The Journal of Engineering

The 14th IET International Conference on AC and DC Power Transmission (ACDC 2018)

IET Journals
The Institution of Engineering and Technology

Bidirectional solid current-limiter for HVDC grids

eISSN 2051-3305
Received on 23rd August 2018
Accepted on 19th September 2018
E-First on 29th November 2018
doi: 10.1049/joe.2018.8484
www.ietdl.org

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Abstract: High-voltage direct current (HVDC) grids have been assumed as a promising technology for its advantages in accommodation and integration of large-scale renewable energy. However, the fault current increases dramatically once the fault occurs in HVDC grids, which makes great difficulty in fault clearance. Therefore, it is necessary to take some measures to limit the fault current. A bidirectional solid current-limiter (BSCL) topology is proposed. The BSCL can improve the performance of inductors to limit DC fault currents through the high-frequency switching between two current-limiting branches. Besides, the BSCL can be installed at both ends of a DC transmission line or between a converter and a DC bus. The feasibility of the proposed topology is demonstrated in power systems computer-aided design/electro-magnetic transient design and control. Simulation results indicate that the BSCL can effectively limit the rising speed and the amplitude of short-circuit currents, decrease the maximum breaking currents of DC breakers and improve the breaking speed of DC breakers.

1 Introduction

Traditional power system is facing the technical challenges such as the access to very large scale, high volatility of the new energy resources and the improvement of the electric power quality. To solve the problems, the technology of flexible DC grids is proposed, which is an energy transmission system with DC terminals interconnected. It has the advantages of smooth access to new energy sources, independent control of active and reactive powers and flexible and safe power flow control. DC grids are a promising technology, and currently the world's energy strategy provides broad development space for the application of DC power grids [1].

Modular multilevel converter (MMC) has the advantages of high modularity, better power quality and low switching frequency. It is suitable for high-voltage and high-power DC transmission applications and has become the preferred converter topology for constructing flexible DC grids [2]. However, due to the properties of the DC power grids itself, it exhibits the characteristics of ‘low inertia, low impedance’. When short-circuit fault occurs in the lines of DC power grids, especially bipolar fault, the energy stored in the capacitor of the sub-module will be quickly released and flow into the fault point, causing the fault current to rise rapidly and the amplitude will reach ten times of the rated current in only a few milliseconds. This will have a tremendous impact and harm to various important power electronic equipment in the DC grids, especially the expensive MMCs’ valves. If the arm current of the converter rises to twice of the rated value, and the DC fault is not isolated yet, this moment MMC must be blocked, which will possibly expand the scope of the failure and then result in a larger area blackout accident, seriously threaten the stable operation of the DC power grids.

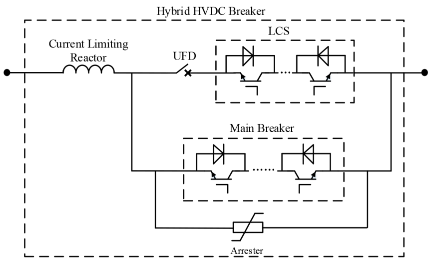

Fig. 1 *ABB DC circuit breaker topology*

Table 1 DC circuit breaker parameters

	SGRI	ABB	ALSTOM
U_N, kV	200	320	120
I_N, kA	2	2	2
times, ms	3	5	5.5
I_{max}, kA	15	8.5	5.2

At present, the two main fault isolation schemes of DC lines are present as follows:

(i) *The converter topology with fault isolation capability:* This method is more suitable for multi-terminal high-voltage direct current (HVDC) transmission systems, but for DC grids it will take more time to isolate the fault.
(ii) *The HVDC circuit breakers fault isolation:* This programme can be used for both the DC grids, but also for multi-terminal DC transmission system.

In the DC network, because of the free connection characteristics of the DC line, if the fault line is not isolated quickly, it will affect the safe and stable operation of the entire DC network [3]. In this case, the first option requires more time and may not guarantee the rapidity of protection. Therefore, HVDC breakers in the DC network are essential [4].

In the development of hybrid DC circuit breakers based on conventional mechanical switches and power electronic devices, in 2012 ASEA Brown Boveri (ABB) developed the hybrid HVDC breaker with a rated current of 2 kA and a maximum breaking current of 8.5 kA and passed the test. Its structure is shown in Fig. 1. Alstom Company and State Grid Corporation of China's Smart Grid Research Institute (SGRI) also completed prototype development in 2013 and 2015, respectively. The specific parameters are shown in Table 1 [5].

Hybrid HVDC circuit breakers inherit the advantages of low loss of mechanical circuit breakers and quick action of solid-state DC circuit breakers. Therefore, the use of hybrid DC circuit breakers to achieve fault isolation on the DC side is considered to be the most potential for DC network protection programme.

ABB's circuit breaker mainly consists of three parts: load commutation switch, ultra-fast mechanical disconnector (UFD) and

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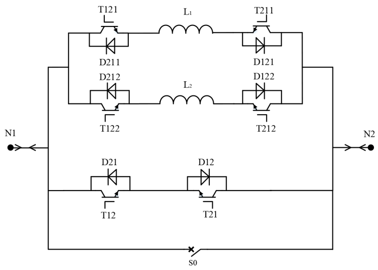

Fig. 2 *Topology of the BSCL*

the main circuit breaker (MB). Current flows through the LSC and UFD during normal operation of the DC grids. When a fault occurs, the current first commutates from the LSC to the MB, waiting for the UFD to open enough dielectric strength and then MB to open the fault current. Finally, the system energy is absorbed by the arresters. On the other hand, in order to ensure the dynamic response of DC control system, it is not allowed to install excessive reactors on the DC line. Normally, the accurate fault detection needs more than 2 ms [6]. In this way, the MB has not been operated and the fault current has exceeded the tolerance limit of the insulated gate bipolar transistor (IGBT). In addition, the transient energy of the fault current after the MB action will have a huge impact on the arrester, which may cause damage to the device and affect the service life of the arrester. Therefore, it is necessary to adopt suitable current-limiting measures before the DC circuit breaker operates.

From the development of the past 20 years, there are mainly two types of current limiters: (i) current limiter based on superconducting technology and (ii) current limiter based on power electronics technology [7]. At present, superconducting current limiters require a special and expensive cooling system that is limited by the technology of superconducting materials. Superconducting current limiting is only suitable for some special occasions and does not meet the requirements of the power industry [8]. However, with the advancement and development of high-power power electronics technology, solid-state fault current limiter is considered as one of the most promising current-limiting schemes for practical applications.

There is literature to propose a current-limiter topology that prevents HVDC commutation failure, alternately conducting two branches so that the DC is equivalent to the AC current, which enhances the current-limiting effect of the inductor on the DC current [9], but did not consider the two-way power flow, only applies to the traditional HVDC system. Some researches use inductors in parallel with solid-state switches to install at both ends of the DC line, and the inductive selection method has been deeply analysed [10]. However, this scheme also affects the dynamic response characteristics of the system. There is a scheme of using a resistor to limit the fault current, which increases the damping of the fault circuit and limits the drop of the DC voltage [11]. It also gives the general principle of parameter selection and its calculation method, but does not consider the overvoltage of parallel IGBTs and loss problem.

On the basis of the above research status of DC circuit breakers and current limiters, a bidirectional solid-state current-limiter topology suitable for DC grids is proposed in this paper, which can be installed at both ends of DC line. When the DC line short-circuit fault immediately starts the current limiter, which can reduce the DC circuit breaker breaking capacity and reduce the impact of transient energy on the arrester. The proper current-limiting measures can extend the service life of DC circuit breakers. At the same time, limit arm currents of the MMC and prevent the bipolar locking.

2 Current-limiter structure and working principle

2.1 Current-limiter topology

In the bidirectional solid-state current-limiter topology shown in Fig. 2, there are four main components of the current limiter: (i) full-control switch (IGBT), code named T; (ii) diode, code named D; (iii) inductor, code L; and (iv) ultra-fast mechanical switch, code named S. To increase the current-limiting effect of the inductor, two current-limiting branches are configured. Each current-limiting branch has an independent inductor L_1, L_2. Current-limiting branch and transition branch are the same, are configured with the reverse direction of the parallel switching devices, which ensure the normal flow path and current-limiting path with bidirectional conduction ability.

2.2 Current-limiter mode of operation

When the DC grids short-circuit fault occurs, the two current-limiting branches alternately turn on, which is based on the inductor that can limit the current change characteristics. Since the DC power flow can be flexibly controlled, the direction of the DC current also changes with the change of the power flow. In the current limiter, the high-power IGBT module reverse series is used to make the current limiter have the capability of bidirectional current limiting. When there is no fault in the system, The current only through the ultra-fast mechanical switch, to ensure that the current limiter will not consume too much active power. The proposed current limiter has four modes of operations as follows.

It is assumed that the current direction flows from the node N1 of the current limiter and flows out from the current-limit node N2 (the reverse analysis is the same and will not be described in detail):

(i) Mode 1, when the system is in normal operation, the DC current only passes through the ultra-fast mechanical switch S0, the current limiter is equivalent of being bypassed and no current-limiting effect is generated. This ensures that the current-limiter minimal loss in the normal operation of the system, the path of DC current through the current limiter is: N1→S0→N2 as shown in Fig. 3*a*.
(ii) In mode 2, when a short-circuit fault occurs in the DC line of the DC power grids, the fully controlled switch T12 is triggered immediately and then the ultra-fast mechanical switch S0 is turned off. The natural commutation technique is used to make the ultra-fast mechanical switch S0 quit running. When the current is commutated from S0 to full-control switch T12, the fault current path through the current limiter is: N1→T12→D12→N2, as shown in Fig. 3*b*.
(iii) Mode 3, after the mode 2 is completed, the full-control switch T121 is triggered immediately, and the fully controlled switch T12 is closed at the same time (here, it is also necessary to ensure that the current is fully commutated to T121 before turning off the T12). At this time, the current limiter has been working in the current-limiting mode. The path of the fault current through the current limiter is: N1→T121→L_1→D121→N2, as shown in Fig. 3*c*.
(iv) In mode 4, after a period of time, mode 3 ends, and then the full-control switch T122 is triggered immediately. At the same time, the full-control switch T121 trigger is switched off. The fault current is rapidly commutated from T121 to T122. The fault current path is: N1→T122→L_2→D122→N2, as shown in Fig. 3*d*.

After the short-circuit fault occurs on the DC line of the DC power grids, the current limiter operates in modes 3 and 4 and switches between the two modes at a certain frequency, which can enhance the blocking effect of the inductor on the fault DC current, which effectively reduces the fault current.

2.3 Control strategy

As shown in Fig. 4, the bidirectional solid-state current-limiter control strategy. It is also assumed that the current direction flows from the node N1 of the current limiter and flows out from the current-limit node N2 (the reverse analysis is the same and will not be described in detail). The control strategy mainly includes the trigger signal of ultra-fast mechanical switch S0, full-control switches T12, T121 and T122, and the timing description of the switch.

It can be seen from Fig. 4 that during the normal operation of the DC power grids, only the ultra-fast mechanical switch S0 can

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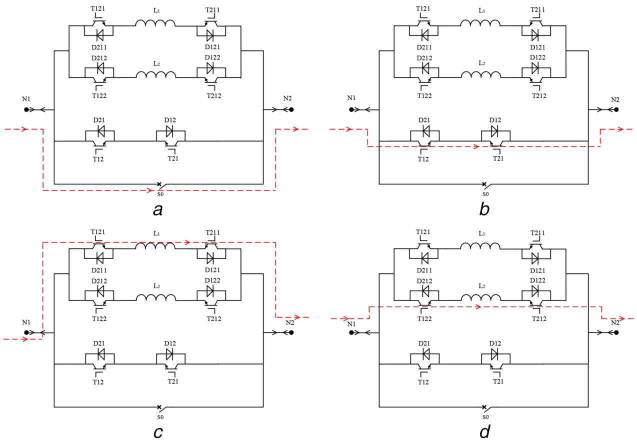

Fig. 3 *Operation mode of the BSCL*
(a) Model 1, ***(b)*** Model 2, ***(c)*** Model 3, ***(d)*** Model 4

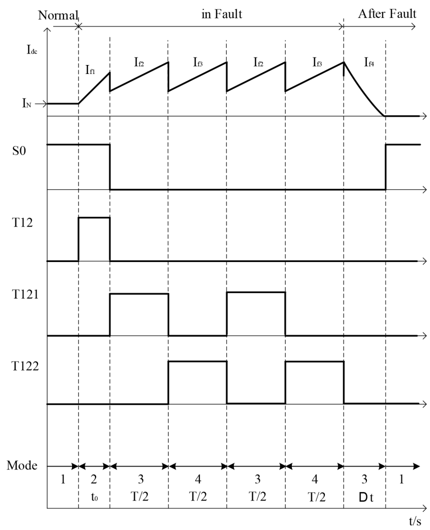

Fig. 4 *Control strategy of the BSCL*

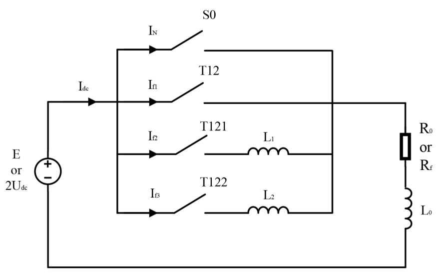

Fig. 5 *Equivalent circuit of the BSCL*

be turned on, and the full-control switches T12, T121 and T122 are all turned off. The DC current I_N flows through S0. The current limiter operates in mode 1, which corresponds to Fig. 3*a*.

When the protection device detects a short-circuit fault on the DC line, the full-control switch T12 is immediately turned on and then the ultra-fast mechanical switch S0 is turned off. After the time t_0, the fault current I_{f1} is gradually commutated from the ultra-fast mechanical switch S0 to the full-control switch T12. Since the current limiter does not have a limiting effect on the fault current during this process, the fault current rises very fast. The current limiter operates in mode 2, which corresponds to Fig. 3*b*.

Then the full-control switch T121 is triggered to turn on, the switch T12 is closed, and the fault current I_{f2} is rapidly commutated from T12 to T121. At this moment, the fault current flows through the inductor L_1, and the current limiter has a limiting effect on the fault current. In a short time, the speed of the fault current drops significantly. The current limiter operates in mode 3, which corresponds to Fig. 3*c*.

After the time T/2, the full-control switch T122 is triggered and the switch T121 is immediately closed. The fault current I_{f3} rapidly changes from T121 to T122. At the same time, the fault current is switched from the inductor L_1 to the inductor L_2, which corresponds to resetting the current-limiter current-limiting capability, fault current amplitude decreases, the current-limiter work in mode 4, which corresponds to Fig. 3*d*.

To maintain the current-limiting capability of the current limiter, the current limiter needs to switch modes 3 and 4 continuously at a certain frequency (period T). After the action of the DC circuit breaker, the DC line current I_{f4} is reduced to zero, the fast mechanical switch S0 is controlled to be re-connected and the full-control switches T12, T121 and T122 are turned off. The current limiter is back to mode 1, which is to cooperate with the DC circuit breaker for reclosing operation.

2.4 Current-limiter mathematical model

The bidirectional solid-state current limiter (BSCL) proposed in this paper is arranged at both ends of the DC power transmission line. It is also assumed that the current direction flows from the node N1 of the current limiter and flows out from the current-limit node N2. The equivalent circuit is shown in Fig. 5, R_0 is the total resistance of the DC line, L_0 is the current-limiting reactance of the DC line when the current-limiter is not in operation.

Fault current rise rate and amplitude are very large, so ignore stray inductance and distribution capacitance of the DC lines and switching devices, respectively. As follows, a mathematical model is established based on the four operating modes of the current limiter.

2.4.1 Working mode 1: When there is no fault in the DC power grids, only the ultra-fast mechanical switch S0 in the current limiter is turned on. In steady state, L_0 is equivalent to a short circuit and the DC line current is

$$I_{dc} = I_N = \frac{E}{R_0} \tag{1}$$

2.4.2 Working mode 2: This paper considers the bipolar short-circuit fault, the most serious is in the DC line 0 km position, and then the DC voltage in the fault circuit becomes $2U_{dc}$. The sum of positive and negative current-limiting reactors is still L_0 and the fault resistance is R_f. When the suspected fault is detected, turn off the S0, turn on T12 and record this moment as 0 s. Assuming that positive and negative pole symmetrical operations before the fault, the positive and negative current amplitudes are equal to

$$|I_{p(0_-)}| = |I_{n(0_-)}| = \frac{E}{R_0} \tag{2}$$

The flux equation of the fault circuit is

$$\frac{L_0}{2} I_{p(0_+)} + \frac{L_0}{2} I_{n(0+)} = \frac{L_0}{2} I_{p(0_-)} + \frac{L_0}{2} I_{n(0_-)} \tag{3}$$

From the flux equation, can be seen on the inductor L_0 current does not suddenly change, so there

$$I_{f1(0_+)} = I_{p(0_+)} = I_{p(0_-)} = \frac{E}{R_0} \tag{4}$$

Available from the fault circuit

$$I_{f1(\infty)} = \frac{2U_{dc}}{R_f}, \quad \tau = \frac{L_0}{R_f} \tag{5}$$

Using the three-element method, solving the current $I_{f1}(t)$ of the fault circuit corresponding to mode 2 as

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$$I_{f1}(t) = \frac{2U_{dc}}{R_f} + \left(\frac{E}{R_0} - \frac{2U_{dc}}{R_f}\right)e^{-(R_f/L_0)t} \quad (6)$$

2.4.3 Working mode 3: After a very short time t_0, T121 conduction, T12 off and record this moment as 0 s. Fault current commutation to L_1, in this mode, the flux equation of the fault circuit is

$$(L_0 + L_1)I_{L1(0_+)} = L_0 I_{L0(0_-)} + L_1 I_{L1(0_-)} \quad (7)$$

Since $I_{L1(0_-)} = 0$, $I_{L0(0_-)} = I_{f1}(t_0)$, so there

$$I_{f2(0_+)} = \frac{L_0}{L_0 + L_1}\left[\frac{2U_{dc}}{R_f} + \left(\frac{E}{R_0} - \frac{2U_{dc}}{R_f}\right)e^{-(R_f/L_0)t_0}\right] \quad (8)$$

Available from the fault circuit

$$I_{f2(\infty)} = \frac{2U_{dc}}{R_f}, \quad \tau = \frac{L_0 + L_1}{R_f} \quad (9)$$

Using the three-element method, solving the current $I_{f2}(t)$ of the fault circuit corresponding to mode 3 as

$$I_{f2}(t) = \frac{2U_{dc}}{R_f} + \left\{\frac{L_0}{L_0 + L_1}\left[\frac{2U_{dc}}{R_f} + \left(\frac{E}{R_0} - \frac{2U_{dc}}{R_f}\right)e^{-(R_f/L_0)t_0} - \frac{2U_{dc}}{R_f}\right]\right\}e^{-(R_f/(L_0 + L_1))t} \quad (10)$$

2.4.4 Working mode 4: In the previous mode, after T/2 s, T122 is turned on, T121 is turned off and record this moment as 0 s. Fault current commutation to L_2, in this mode, the flux equation of the fault circuit is as below:

$$(L_0 + L_2)I_{L2(0_+)} = L_0 I_{L0(0_-)} + L_2 I_{L2(0_-)} \quad (11)$$

Since $I_{L2(0_-)} = 0$, $I_{L0(0_-)} = I_{f2}(T/2)$, so there

$$I_{f3(0_+)} = \frac{L_0}{L_0 + L_2} \times I_{f2}\left(\frac{T}{2}\right) \quad (12)$$

Available from the fault circuit

$$I_{f3(\infty)} = \frac{2U_{dc}}{R_f}, \quad \tau = \frac{L_0 + L_2}{R_f} \quad (13)$$

Using the three-element method, solving the current $I_{f3}(t)$ of the fault circuit corresponding to mode 4 as

$$I_{f3}(t) = \frac{2U_{dc}}{R_f} + \left\{\frac{L_0}{L_0 + L_2} \times \left\{\frac{L_0}{L_0 + L_1}\left[\frac{2U_{dc}}{R_f} + \left(\frac{E}{R_0} - \frac{2U_{dc}}{R_f}\right)e^{-(R_f/L_0)t_0} - \frac{2U_{dc}}{R_f}\right]\right\}e^{-(R_f/(L_0 + L_1)) \times (T/2)} - \frac{2U_{dc}}{R_f}\right\}e^{-(R_f/(L_0 + L_2))t} \quad (14)$$

Subsequently, before the DC circuit breaker operates, the current limiter continuously switches between the mode 3 and the mode 4 at the frequency f (period T). As is clear from (8), (10), (12) and (14), the fault current will drop significantly at the instant of two current-limit mode switching.

3 Simulation analysis

3.1 Flexible DC system

To verify the current-limiting effect of BSCL proposed in this paper, two-terminal flexible DC transmission system is built on power systems computer-aided design/electro-magnetic transient design and control software. The voltage level of MMC is ±200 kV, the number of MMC sub-modules is 100 and the detailed parameters of DC system are shown in Table 1 and 2.

3.2 Parameter of the protection

Install current limiters and hybrid DC circuit breakers [12] at both ends of the DC line. The inductors L_1, L_2 of the current limiter are taken as 10 mH. Fault current rises faster, so the two current-limiting mode switching frequency is set to 3000 Hz (Table 3).

In the DC circuit breaker, protection voltage of the arrester is set to 500 kV. The action of the current limiter on the system just has a small impact, when the protection device to determine the suspected fault and then start the current limiter, so set the delay of 0.3 ms after the fault action. The action of the DC circuit breaker action has a great impact on the DC system; it needs to wait for the protection device accurately determine the fault, so set its delay 2 ms.

3.3 Case analysis

At the converter station A1, the permanent bipolar short circuit is set at the 0 km of the DC line, the time is 1 s and the fault resistance $R_f = 0.1\ \Omega$. To verify the effect of the current limiter, the following two cases are presented:

Case 1: The current limiter is blocked; only the DC circuit breaker is allowed to operate.
Case 2: The current limiter and DC circuit breaker can be normal operation.

The simulation results in Fig. 6 show that the bipolar short-circuit fault occurs at 1 s, and the fault current rises rapidly. As described in Section 3.2, the current limiter starts after a delay of 0.3 ms and the DC circuit breaker delays for 2 ms to start (another 2 ms is required for the internal operation of the DC circuit breaker). As can be seen from the comparison of Fig. 6, with the current limiter installed, the maximum value of the fault current is reduced from 16.5 to 3.5 kA, a drop of about 78%. Breaking the fault current time is also reduced by about 2 ms.

Fig. 7 shows the voltage of DC circuit breaker during breaking and Fig. 8 shows the energy absorbed by the arrester. As can be seen from Figs. 7 and 8, after the current limiter is configured, the voltage across the DC circuit breaker decreases slightly, but the energy absorbed by the arrester drops significantly. See Table 4 for a detailed comparison of the two cases.

Table 2 Parameters of the DC line

DC line resistance	DC limiting reactor	DC line voltage	DC line current
0.015 Ω/km	$L_0/2 = 30$ mH	± 200 kV	$I_N = 1$ kA

Table 3 Parameters of the MMC

Converter station	Control strategy	Arm reactance	Sub-module capacitance
A1	$U_{dc} = 400$ kV $Q = 0$ MVar	29 mH	10,000 μF
A2	$P = 400$ MW $Q = 0$ MVar	29 mH	10,000 μF

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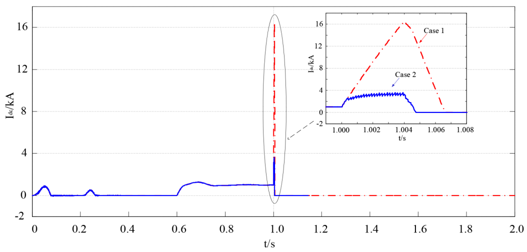

Fig. 6 *Fault current of two cases*

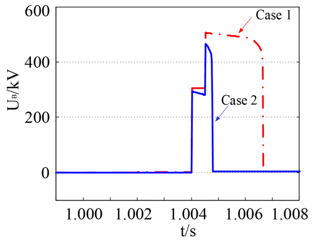

Fig. 7 *Voltage of DC circuit breaker*

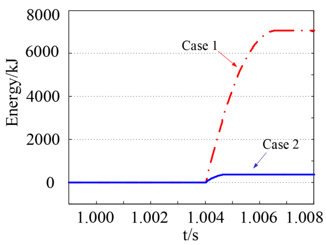

Fig. 8 *Energy of arrester*

4 Conclusion

In this paper, based on the research status of DC circuit breakers and current limiters, a BSCL topology suitable for DC grids is proposed. Four operation modes of the current limiter are defined, and a detailed control strategy is given. The mathematical model of the current limiter under the bipolar fault of the DC system is deduced. The current limiter can be installed on both ends of the DC line, and the analysis shows that the current limiter can effectively reduce the fault current. Finally, the simulation verifies that the current limiter can reduce the rising rate of the fault current. That is to say, when combining the BSCL with the DC circuit breaker for fault isolation, it can reduce the breaking capacity of the DC circuit breaker and reduce the impact of the transient energy on the arrester, which can prolong the service life of the DC circuit breaker.

Table 4 Comparison of the two cases

	Maximum current, kA	Maximum voltage, kV	Arrester energy, kJ
case 1	16.5	506	7067
case 2	3.5	406	363

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