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Fault-tolerant control of MMCs based on SCDSMs in HVDC systems during DC-cable short circuits

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ABSTRACT

This paper proposes a fault-tolerant control of the high-voltage direct current (HVDC) systems based on modular-multilevel converters (MMC) under DC-cable short-circuit faults, where the MMCs are configured by hybrid scheme of series-connected double submodules (SCDSM) and half-bridge submodules (HBSM). Under faults, the SCDSM-based MMCs are able to control the real and reactive powers, which assists to adjust the fault currents in an allowable range and stabilize the grid voltage. For this operation mode, the SCDSMs are utilized to generate the bipolar output voltages, which are based on the arm current direction. In a converter leg, an arm is operated in the blocked state, while the other arm is controlled in the conducting mode to produce desirable output voltages for regulating the phase currents of the MMC. With this configuration, the SCDSM-based MMCs in the HVDC system still provide the capabilities of fault-current blocking as well as the reactive power compensation. Furthermore, the power loss and investment cost of the MMC based on the SCDSMs are lower than those of the HVDC system based on the MMCs with the hybrid SMs and clamp double SMs (CDSM). Simulation results for 400 MW–320 kV HVDC system are presented to verify the proposed control scheme and the fundamental operation of the MMC based on the SCDSMs is proved by experimental results for a rescaled prototype in laboratory.

1. Introduction

Nowadays, modular-multilevel converter has been considered as the most preferred choice for the applications of HVDC transmission systems for delivering power between two distant AC sources or an offshore wind power plant to the onshore AC grids. It is known that the MMC possesses the advanced and proper characteristics for these applications, which are modularity, easy scalability, low voltage stresses for semiconductor devices, less distortion of output voltages, small-sized filters required, etc. [1–6]. The basic unit with half-bridge submodules (HBSM) is a cost-effective scheme and low power loss to constitute the MMCs. However, the MMCs with the HBSMs lack the DC-fault handling capability under the short-circuit conditions in the DC side, which is the major issue of the HVDC transmission systems [7–9]. This demerit restricts the development of the HBSM-based MMCs for the HVDC applications. Fig. 1 shows an MMC based on the HBSMs in the HVDC transmission system integrating with the grid, where a fault current path through freewheeling diodes under DC short-circuit condition is depicted.

To prevent a damage of the converter devices or avoid unexpected tripping of the system during the DC short-circuit faults, the HVDC systems with the MMC based on the HBSMs require additional devices, where traditional protection methods are based on the circuit breakers (CB) [10–13]. However, drawbacks of the CBs are that, the AC circuit breakers take a long time to extinguish the fault and restart the system after a fault clearance, while the DC circuit breakers are costly and immature for high-voltage and high-power applications [14,15].

Another solution to protect the semiconductor devices of the MMC under the short-circuit faults is based on the modification of SM circuits. By adding thyristors (SCR) in single HBSM, the MMC based on these SM structures is able to isolate the DC fault currents, where the fault currents from AC side mainly flow through the SCRs. This helps protect the insulated-gate bipolar transistors (IGBT) of the HBSMs [14]. However, using the additional SCRs significantly increases the volume and cost of the converter and the excessively high currents still exist in the AC side. The modified SMs, which are able to create a reversed-bias voltage from the SM capacitor voltages to block the freewheeling diodes, are considered as effective alternatives functioning as the CBs under the DC-cable short-circuit faults. The MMC based on full-bridge submodules (FBSM) offers a fast fault-current clearance under the DC short circuits, since all the SM capacitors are inserted to form the reversed-bias voltage [2]. However, the FBSM-based MMC requires a

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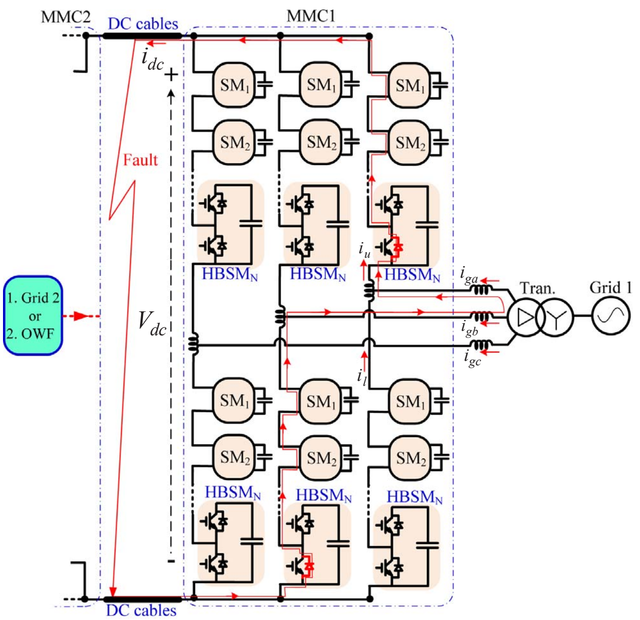

Fig. 1. Fault-current path in the HBSM-based MMC in HVDC system under DC short-circuit condition.

significant increase of the switches, which causes high power loss, volume, and capital cost of the converter. For reducing the device count of the MMCs, several modified structures called hybrid submodules consisting of HBSMs and FBSMs, three-level cells, or unipolar-voltage full-bridge submodules (UFBSM), have been introduced, where the sufficient reversed-bias voltage for turning off the freewheeling diodes is created from the capacitor voltages of the FBSMs [3,8,16]. Merlin et al. [17] suggested a hybrid multilevel converter called the alternative arm converter (AAC), where each arm of the AAC is composed of a series connection of FBSMs and a direct valve. Another SM circuit called clamp double SM (CDSM) was proposed in [18], where one of two capacitor voltages in double SMs is inserted for creating the reversed-bias voltage. An additional advanced feature of the MMCs with the FBSMs, hybrid SMs, AAC, and CDSMs is that, the MMCs can operate as STATCOM to provide reactive power to the grid under the short-circuit faults [3,17,19]. It is worth noting that from the expectation of the power system operators, the MMCs in the HVDC transmission systems should play an active role for the grid voltage stability even under the DC short-circuit faults, where the MMCs are required to remain on continuous operation for helping the grid with reactive power compensation, balancing the SM capacitor voltages, and restarting the normal operation quickly after fault clearance [19–21]. However, a major drawback of these SM structures is that the count of semiconductor devices of the MMCs is still high, which causes an increase in investment cost, volume, and power losses of the converters. Recently, an MMC topology called hybrid-arm bipolar MMC (UHA-BMMC) based on the UFBSM was proposed, where this MMC configuration is just applied for the three-pole HVDC systems [22]. The analysis about the loss and cost of the MMCs based on different SM structures has been introduced in [4,8], which will be also analyzed in this work. Compared to the MMCs with the aforementioned SM circuits, the MMCs based on the series-connected double submodule (SCDSM) also provide the DC-fault current blocking capability and the conduction loss and investment cost of the semiconductor devices are less [23]. It is found that the SCDSM-based MMCs can operate as STATCOM under the DC short-circuit faults, which have not been introduced in the published articles.

In this paper, a fault-tolerant control of the HVDC transmission systems with the SCDSM-based MMCs under faults is introduced, where the MMCs not only provides a fault-current blocking capability but also offers the STATCOM function during the DC line-to-line short-circuit conditions. Utilizing the bipolar voltage generation of the SCDSMs in the certain current direction, the SCDSM-based MMCs can be modified to operate as a three-phase cascaded multilevel converter, where the SCDSMs can produce five voltage levels with negative, zero, and positive values. For doing so, based on the phase current direction, an arm of the MMC leg is operated in the blocked state, while the other arm is controlled to produce desirable output voltages for regulating the arm and phase currents of the MMC. So, the MMCs can adjust the active power to mostly zero and control the reactive power injecting into the grid. With this operation, the HVDC system based on the MMC with the SCDSMs can handle the DC-cable short circuits and provide a reactive power compensation same as the MMCs with hybrid SMs and CDSMs, and the SCDSM-based MMCs offer advantages in terms of power losses, cost, and volume. The simulation results for 400 MW–320 kV HVDC system with a 9-level MMC are presented to demonstrate the proposed control scheme and the fundamental operation of the MMC based on SCDSMs is proved by the experimental results for the rescaled prototype in laboratory.

The main contribution of this paper is introducing a fault-tolerant control of the SCDSM-based MMCs in the HVDC system under DC-cable short-circuit faults, where the MMCs can block the fault currents and provide a reactive power compensation to the grid. This operation strategy has not been introduced so far. Another contribution of the research is that a hybrid of the HBSMs and SCDSMs instead of only the SCDSMs is employed for the MMCs, where a selection of the SCDSM number and the analysis for the MMC based on the HBSMs and SCDSMs have been introduced in details to obtain a full controllability of the STATCOM operation.

2. HVDC transmission systems based on MMCs with SCDSMs

2.1. Series-connected double submodules

A circuit of the SCDSM is shown in Fig. 2(a), which consists of two HBSMs (T_{11}, T_{12} for $HBSM_1$ and T_{21}, T_{22} for $HBSM_2$) connected in series through an IGBT T_s [23]. The anti-parallel diodes of T_s is connected inversely with the freewheeling diodes of the HBSMs. A diode D_{cl} is used to conduct the fault current and create a reversed-bias voltage from the SM capacitor voltages to block the freewheeling diodes of HBSMs when all IGBTs are switched off as shown in Fig. 2(b). At normal condition, the series IGBTs T_s are continuously turned on and the clamped diodes D_{cl} are turned off. The $HBSM_1$ and $HBSM_2$ of the SCDCMs are operated as the normal HBSM producing two voltage levels of 0 and V_{dc}/N, where V_{dc} is the DC-link voltage of HVDC system and N is the number of submodules per converter arm. Due to continuous conduction of the additional series IGBTs in the SCDSMs, the thermal stress and management for these devices should be considered. In this

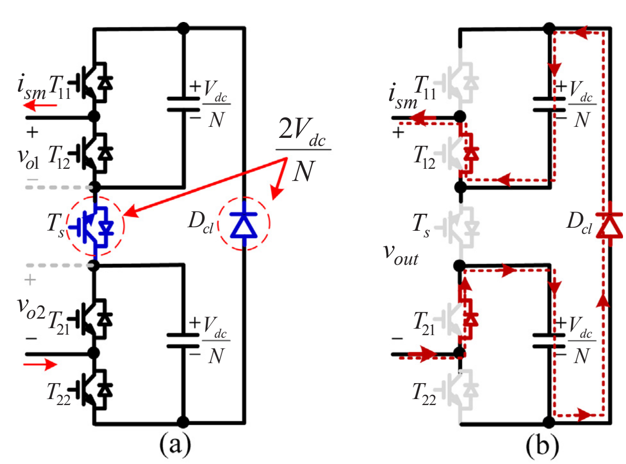

Fig. 2. Circuit of SCDSM. (a) Topology. (b) Current path as all IGBTs blocked.