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Control and protection sequence for recovery and reconfiguration of an offshore integrated MMC multi-terminal HVDC system under DC faults

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ABSTRACT

A comprehensive process of the control and protection against a DC fault in a voltage source converter (VSC) based high-voltage direct current (HVDC) system typically includes fault detection, fault isolation and system recovery. Regarding an offshore wind farm (OWF) integrated modular multilevel converter (MMC) based multi-terminal HVDC (MTDC) system with two control paradigms, i.e. master-slave control and droop control under DC faults, this paper presents the fault isolation, including the isolation of the faulted line section, with detailed control and protection sequence, which would be useful for practical engineering. The control and protection sequence at the system recovery/reconfiguration phase is comprehensively investigated, which includes: (1) when to start the recovery/reconfiguration control; (2) the sequence between deblocking the MMCs and reclosing the AC circuit breakers (AC CBs); and (3) the recovery sequence of each HVDC terminal. Based on the analysis of the system characteristics, a preferred recovery/reconfiguration scheme is proposed. Simulation results on the real-time digital simulator (RTDS) validate the proposed scheme and demonstrate the advantages through comparison with a different recovery sequence. The impact of transient and permanent DC faults on the system recovery/reconfiguration control is discussed. In addition, the recovery/reconfiguration control of the MTDC in radial and meshed topologies is compared and demonstrated. Based on the analytical and simulation studies, a general guideline on the recovery/reconfiguration control of MMC MTDC systems is proposed.

1. Introduction

Intensive research has been conducted on the control and protection against DC faults for the VSC based HVDC grids. Generally, a complete process of control and protection against a fault comprises 3 phases [1,2]: fault detection, fault isolation and system recovery/reconfiguration, as illustrated in Fig. 1.

The fault detection at Phase 1 consists of detecting and locating the fault based on the fault characteristics. Some researchers proposed solutions for detecting and locating DC faults in a VSC MTDC grid [3,4]. The fault isolation at Phase 2 comprises isolating the fault by associated protective action and then isolating the faulted line section. A DC fault could be isolated by tripping the AC CBs and the faulted line section could be isolated by opening DC disconnectors [2,3]. In addition to that, it was reported that the isolation of DC faults could also be achieved by the use of DC-DC converters [5,6], full-bridge/hybrid MMC [7–9] and hybrid DC CBs [10–14]. However, the technique of DC-DC converters is mainly limited due to the high losses and cost of DC-DC converters; the applications of full-bridge/hybrid MMCs are limited by increased losses and cost of switching devices compared with those of using the half-bridge MMCs; the hybrid DC CB has only been demonstrated on the voltage scale of laboratory, and may not be commercially available for real higher voltage applications, and the cost of such a DC CB is considerable.

Previous research predominantly focused on the control and protection at Phase 1 and Phase 2, while the control and protection strategy proposed so far has been rarely comprehensive for the system recovery/reconfiguration at Phase 3 after the fault isolation.

This paper investigates the control and protection process at Phase 2 and Phase 3 after the fault detection and mainly focuses on the control and protection sequence at Phase 3, of an OWF

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Nomenclature

T_n	terminal n ($n = 1, \ldots, n$)
t_n	time n ($n = 1, \ldots, n$)
CB	circuit breaker
SM	sub-module
VSC	voltage sourced converter
MMC	modular multilevel converter
OWF	offshore wind farm
OHL	overhead line
PCC	point of common coupling
DFIG	doubly-fed induction generator
HVDC	high-voltage direct current
MTDC	multi-terminal HVDC
IGBT	insulated-gate bipolar transistor
RTDS	real-time digital simulator
AC CB	AC circuit breaker
DC CB	DC circuit breaker

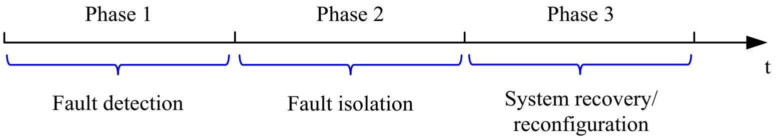

Fig. 1. Complete control and protection process against a fault.

integrated MMC MTDC system following DC faults. Since wind power has been recognized as one of the most promising renewables and its application is increasing at an annual rate of 20% [15,16], the integration of wind energy into electric power grids by HVDC technique, including the MTDC, has become particularly popular in recent years [15–17]. However, regarding the offshore integrated MTDC network, emphasis has been predominantly put on the grid integration of the OWFs [18,19], while less attention has been paid to the control and protection of the system following DC faults and the recovery/ reconfiguration control after the clearance/isolation of the fault.

Although the use of DC-DC converters, full-bridge/hybrid MMCs and hybrid DC CBs could become applicable in operation and may be more effective in dealing with DC faults in the future, it is necessary to comprehensively investigate a feasible control and protection strategy before they could become commercially available and viable.

In this paper, the control and protection strategy at the DC fault isolation phase is presented with detailed control and protection sequence, which would be useful for practical applications. Then the emphasis is put on the system recovery/reconfiguration sequence, including (1) when the recovery control should be started after the fault isolation; (2) the sequence between deblocking the MMCs and reclosing the AC CBs; and (3) the recovery sequence of each HVDC terminal. Based on the theoretical analysis, a preferred recovery/reconfiguration scheme is proposed. A 4-terminal MMC HVDC system with 1 terminal integrated with an OWF is established on the RTDS. The effectiveness of the proposed scheme is verified by real-time simulation results. The impact of transient and permanent DC faults at on the system recovery/ reconfiguration control is discussed. In addition, the recovery/ reconfiguration control of the MTDC in radial and meshed topologies is compared and demonstrated. Synthesizing the analytical and simulation studies, a general guideline for the recovery/reconfiguration control of MMC MTDC systems is proposed.

The rest of this paper is organized as follows. Section 2 presents the system configuration, the basic control modes of the MMCs and the DFIG-based OWF, and the system fault isolation strategy. The system recovery/reconfiguration control and protection sequence is comprehensively investigated and a preferred scheme is proposed in Section 3. Case studies are demonstrated in Section 4. A general guideline on the recovery/reconfiguration control of MMC MTDC systems is proposed in Section 5. Several conclusions are drawn in Section 6.

2. Offshore integrated MMC MTDC system

This section presents the investigated system configuration, control modes of the MMCs and the DFIG, and the system DC fault isolation strategy.

2.1. System configuration

Fig. 2 shows a single-line schematic diagram of a 4-terminal MMC HVDC system with the integration of an OWF. T_n ($n = 1, \ldots, 4$) denotes each terminal of the MTDC system. MMC-n ($n = 1, \ldots, 4$) denotes the MMC at each terminal. On the AC side of the MTDC system, the OWF is connected with T_1 of the MTDC system. The OWF consists of 60 wind turbines. *CBW* denotes the AC CB of the wind farm. *CBn* ($n = 2, \ldots, 4$) denotes the AC CB at each terminal. On the DC side, DC *ISWn* ($n = 1, \ldots, 4$) denotes the DC isolation switch and is equipped at each terminal. The DC grid is modeled by DC OHL. The length of each DC OHL is 100 km. The MMC at each terminal is half-bridge, 7-level converter. Fig. 3 illustrates the structure of MMC-n. The system parameters at each terminal are the same, only the control modes of the MMCs are different. Detailed parameters of the system are shown in Table 1.

2.2. Basic control mode

The control mode of the MMC at each HVDC terminal and the DFIG is briefly introduced as follows.

2.2.1. MMCs

Since the OWF is integrated at T_1, AC voltage and frequency (V_{ac}-f) control [18] is employed by MMC-1 to stabilize the magnitude and frequency of the AC voltage at the PCC for the integration of the OWF. The other three MMCs apply the well-known *dq* decoupled control. Regarding the power balancing in the MTDC systems, two main control paradigms, master-slave control [20–22] and voltage droop control [23–25], are generally utilized. In the following analysis, master-slave control is applied for the MTDC: MMC-2 is operated as the master terminal controlling the DC voltage; MMC-3 and MMC-4 are both operated as power dis-