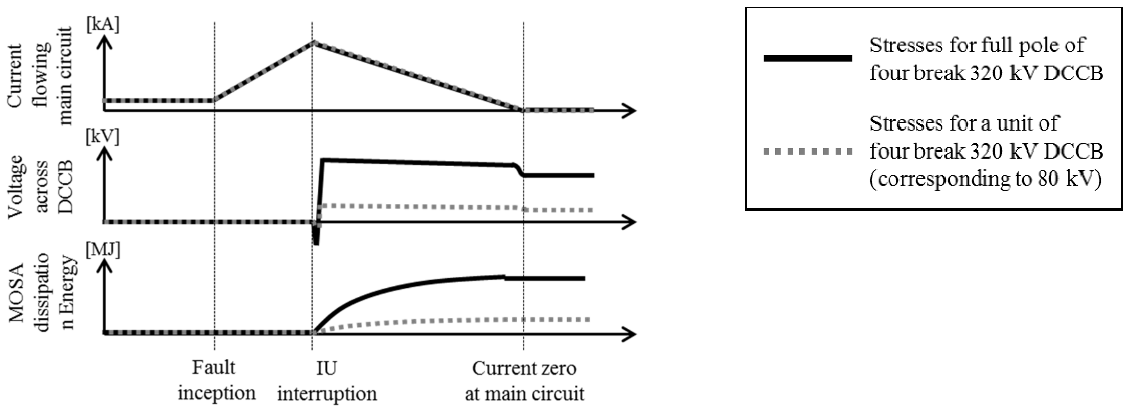



Figure 9: Stresses for full pole of four break 320 kV DC circuit breaker (black line) and those for one unit of 80 kV DC circuit breaker (Gray dotted line)

### 3.1 Synthetic test method

Figure 9 (a) and (b) shows a schematic interruption test circuits for HVDC circuit breakers with only AC short circuit generator (only current source) and with additional voltage sources, respectively. The additional voltage source has a pre-charged capacitor bank ($C_a$) in series with switch (typically a spark gap). When the current through the current source (AC short-circuit generator) cross the current zero, the auxiliary interrupter will isolate the generator from the test object (and the synthetic source). As the result, a DC recovery voltage can be imposed across the contacts of test DC circuit breaker.

Figure 10 compare the current and voltage stresses along with the MOSA energy dissipation compared with test method with only current source and the synthetic test method with current and voltage sources. The additional voltage source can supply the superimposed current and voltage stresses by triggering a spark gap shortly before the natural current zero supplied through the generator. This synthetic test method can compensate the voltage and current stresses especially required for the MOSA energy dissipation.

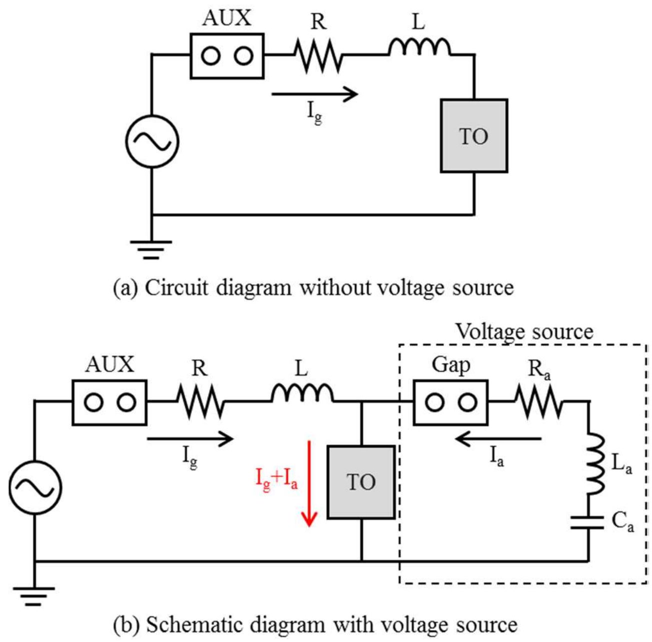



Figure 10:A synthetic test method for DC circuit breakers

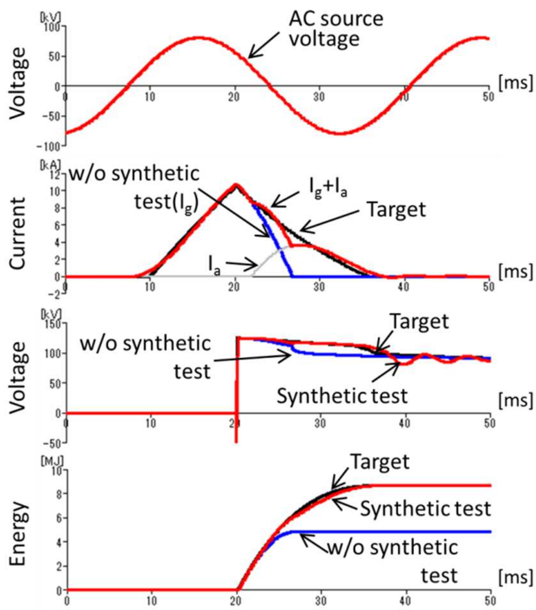



Figure11: Simulation result of the stresses

### 3.2 Multi-part test

During the whole interruption process, there is no interaction between interruption performance of the HVDC circuit breakers and energy dissipation of MOSA. Therefore a multi-part test method may be applied to evaluate the interruption test of HVDC circuit breakers and MOSA energy dissipation capability separately (at different steps). In case of HVDC mechanical circuit breaker, the DCCB can be tested in two parts, as shown in Fig. 12. The first part-test (a), can evaluate the DC interruption performance focusing on the IU at current zero. The second part-test can evaluate MOSA energy dissipation performance. This multi-part test method allows the full stresses to be assessed, with the use of existing facilities (saving additional investment in testing laboratories).

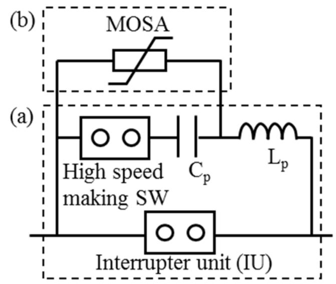



Fig. 12 Schematic of multi-part test method

### 3.2.1 First part-test (a): Interruption Performance Evaluation

The first part test to evaluate the interruption performance with IU is proposed in this section. Not only interruption performance of IU but also voltage withstand performance across DC circuit breaker can be evaluated in the first part. DC circuit breakers should be tested with a complete structure including MOSA part in this test. Fig. 13 shows an example of simulation result for this part test. The synthetic test method, described in Section 3.1, is applied here to impose the dc recovery voltage current zero interruption. The current interruption period and voltage profiles have been reproduced well by the synthetic circuit. However, the current magnitude, and thus energy, during the energy dissipation period is lower, due to a smaller contribution from the synthetic source. The requirement for MOSA stored energy should be evaluated in a separate test method.

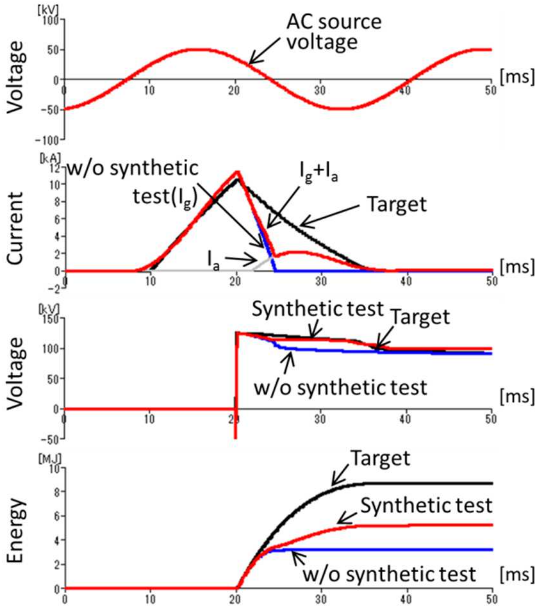



Fig. 13: Simulation result of the part test for evaluation of interruption performance of IU

Table 3: Simulation parameters

| Parameter | Part test for IU | Target |
|---|---|---|
| Vs(kVpeak) | 50 | - |
| $C_a$[μF] | 300 | - |
| $V_{ca}$[kV] | 160 | - |
| $L_a$[mH] | 50.0 | - |
| $R_a$[Ω] | 10.0 | - |
| Frequency of current source [Hz] | 30 | - |
| Peak Current [kA] | 11.3 | 10.5 |
| Energy Dissipated [MJ] | 5.2 | 8.7 |

### 3.2.2 Second part-test (b): Energy Dissipation Evaluation

The second part test to evaluate the energy dissipation performance with MOSA. In this part, only the MOSA unit can be verified. The MOSA can be tested by using AC short-circuit generator, as shown in Fig. *14*, where the voltage level of the current source is larger than the MOSA restriction (clipping) voltage. The source inductance is adjusted to control the current, and thus power, supplied to the MOSA, and the auxiliary breaker opening instant is adjusted to control the total energy to be dissipated. Figure 14 shows typical simulation results. The target waveform is that same as that given in Fig. 13. In the test the generator is operated at 50 Hz, and three cases are considered (by varying $L_a$). The simulation results show that, with appropriate choice of inductance, the target energy dissipation can meet with the requirements, in both magnitude and duration.

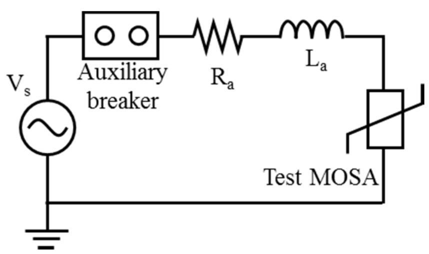



Fig. 14 Second part test circuit

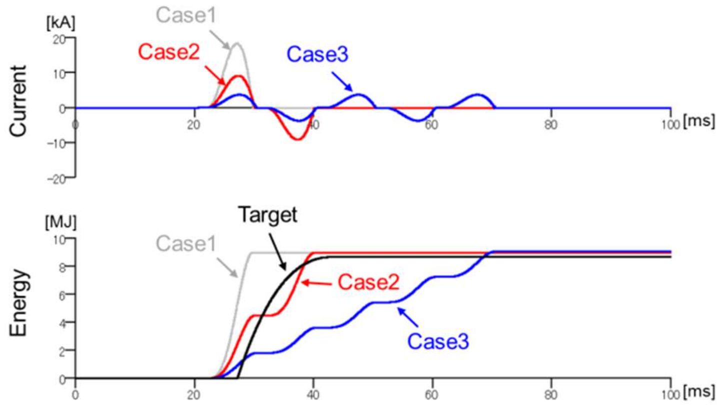



Fig. 15 Simulation results of the second part test for MOSA

### 3.3 Unit test for multi-break HVDC circuit breaker

Unit tests are specified in the international standard to evaluate HVAC circuit breakers. The method can be applied to test a unit of multi-break HVDC circuit breakers. Although the test methods should be considered the influence of uneven voltage distribution for each unit and imbalance of the stress imposed on each unit due to different operation times, unit test can allows to carry out the interruption tests with reasonable and economical cost, since it could reduce the huge investment to upgrade the test facility to realize full-pole test of high voltage DC circuit breakers.

Moreover, unit test can be combined with synthetic test or multi-part test proposed in previous sections. If it is combined with the synthetic test or the part test for evaluating IU interruption performance of multi-part test, the test voltage can be reduced to that for one unit. Also, if it is combined with the part test for evaluating MOSA energy dissipation performance of multi-part test, test voltage and also injection energy into MOSA can be reduced to those for one unit.

## 4 Conclusions

DC interruption tests with HVDC circuit breaker with active resonant current zero creation scheme (current injection type) composing of single break and double break vacuum interrupters are demonstrated at both high fault current and low nominal current conditions. Lower current condition is more severe DC interrupting duty for the mechanical HVDC circuit breaker with this scheme. The effect of stray capacitance and grading capacitance with dead tank and live tank double break design on voltage sharing after interruption was assessed by theoretical and analytical approaches. It was found that uniform voltage sharing can be achieved by applying reasonable range of grading capacitance in case of double break design. The DC interruption tests reveals that HVDC circuit breakers with multi break interrupters can reduce the arcing time, which lead to reduction of overall circuit breaker operation time. Therefore, HVDC circuit breaker composing of double-break interrupters is more favorable than single break design in case that higher thermal and dielectric interruption performance with short breaking time is required for example for EHV applications. Several equivalent HVDC interruption testing methods are investigated in detail, which can allow the use of existing testing facilities used for HVAC circuit breaker tests even in the case of severe tests for EHV levels.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