A New Type of Hybrid DC Current Limiting Circuit Breaker suitable for HVDC

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Abstract. Multi-terminal DC transmission technology based on voltage source converter is one of the important technical means to solve the problem of grid connection and consumption of renewable energy. In this regard, encountering the fault current during fault period remains an important issue. Thereby, devices and circuits to suppress the fault current have become a hot topic in recent years. In this paper, a new type of current-limiting circuit breaker structure is proposed. Under normal conditions, the load current flows through the low-loss main branch. After the fault occurs, the power electronics based switches are disconnected, and the fault current is shifted to the auxiliary branch of current limiting device. The current limiting device suppresses the rise of the fault current. Finally, the power electronics based switches in the auxiliary branch open, and eventually the residual current is absorbed by the MOA. Moreover, the proposed topology of current-limiting circuit breaker is verified using PSCAD/EMTDC based simulation experiments. In comparison with ABB circuit breaker, the proposed topology has small on-state losses and good damping characteristics under normal conditions, and in the fault state too. Besides, the proposed topology owns the benefit of high reactance, therefore, allow the suppression of fault current effectively and have advantage to cut-off large amount of fault current.

1. Introduction

Large-scale applications of fully controlled power electronic devices result in the DC transmission based on voltage source converters (VSC), which mitigate the shortcomings of conventional high voltage DC transmission based on Line-Commutated Converters (LCC). The utility of VSC-HVDC allows the capitalization of renewable energy resource and smart grid links more effectively. One of the biggest advantages of VSC-HVDC is the independent control of both active and reactive power [1-4]. However, in the cause of fault at any point in the DC transmission line, the DC link capacitors discharge rapidly. As a result, DC current increases exponentially and system voltage decay sharply, these implications can cause huge damage to power converters at the converter station [5-8]. It is the obvious reason, that protection of DC grid is still the hot topic for research.

The means of handling the DC side short-circuit fault can be divided into three types according to the processing area [9-11]: 1) The AC circuit breaker which is used to cut off the connection between the DC network and the AC system on the AC side, 2) The self-clearing of the DC side short circuit fault realized by the converter itself control and 3) The DC circuit breaker in DC side. The first two methods can effectively suppress the fault current fed by the AC side, but cannot suppress the inrush current generated by the DC link capacitor discharge. The DC circuit breaker can effectively suppress...
the inrush current of the capacitor discharge, but there are some technical difficulties in the development of the high-voltage DC circuit breaker, mainly the high breaking capacity and the short-time cutting fault.

At the end, Reference [12] proposed a new type of circuit breaker topology with fault current limiting function. The circuit breaker is composed of three branches with inductance and power electronic switching devices. The topology has functions such as open circuit and current limiting, and has advantages that on-state loss is small, the short-circuit current is large, and the voltage level is high. Reference [13] proposed a rectified hybrid high-voltage DC circuit breaker topology, which uses a bridge-type reversing valve group and a one-way switch valve group to form a branching branch. This topology uses half the number of insulated gate bipolar transistors compared with the conventional topology, and can realize bidirectional current breaking, which is economical and reliable. Reference [14] proposed a circuit breaker topology with forced commutation circuit, which can block the fault current within a few milliseconds, and the topology realizes the zero current open circuit of the mechanical switch. The circuit breaker can maintain the conduction state even if the semiconductor devices suddenly experiences blackout.

This paper proposes a new type of current-limiting high-voltage circuit breaker topology. Then analyses the stress characteristics of the fault current, and research the influence of the selection of resistance and inductance parameters of the current limiting device on the fault current. Finally, the rationality of the proposed method is verified by the simulation model in PSCAD/EMTDC.

2. Working principle

2.1. Topology

The topology of the circuit breaker proposed in this paper is shown in Figure 1. Among the components of proposed topology, L1 is a current limiting inductor. Whereas, the auxiliary branch is composed of single-conducting IGBT tubes. The bidirectional shutdown of the current is realized by the rectifier bridge. The auxiliary branch can also be directly guided by a pair of IGBT tubes, as shown in Figure 2. The auxiliary branch is connected in parallel with the MOA, and the MOA protects the IGBT tube from overvoltage. A current limiting circuit is connected in series with the auxiliary branch. It is important to mention that, the current limiting circuit is composed of an inductor and a resistor in parallel as depicted in Figure 1 and Figure 2. When the fault current is transferred from the main branch to the auxiliary branch, the current limiting circuit suppresses the rise of the current and seeks more time for cutting off the fault.

2.2. Working principle

The operation of the new current limiting high voltage circuit breaker can be divided into three phases. The first phase is the fault detection phase, and the fault current flows through the main branch. The second phase is the current transfer phase. The power electronic device switch of the main branch is disconnected, the IGBT of the auxiliary branch turned on, then the fault current is transferred from the main branch to the auxiliary branch, and the ultrafast disconnector of the main branch is disconnected. On the third, the switches of stage auxiliary branch are opened, the current is absorbed by the MOA, and the current will be reduced to 0, then the fault can be removed.
2.2.1. System Operation During $t_0 \leq t < t_1$. The flow of current during $t_0 \leq t < t_1$ is elucidated in Figure 3. Ignore the conduction loss of the IGBT and the ultrafast disconnector. The circuit breaker can be equivalent to an inductor. The current of the line is as follows:

$$I = \frac{U}{L_1} (t-t_0) + \frac{U}{R_i}$$  \hspace{1cm} (1)

The ABB circuit breaker has the capacity to the cut-off current of 9kA and rate of fault current raise is less than 5kA/ms. The parameters of the circuit breaker in this paper are also designed according to this, and two constraints can be obtained:

$$\begin{align*}
I(t_1) &< 9kA \\
\frac{dI}{dt} &< 5kA/ms
\end{align*}$$  \hspace{1cm} (2)

According to Equation 2, the range of values of the inductor $L_1$ can be obtained.

2.2.2. System Operation During $t_1 \leq t < t_2$. The flow of current during $t_1 \leq t < t_2$ is highlighted in Figure 4. Neglecting the on-state losses, power electronics based switches have no impact on fault current. Application of KVL yields in equation (3):

$$L_2 I(s) + \frac{R_i L_2}{R_c} I(s) = \frac{U}{s} + L_i (t_1)$$  \hspace{1cm} (3)

Assuming that the initial current of the inductor at time $t_1$ is $k$, the fault current is available:

$$I(t) = \frac{U}{L_1 + L_2} t + \frac{R_i L_1 k + R_i k L_1 L_2 + U L_2^2}{R_i (L_1 + L_2)^2} - \frac{R_i L_1 k + R_i k L_1 L_2 + U L_2^2}{R_i (L_1 + L_2)} e^{\frac{L_i (t_1 - t_1)}{L_1}}$$  \hspace{1cm} (4)

In equation (4), $I(t_1) = I(t_1^-)$ can be found, so the current is continuous and the inductor does not generate an overvoltage. Deriving the current leads to equation (5):

$$I(t) = \frac{U}{L_1 + L_2} - C e^{\frac{L_i (t_1 - t_1)}{L_1}}$$  \hspace{1cm} (5)

Where $C$ is $\frac{R_i L_1 k + R_i k L_1 L_2 + U L_2^2}{L_1 L_2 (L_1 + L_2)}$, from Equation 6, it can be found that the current is first decreased and then increased. Therefore, in the design of the inductor and resistor parameters, the minimum value of the current should be as close as possible between $t_1$ and $t_2$. 

![Figure 3. Current flow during $t_0$-$t_1$ period](image)

![Figure 4. Current flow during $t_1$-$t_2$ period](image)

![Figure 5. Current flow after $t_2$](image)
2.2.3. System Operation for $t \geq t_2$. After the auxiliary branch switch is turned off, the MOA absorbs the residual current and the current drops rapidly to zero. The current flow path at this stage is shown in Figure 5.

3. Simulation and Results
To verify the theoretical implications of the proposed topology of the circuit breaker, a series of simulation-based experiments were conducted using PSCAD/EMTDC. Table 1 represents the values of different components used for simulation purpose.

| $U_{dc}$/kV | $R_1$/$\Omega$ | $R_2$/$\Omega$ | $L_1$/$\mathrm{H}$ | $L_2$/$\mathrm{H}$ |
|-------------|----------------|----------------|-------------------|-------------------|
| 500         | 166.7          | 100            | 0.17              | 0.4               |

Assume that a fault at 0.2 sec occurred in the system, power electronic switches in the main branch are turned off at 0.202 sec. Likewise, the power electronic switches in the auxiliary branch are turned off at 0.205 sec. In order to study the influence of resistance in the current limiting circuit on fault current, the value of resistances was changed to 10, 50, 100, 1000 ohms respectively, while other parameters of the system remained unchanged. The line current under influence of different resistive values is depicted in Figure 6.

In Figure 6, it can be observed that larger the resistance smaller the value of maximum current and quicker the decay time. However, if the resistance is too large, the inductor can cause an overvoltage. It must be noted that the resistance cannot be chosen too small, because when the resistance is less than a certain value, the current transferred to the auxiliary branch will not drop and will continue to rise. The value of the resistor should be as close as possible to the point where the current reaches the minimum value point in the middle of the auxiliary branch conduction period.

Similarly, in order to study the influence of the inductance change (on the fault current) in the auxiliary branch of the current limiting circuit, the value of inductance is changed, the values chosen for inductance are 0.1, 0.2, 0.4, 1H respectively, whereas, other parameters remained unchanged. The line current under influence of different inductances is depicted in Figure 7.

It can be seen from Figure 7 that the inductance mainly affects the rate of change of current. The ABB hybrid circuit breaker (inductance value 0.45H) is compared with the scheme proposed in this paper. The simulation results are shown in Figure 8.

It can be found that although the circuit proposed in this paper has a faster current rise between 0.2 and 0.202 s, the current suppression effect is much better than that of the ABB circuit breaker between...
0.202 and 0.205 s. At the same time, the energy dissipation is faster than ABB breakers. Moreover, under normal operating conditions, the scheme of this paper has less on-state loss and better dynamic characteristics.

4. Conclusion
A new topology of the circuit breaker with current limiting capability was purposed in this paper. Theoretical analysis inclusive of working principle, parameters estimations and influence of different components was backed by simulation based experiments on PSCAD/EMTDC, which mimic the correctness of proposed topology. The topology discussed in this paper owns the following distinct advantages: 1) In normal operating condition the inductance of the line is relatively small, as a result loss is small too, and the dynamic characteristics are good. 2) Under the fault condition, the maximum value of current is not too high, besides, the rate of rise of current during the fault is also minimized effectively.

The future work will be to study the calculation method of the key parameters of the circuit breaker and verify it in the multi-terminal flexible DC transmission model.

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