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Novel dc/dc choppers with circuit breaker functionality for HVDC transmission lines

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ABSTRACT

This paper proposes two novel dc/dc choppers with dc circuit breaker functionality for HVDC transmission lines. These converters feature step-up and/or step-down functions with instant interruption of short-circuit faults. Compared to other state-of-the-art converter topologies described in the literature, the proposed topologies have better control functions, lower manufacturing costs and reduced energy losses. A double closed-loop controller is designed to regulate the inductor current and output voltage of the converters. An auxiliary controller is also proposed to ensure proper shut-down of the circuit breaker in the event of dc short-circuit faults. The simulation and experimental results are presented to validate the effectiveness of the proposed converter configurations and control scheme.

1. Introduction

1.1. Research objective

As prices of fossil fuels rise and as concern about the dangers of global warming grows, electricity production from renewable energy sources such as wind and photovoltaic (PV) energy conversion systems is a subject of great interest nowadays. Many megawatt-level PV plants and offshore wind farms have been installed around the globe [1,2]. The high voltage direct current (HVDC) transmission is a promising solution to integrate the power generated from these renewable energy sources into the existing power grid. The technological advancements in power electronics have enabled the lower cost and higher performance operation of HVDC transmission lines [3,4].

Earlier HVDC transmission lines were mainly configured as two terminal systems with limited applications, and recently there has been significant interest for multi-terminal HVDC and HVDC grids [5–7]. They allow integration of many energy sources and the tapping of industrial and consumer loads [8,9]. A typical multi-terminal HVDC system with such a flexible power integration and allocation is shown in Fig. 1. The important technical and operational requirements for multi-terminal HVDC system are summarized below:

- Depending on the different power requirements, the tapped loads demand step-up or step-down of the transmission-level dc voltages. When the tapped loads need more power, the output voltage should be forced to step-up, and when some of the tapped loads shut down, the output voltage should be forced to step-down. For example, a 200 kV dc voltage should be stepped-up to 300 kV or stepped-down to 100 kV.
- In the event of short-circuit fault at the low voltage terminal of the HVDC transmission line, the main HVDC transmission lines should be isolated from the fault instantly to ensure the whole grid safety [10]. To fulfill the above two important requirements, dc/dc choppers as depicted in Fig. 1 are used. They perform step-up and step-down functions in addition to the dc circuit breaker (DCCB) functionality.

1.2. Research background

Various dc circuit breakers are researched for HVDC systems such as: mechanical DCCB [11], solid-state DCCB [12], hybrid DCCB [13] and power electronic converter based DCCB [14–19]. A comprehensive analysis with fault clearance time, control complexity, costs and losses indicates that the power electronic converter based

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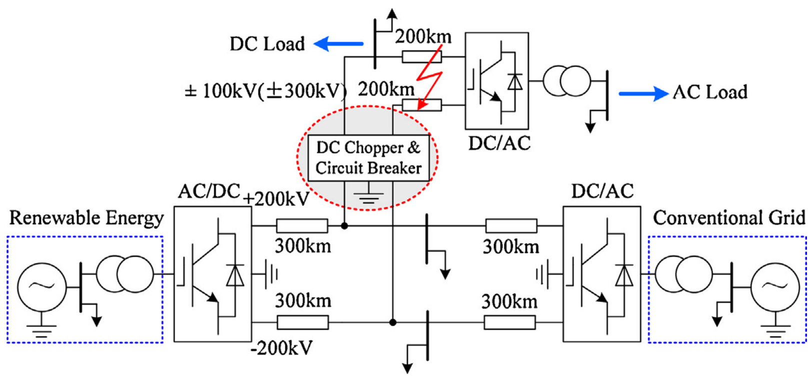

Fig. 1. Multi-terminal HVDC system with a dc circuit breaker (dc/dc chopper).

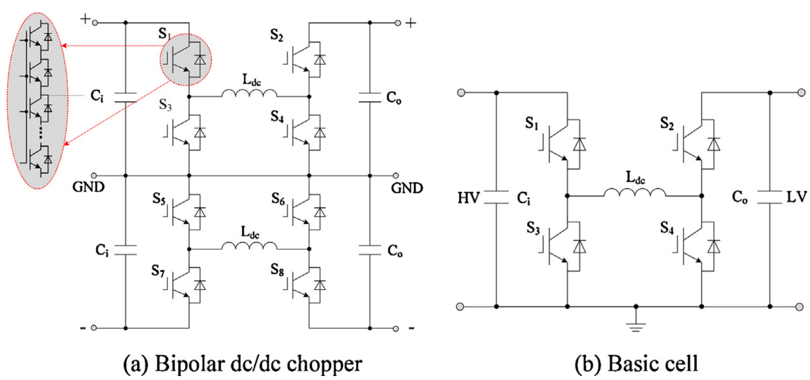

Fig. 2. The four-switch dc/dc choppers employed in HVDC systems [18].

DCCB is a good choice because it has shorter fault clearance time and also can change the transmission voltage level which is fit for flexible power supply. Recently some scholarly works have been carried-out to integrate the circuit breaker function into the dc/dc choppers [14–19].

The circuit breaker illustrated in Fig. 1 can perform fault clearance in addition to the step-up and/or step-down functions. A multi-functional four-switch dc/dc chopper with short-circuit protection functionality has been analyzed for high power application in [18] and the topology is shown in Fig. 2. Comparing with the mechanical DCCB and the hybrid DCCB, this configuration has more functions [19]. However, this configuration is costly due to the greater number of active switches which are realized by MV-IGBT's or IGCT's. Many active switches need to be connected in series and in parallel to handle the high voltage level and high peak fault current. For example, the test system showed in Fig. 1 needs a string with 134 IGBT's (4.5 kV, 650 A) in series and 3 strings in parallel. Moreover, compared with diodes, the price of IGBT's or IGCT's is much higher. The control complexity is also greater as it needs to generate more gating signals.

A modified converter configuration is described in [19] with one active switch group replaced by a diode group and the topology is shown in Fig. 3. These two choppers can offer bidirectional power flow. But, most of the ac or dc tapped loads do not need to provide power back to the main HVDC lines [8,9]. In addition, the cost of the DCCB is very high because of the huge number of the active switches and control devices.

In order to reduce cost and complexity of DCCB, two new converter configurations are proposed. These configurations deal with the unidirectional power flow and make them more suitable for the HVDC systems. The proposed configurations use less number of active switches compared to the existing ones, and thus they decrease the overall cost, control complexity and power losses. These choppers can step-up and/or step-down the transmission-level dc voltages in addition to the circuit breaker functionality. The comparison between proposed and existing DCCB's is given in Table 1. The one-switch topology saves 2412 IGBT's compared the four-switch topology and the two-switch topology saves 1608 IGBT's. The cost of one IGBT module includes the cost of itself and the control platform which produces the switching signals. The losses of one IGBT module include conduction losses and switching losses which are decided according to the curves in manufacturer's sheets and the circuit parameters. The losses of the active switches are the main losses in the IGBT-based converters [19].

In addition, the control scheme development is as important as of the converter configuration. In [19], double-loop control algorithm has been proposed for the operation of DCCB. However, this control scheme cannot interrupt and isolate the short-circuit faults completely. To solve this issue, a novel auxiliary controller is also proposed to properly shut-down the chopper in the event of short-circuit faults. The proposed converter configurations and

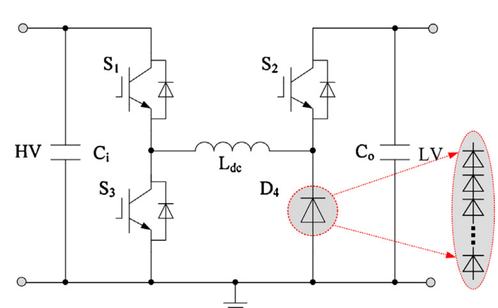

Fig. 3. Three-switch topology [19].