

Fault mode operation strategies for dual H-bridge current flow controller in meshed HVDC grid

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ABSTRACT

Current flow controllers (CFCs) can remove grid bottlenecks or extend grid operation area by changing amount of power flowing through DC transmission lines. This study focuses on behavior of interline H-bridge CFC in a DC grid in fault condition. In addition to the CFC circuit level fault studies, non-linear and linearized simplified models are developed for system level analysis. The analysis and fault study shows that the interline H-bridge CFC cannot survive during DC transmission line and bus faults due to an overvoltage occurring in its capacitor. Further investigation figures out that this overvoltage cannot be avoided even in presence of fast HVDC circuit breakers. Hence, an improved control system together with circuit level modifications are proposed to improve the CFC post-fault operation and to retain its components from possible damages.

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1. Introduction

As a consequence of development of large offshore wind farms, there is an increasing demand for realization of multi-terminal HVDC (MT-HVDC) grids [1]. The complex form of MT-HVDC grid is identified as meshed HVDC (M-HVDC) grid, which offers interconnection between different geographical areas to increase renewable energy resources diversity and supply reliability [1].

In addition to protection issues, a meshed DC grid might face power flow control problems [1,2]. The power flow in M-HVDC grid is controlled by regulating DC voltage of converters considering transmission line impedance. Due to grid topology, multiple paths for current flow between two different nodes may exist. Consequently, some of the lines can be overloaded because of their lower impedances. Current flow controllers (CFCs) can be inserted into the M-HVDC grid to solve this issue [2].

Several variants of CFCs, including modular bidirectional PFC with fault blocking capability [3], switched resistors for power flow control of the short transmission lines, DC/DC converters for long transmission lines [4], floating CFC [5] and thyristor based power flow controllers [6,7] have been proposed in the literature. Fur-

thermore, IGBT based CFCs with the AC grid connection [8], dual H-bridge CFC [9], cascaded and hybrid PFCs [10], double full-bridge DC/DC converters based CFC [11], a multi-port CFC [12] and interline CFC based on coupled inductors [13] have been investigated in recent years.

Among several proposed topologies the interline series connected CFCs without the AC grid connection are more attractive due to their lower voltage rating, power losses and implementation costs [2]. Particularly, the H-bridge based floating CFC topology with reduced number of switches has several technical superiorities [5]. Although the modeling and control principles of the interline CFC has been scrutinized [2], its behavior during a DC fault has not been considered, yet.

The present paper analyzes behavior of the interline dual H-bridge CFC during M-HVDC grid faults. The system and the circuit level analysis confirms the vulnerability of CFC against short circuit faults in M-HVDC grid even in presence of fast DC circuit breakers (DCCBs) and fast protection schemes. To overcome this issue, the CFC control system and its circuit topology are improved. The performance of CFC based on the proposed methods are validated through simulation studies.

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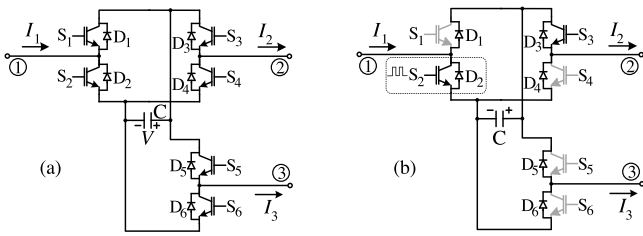


Fig. 1. (a) The topology of H-bridge based interline CFC topology with reduced number of switches [5] and (b) switch states to control I_{12} .

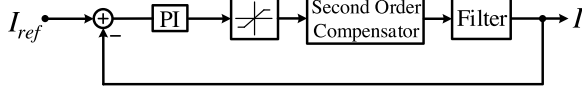


Fig. 2. Generic control system of the interline CFC [2].

2. Interline CFC with reduced switch number

The topology of CFC under study is depicted in Fig. 1(a) [5,9]. The CFC can be placed between two lines and a DC bus to control the current in one line by charging and discharging its capacitor and exchanging power between two lines.

2.1. Normal operation

Depending on current direction, the desired voltage can be generated by selecting a suitable set of states of switches. Table 1 shows the switch states for both negative and positive currents [2]. The capacitor voltage is represented by V in Table 1. The current can be controlled using a PI and a second order compensator. The linearized average model of the CFC represented by a couple of voltage sources can be used to design the current control system [2]. As shown in Fig. 1, I_1 , I_2 and I_3 are the currents flowing through terminal 1, 2 and 3 of the CFC, respectively. Based on the switching states in [2], I_2 can be controlled by applying PWM signal to S_2 if I_1 is incoming and I_2 and I_3 are outgoing currents. As shown in Fig. 1(b), S_1 , S_4 , S_5 and S_6 are opened and S_3 is closed. A generic control system of CFC including a PI controller, a second order compensator and a filter is shown in Fig. 2.

3. CFC integration into the M-HVDC grid

3.1. M-HVDC grid

M-HVDC grid can be formed by connecting DC sides of more than two converters through transmission lines. Various VSC technologies can be employed in an M-HVDC grid. Modular multilevel converters (MMCs) demonstrate better performance versus other types of converter for HVDC applications. Among various MMC topologies, the half-bridge MMC has less power losses and lower implementation cost. Nowadays, different variants of half-bridge MMC are widely employed by HVDC project developers [1]. However, the half-bridge MMC is unable to block DC short circuit fault current [1]. In an M-HVDC grid, due to the contribution of adjacent transmission lines [14] and significant reduction in faulty transmission line frequency dependent inductive characteristics due to the high frequency components of DC fault current [15], the DC fault current can rise up quickly. Hence, the meshed DC grids need to be effectively protected against the DC side faults [1,16,17].

Several protection strategies have been proposed for MT-HVDC and M-HVDC grids [14,1,18–20]. However, fast DC circuit breakers (DCCB) are to be most promising solution for M-HVDC grid. In a system protected by a fully selective protection scheme, every line

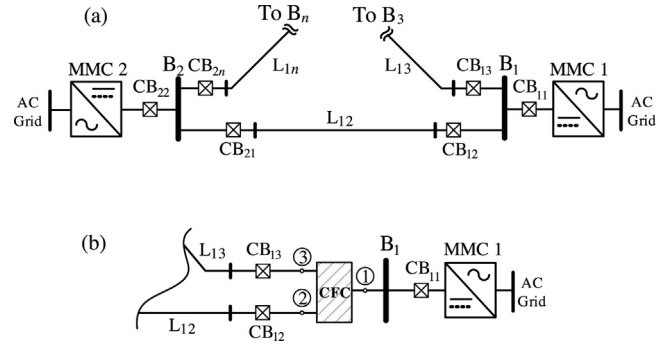


Fig. 3. M-HVDC grid (a) DCCB arrangement and (b) CFC integration.

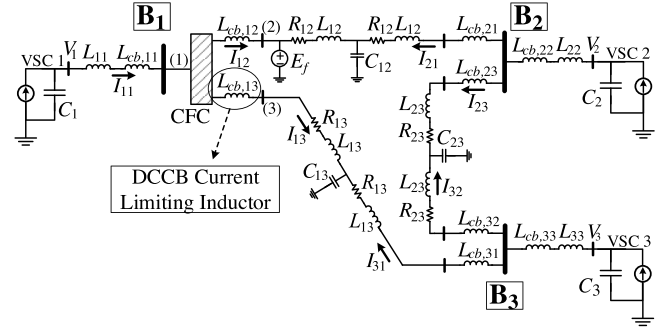


Fig. 4. Three-terminal grid including CFC and DCCBs.

is equipped with one DCCB at each end. The converter may be protected by either a DCCB at its DC side or an AC circuit breaker at its AC side [18]. A possible arrangement of DCCBs in a fully protected M-HVDC grid is shown in Fig. 3(a). The fast DCCBs such as hybrid (HCB) and solid-state (SSCB) ones employ a current limiting inductor in series with their structure that should be considered in modeling [14,21].

3.2. CFC integration into M-HVDC grid

Typically, the interline CFC is installed between two transmission lines and a DC bus. A possible integration of interline CFC into a DC bus is depicted in Fig. 3(b). The CFC is installed between L_{12} , L_{13} and B_1 . For sake of protection selectivity, the DCCBs should be relocated as seen in Fig. 3(b). No DCCB is required between the CFC and DC bus, but a disconnecter might be needed. Therefore, fault on either L_{12} or L_{13} can be cleared by CB_{12} or CB_{13} (and remote DCCBs) and a fault at B_1 can be interrupted by adjacent DCCBs.

4. CFC during DC fault

DC fault may occur on adjacent lines or at DC bus. The mentioned incoming and outgoing CFC currents scenario in Section 2.1 is used to analyze the fault behavior of the CFC from system and circuit points of view. However, this study can be extended to other possible scenarios. The CFC behavior is analyzed when it operates in the normal condition and a DC fault occurs.

4.1. System level modeling

The CFC behavior in an HVDC grid during a DC fault is studied considering a three-terminal M-HVDC grid. Fig. 4 shows the three-terminal grid model including the current limiting inductors of DCCBs. The parameters of three-terminal grid are illustrated in Table 2.

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