AORC International Conference
March 24-28, 2019
Bali, Indonesia

Development and testing of EHV DC circuit breaker with current injection

S. Tokoyoda, T. Inagaki, R. Kamimae, K. Tahata, K. Kamei,
T. Minagawa, D. Yoshida, H. Ito
Mitsubishi Electric Corporation
Japan

Summary

The paper presents recent development progress of a mechanical EHV DC circuit breaker with current injection scheme. An EHV level DC circuit breaker composed of multi-break HV vacuum interrupters, a current injection circuit and a metal oxide surge arrester (MOSA) energy absorption unit. 320/400 kV DC and 525/600 kV DC circuit breakers consist of 4 and 6 series connected 100 kV vacuum interrupters, respectively. There are two fundamental design concepts employed with common (combined design) or separate (module design) current injection circuit with a bunch of charged capacitors[1]. The module design with the separate current injection circuits as well as separate MOSA energy absorption units has an advantage in terms of flexible design to meet different higher DC voltage ratings. However, some control coordination is required to operate each module of the current injection circuits simultaneously.

A prototype of mechanical HVDC circuit breaker module (80 kV rated voltage level) based on active current injection was tested to demonstrate DC current interruption performance at different current magnitudes ranging from 2 kA to 16kA with both directions of positive and negative currents by creating a current zero immediately after the current injection. The MOSA energy absorption units also shows successfully energy dissipation performance up to 4 MJ with parallel column arrangement.

The interrupting and energy dissipating performances of HVDC circuit breakers were demonstrated at DNV-GL/KEMA laboratory supported by the PROMOTioN projects, funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 691714. A test circuit of DC current interruption uses AC short-circuit generators operated at reduced power frequency, which is capable of providing the stresses evaluated from various DC fault conditions with a simple multi-terminal HVDC grid[1-6].
The paper will describe the performance and recent development progress in detail.

Keywords

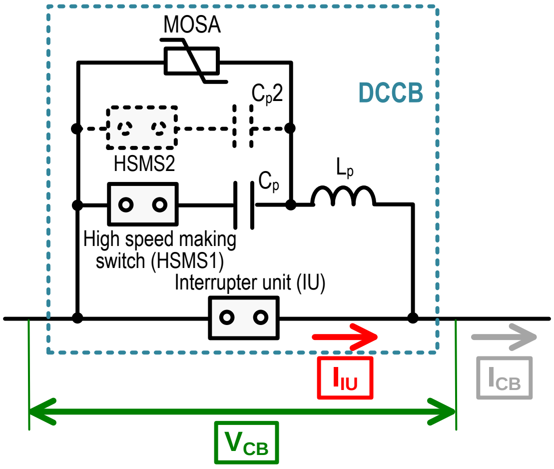
HVDC circuit breaker, Multi-terminal HVDC transmission, Vacuum interrupters, Active resonant current injection, DC current interruption, MOSA energy dissipation

1. MECHANICAL HVDC CB WITH CURRENT INJECTION SCHEME

The mechanical HVDC circuit breaker (CB) with current injection scheme is composed of multi-break vacuum interrupters in the main current path, a parallel circuit to superimpose high-frequency current on the DC current, and metal oxide surge arrester (MOSA) energy absorption units as shown in Figure 1 (a). The current injection is controlled by a high-speed making switch which can generate the high-frequency (in the order of several kHz) oscillating current from a pre-charged capacitors through a reactor.

Figure 1 (b) shows voltage and current behaviours during the current injection. The oscillation frequency and current magnitude are determined by the reactance and capacitance of passive components (reactor and pre-charged capacitor). The high frequency current generates a current zero immediately after the contact separation, which can typically be achieved within a few milliseconds from a trip order from the DC relay.

The topology can perform consecutive DC interruptions with short intervals if auto-reclosing is required. This can be achieved by a parallel connection with another set of a making switch and pre-charged capacitors, which is shown as HSMS2 with a dotted line in Figure 1 (a). After the first interruption is performed, the first high-speed making switch (HSMS1) is remained in the open position. Then HSMS2 is closed to inject a second high frequency oscillating current to create a current zero.



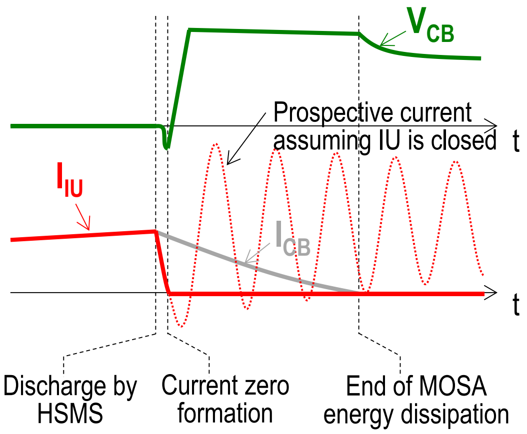


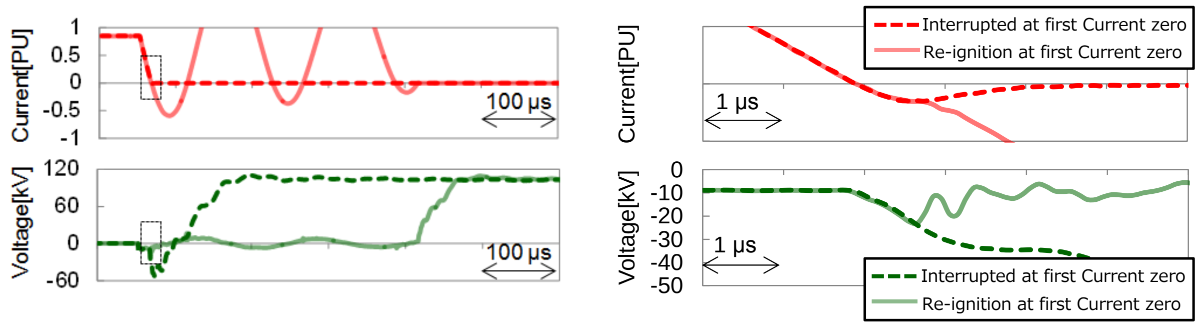
Figure 1(a): Configuration of HVDC circuit breaker composing vacuum interrupters with active resonant injection current zero creation scheme, (b) voltage and current waveforms during current interruption process

2. HIGH FREQUENCY CURRENT INTERRUPTION CAPABILITY USING A HV VACUUM INTERRUPTER

A vacuum interrupter considerably has excellent thermal interruption capability as compared with SF6 circuit breakers, however, there is a certain thermal interruption performance limitation, which corresponds to the maximum capable rate of change of interruption current (critical di/dt) and the associate rate of rise of recovery voltage (dV/dt) at current zero. Therefore, first fundamental characteristic of the critical di/dt with a vacuum interrupter after the current interruption up to DC 20 kA was evaluated in order to optimize the current injection circuit[7].

Figure 2 (a) and (b) show examples of the current and voltage behaviours with a prototype 100 kV vacuum interrupter during the current zero creation due to current injection with different time scales. A solid line shows the case of interruption failure at first current zero and a broken line shows the case of successful interruption.

Figure 3 shows the plots of the di/dt of these interruption success and failure when the vacuum interrupter interrupts the DC currents up to 20 kA as a function of DC current before interruption. The critical di/dt slightly decreases with an increase of DC interrupting current. It was confirmed that the critical di/dt (corresponding to thermal interruption capability) with a HV vacuum interrupter is 10 times higher than that of a modern HV circuit breaker with SF6.



(a) (b)

Figure 2: Current and voltage behaviours during the first current zero creation due to current injection (a) lower magnification, (b) higher magnification

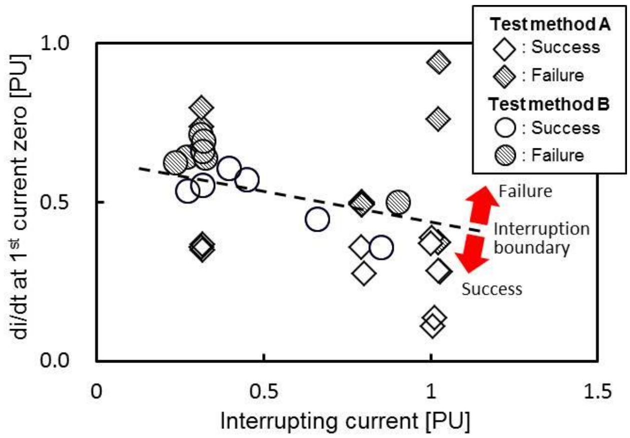


Figure 3: The critical di/dt evaluation using a prototype 100 kV vacuum interrupter at current zero dependence on DC current before the interruption

3. HVDC CIRCUIT BREAKER INTERRUPTING TESTS DEMONSTRATED AT DNV-GL/KEMA LABS

A mechanical DC circuit breaker composed of a HV vacuum interrupter using a rapid operating mechanism with current injection was tested with currents up to 16 kA. DNV-GL/KEMA established the DC short circuit testing platform supported by the PROMOTioN project, funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 691714[8][9]. The test was a first trial to demonstrate the HVDC current interrupting performance with HVDC circuit breaker and also conducted at the new testing platform of DNV-GL/KEMA labs under the witness of the PROMOTioN project members. Figure 4 shows a photo demonstrating the DC current interrupting performance of a mechanical HVDC circuit breaker with current injection.

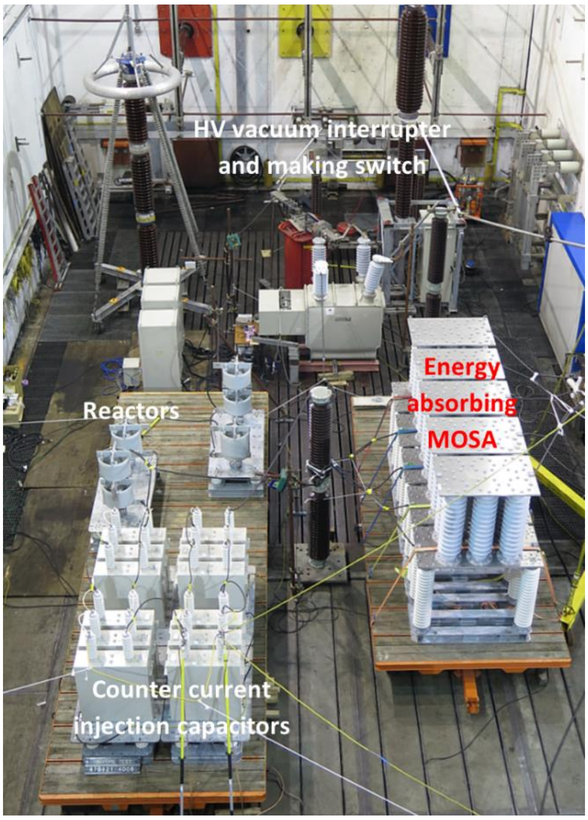


Figure 4: HVDC circuit breaker test conducted at the KEMA laboratory [1]
(Courtesy of DNV GL, KEMA Laboratories)

The current injection circuit consists of a capacitor (Cp), a reactor (Lp), a spark gap (fast making switch) and MOSA connected in parallel to the pre-charged capacitors. For the DC circuit breaker interruption tests, the discharge time of the pre-charged Cp kept at a constant applied voltage had only a few millisecond delay after the contact separation of the HV vacuum interrupter. The active resonant current injection circuit discharge created a current zero by superimposing a high frequency inverse current injected by the series connected Cp and Lp. The interrupting current was supplied by an AC short circuit generators operating at the reduced power frequency (e.g. 30 Hz), which can provide an equivalent DC current stresses when the DC circuit breaker interrupts the reduced power frequency short circuit peak current.

Testing conditions were determined in accordance with the dielectric requirements for a high voltage AC circuit breaker and the DC interrupting currents ranged from 2 kA (corresponding to the nominal current) up to 16 kA. The rate of rise of the recovery voltage becomes more severe for smaller interrupting currents. The overvoltage generated after interruption is determined by the following equation.

$$V_p = k\sqrt{\frac{L_s}{C_p}} \cdot I$$

Where, Ls is the inductance of the source circuit, Cp is the capacitor connected in parallel to the interrupter unit, I is the breaking current and k (<1) is a damping factor caused by the component of the resistance of the circuit. Therefore, overvoltage (Vp) becomes higher when the breaking current I is large, however the recovery voltage is limited by the restriction voltage of the MOSA connected in parallel to Cp.

Figure 5 shows examples of voltage and current waveforms recorded during DC interruption tests with the mechanical HVDC circuit breaker at interrupting currents of DC 16 kA. The tests were conducted with both bidirectional DC currents with a positive and negative polarity. In both polarity tests, the current injection capacitor of the HVDC CB is charged with the same polarity. This means that the current injection from the pre-charged capacitor is superimposed to interruption current as forward polarity (not inverse polarity) at first and then decreases to current zero, in case of the negative polarity current interruption (case (b)). After the current is extinguished by the interrupter, there is an oscillation of a few hundreds of Hz. This is due to the interaction between the charged capacitor of the HVDC CB and the inductance in the circuit.

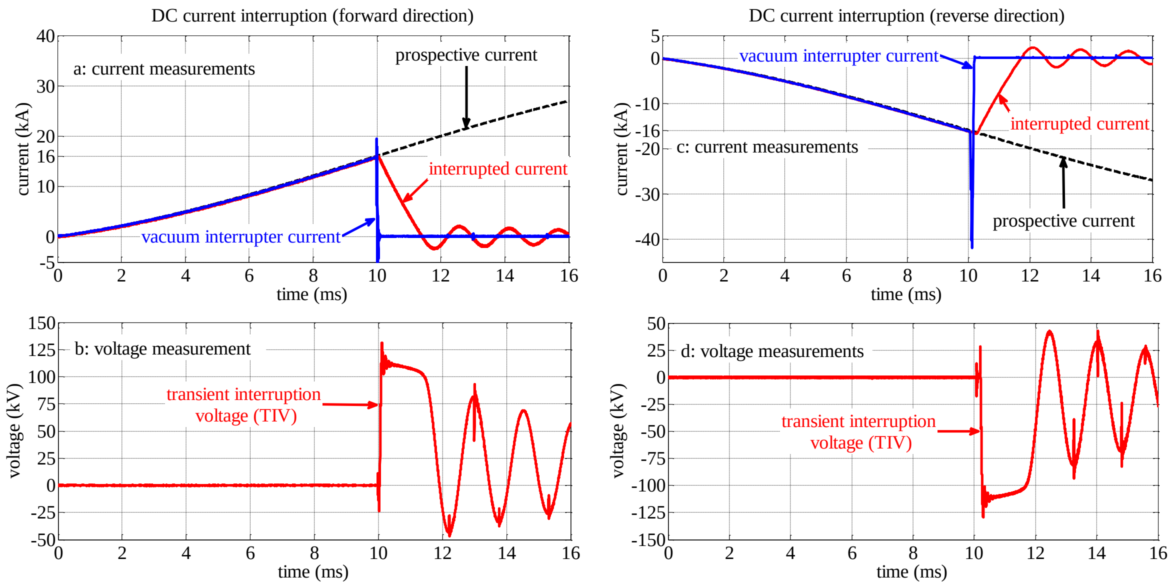


Figure 5: Voltage and current waveforms recorded during DC interruption tests on the DC circuit breaker with interrupting currents of 16 kA with positive and negative polarities[1]

4. MULTI-BREAK MECHANICAL DCCB FOR 320/400 kV AND ABOVE

In order to cope with EHV level HVDC transmissions, EHVDC CB should be composed of multi-break HV vacuum interrupters (unit voltage of 100 kV level). There are two fundamental configurations: combined type (shown in Figure 6) and separate module type (shown in Figure 7). Using 100 kV vacuum interrupter unit, 320/400 kV DC CB can be attained with 4 breaks and 525/600 kV DC CB can be done with 6 breaks.

Figure 6 shows a configuration of EHVDC CB with the combined type composed of common current injection circuit as well as common MOSA energy absorbing unit. In this configuration, the voltage stress (energy absorption requirement) per each MOSA column is uniform irrespective of the operation times of the high-speed switches. The design and sequence of the current injection circuit for the pre-charged capacitor is relatively simple.

Figure 7 shows another configuration of EHVDC CB with the module type composing of separate current injection circuit and MOSA energy absorbing unit per each HV vacuum interrupter. This configuration has an advantage of flexible design to attain the higher DC voltage ratings. However, the allowance for the voltage sharing per each break must be considered and equal voltage dividing is essential to reduce the number of breaks. Each separate capacitor Cp is also required to be pre-charged uniformly before operation.

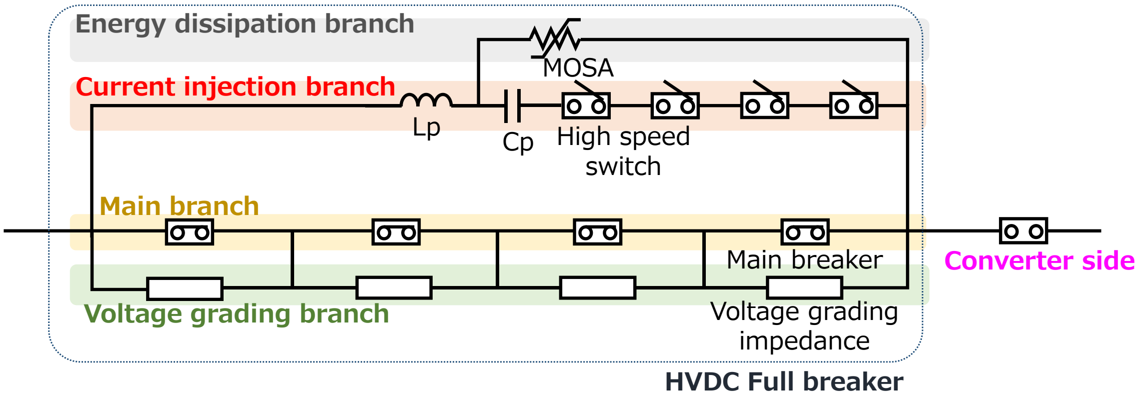


Figure 6: Configuration of multi-break HVDC CB with combined design

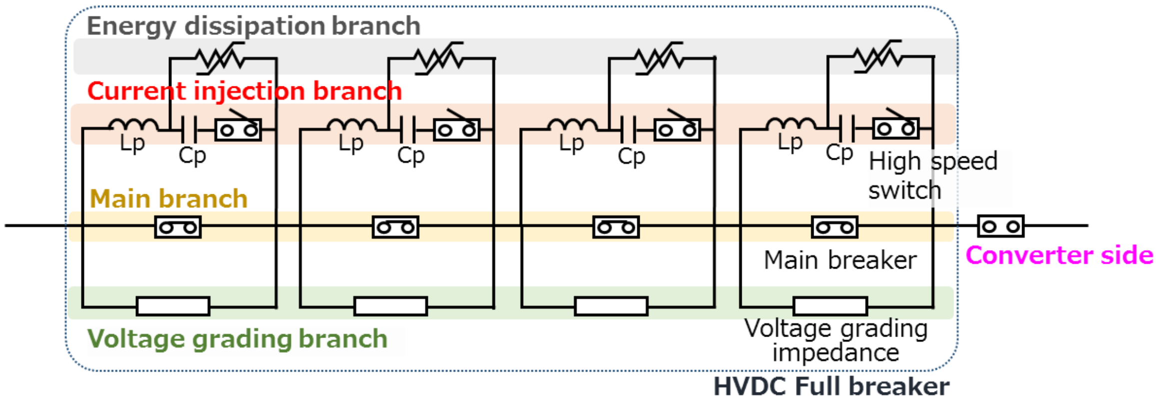


Figure 7: Configuration of multi-break HVDC CB with module design

Table 1: Comparison of multi-break HVDC CB configuration

Item	Configuration 1 "Combined"	Configuration 2 "Module"
Capacitor charging	**<Simple>** C_p can be charged in the same way as that for single break HVDC CB.	**<Complicated>** Each capacitor C_p should be pre-charged uniformly before operation.
Voltage class flexibility	**<Low>** Current injection branch should be optimized for each system voltage.	**<High>** Higher DC voltage can be available by adjusting the number of the module.
Impact of mechanical switch operation variation	**<Small>** The scatter of operation times of high-speed switches doesn't affect the performance	**<Large>** Impact of the operation time scatter of high-speed switches may affect the energy dissipation requirements

Figures 8 and 9 show conceptual drawings of combined design for 320/400 kV DC CB can be attained with 4 breaks and 525/600 kV DC CB can be done with 6 breaks.

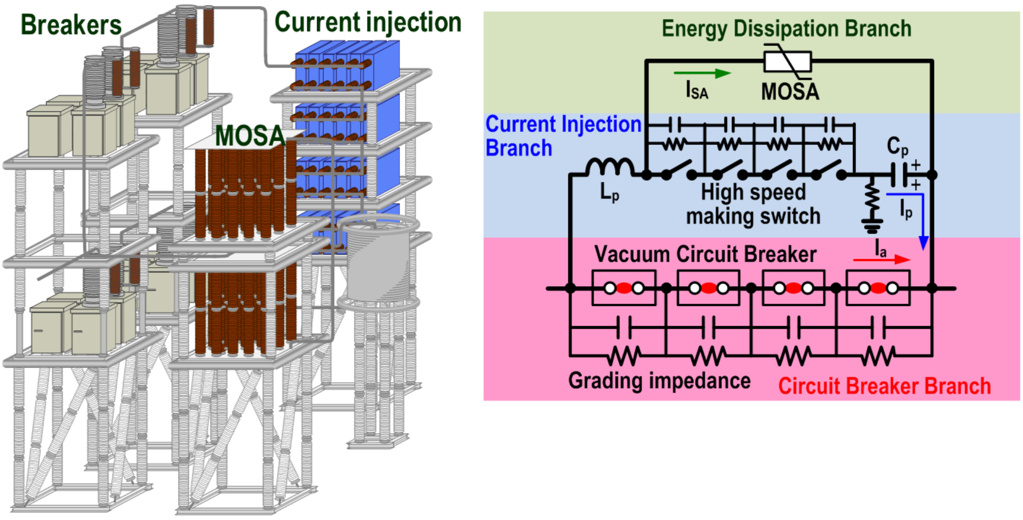


Figure 8 : Conceptual design of 320/400 kV DC circuit beraker with 4 breaks

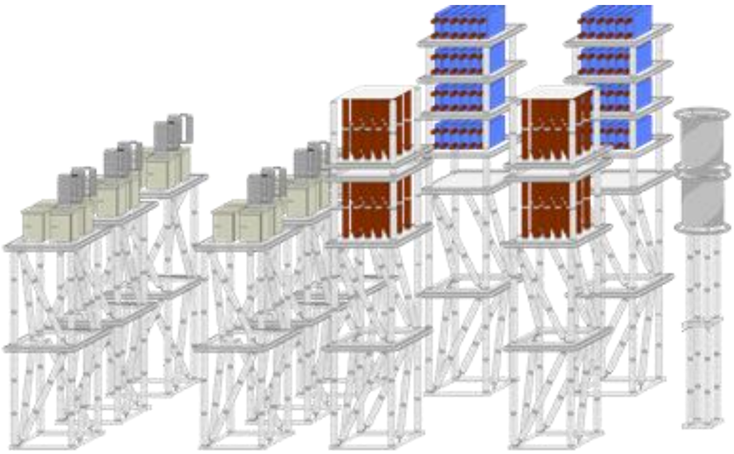


Figure 9 : Conceptual design of 525/600 kV DC circuit breaker with 6 breaks

5. CONCLUSION

A mechanical DC circuit breaker composed of a HV vacuum interrupter using a rapid operating mechanism with current injection was tested with currents up to 16 kA at the new testing platform of DNV-GL/KEMA labs under the witness of the PROMOTioN project members. The mechanical DC circuit breaker successfully interrupted both bidirectional DC currents with a positive and negative polarity.

The paper also presented the recent development progress of the mechanical EHVDC circuit breakers (320-525 kV levels) composed of multi-break vacuum interrupters. There are two fundamental configurations: combined type and separate module type. Using 100 kV vacuum interrupter unit, 320/400 kV DC CB can be attained with 4 breaks and 525/600 kV DC CB can be done with 6 breaks.

6. ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 research and Innovation program under grant agreement No. 691714.

Bibliography

[1] N. A. Belda et al., “Full Power Short-circuit Tests of HVDC Circuit Breakers using AC Generators Operated at Reduced Power Frequency”, CIGRE Paris session report, A3-115, 2018
[2] K. Tahata, S. Ka, S. Tokoyoda, K. Kamei, K. Kikuchi, D. Yoshida, Y. Kono, R. Yamamoto and H. Ito, "HVDC circuit breakers for HVDC grid applications," in CIGRE AORC Technical meeting, Tokyo, Japan, 2014.
[3] N. A. Belda, C. Plet and R. P. P. Smeets, "Analysis of Faults in Multi Terminal HVDC Grid for Definition of Test Requirements of HVDC Circuit Breakers," IEEE Transactions on Power Delivery, vol. 33, no. 1, pp. 403-411, 2018.
[4] S. Tokoyoda, K. Tahata, K. Kamei, K. Kikuchi, D. Yoshida, S. Oukaili, R. Yamamoto and H. Ito, "DC circuit breakers for HVDC grid applications HVDC and Power Electronics technology and developments," CIGRE SC A3 & B3 joint colloquium, No.122, 2015.
[5] PROMOTioN Deliverable 5.3, "Fault Stress Analysis of HVDC Circuit Breakers", 2016.
[6] CIGRE JWG A3/B4.34 TB 683, "Technical requirements and specification of the state-of-the-art HVDC switching equipment," CIGRE, 2017
[7] S. Tokoyoda , T. Inagaki , F. Page , M. Sato , K. Kamei , M. Miyashita , H. Ito, “Interruption characteristics of vacuum circuit breaker and the application to DCCB”, ACDC2017, Manchester, UK, 2017
[8] N. A. Belda, R. P. P. Smeets, C. A. Plet and R. Nijman, "Stress Analysis of HVDC Circuit Breakers for Defining Test Requirements and its Implementation", in CIGRE Colloquium, Winnipeg, Canada, 2017
[9] N. A. Belda and R. P. P. Smeets, "Test Circuits for HVDC Circuit Breakers", IEEE Transactions on Power Delivery, vol. 32, no. 1, pp. 285-293, 2017.