Electrical Power and Energy Systems 73 (2015) 475–483

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A novel fault detection method for VSC-HVDC transmission system of offshore wind farm

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ARTICLE INFO

Article history:
Received 4 January 2014
Received in revised form 18 January 2015
Accepted 25 April 2015
Available online 2 June 2015

Keywords:
Fault detection
Offshore wind farm
VSC-HVDC system
DC fault
Cable sheath

ABSTRACT

VSC-HVDC transmission system is going to become the most economical way of power delivery for large and remote offshore wind farms. An accurate and fast fault detection method is necessary to protect sensitive devices of these systems and maintain uninterrupted power delivery. This paper investigates an innovative technique for recognizing DC zone faults including HVDC cable faults and unbalancing of DC capacitor bank. Sheath voltage is presented as a novel criterion for detecting abnormal situations in the system. Transient voltage of cable sheath and Wavelet transform are used to identify different types of DC faults. Extensive simulation examples are performed on EMTDC–PSCAD platform and post-processed using MATLAB. The results illustrate that the proposed technique gives a robust performance and can be applied to protection scheme of offshore wind farms.

Introduction

Wind energy has been presenting itself as an attractive renewable energy and is going to become highly penetrative energy source in the electrical power systems. In addition to land-based wind farms, Offshore Wind Farms (OWFs) have great potential to supply the main grid with the electrical power [1,2]. In fact, the electrical power which can be received from the OWFs is more than the land-based wind farms because of high winds at sea.

From power transmission's point of view, there are two types of connections, HVDC and AC connection. Economic matters play major role in selecting the best way to transmit the electrical power from offshore substation to onshore substation. Research studies have been mentioning two factors as the principal factors in this case: 1. Distance of the OWF from the onshore substation (the main grid) 2. Nominal active power of the OWF [3,4]. According to these studies, for large and remote OWFs, the HVDC transmission sounds more interesting way to deliver the electrical power to the main grid.

Traditional HVDC systems use Line-Commutated Converters (LCCs) that can reverse power transmission direction by changing voltage polarity. From two previous decades, an interesting replacement for the LCCs has been presented that can alter the power transmission direction by reversing current direction called Voltage Source Converter (VSC). The VSC-HVDC systems have some great advantages. They can remarkably control active and reactive power independently. Therefore, the system does not need reactive compensators which are necessary for the LCCs. Moreover, it becomes possible to use of inexpensive Cross Linked Polyethylene (XLPE) cables in the HVDC systems [5–7].

An undetected fault may have a catastrophic impact on the VSC-HVDC systems which connect the OWF to the main grid. It is vital to apply a fast and reliable fault detection method with regard to sensitivity and vulnerability of these systems. Most of studies presented in this field are related to the protection scheme of the system rather than focusing on DC fault detection. In [8], a protection scheme for HVDC line including cable has been proposed based on differential current methods. When a DC fault occurs in the VSC-HVDC transmission systems, their Insulated Gate Bipolar Transistors (IGBTs) which are not capable of clearing fault, will be by-passed and anti-parallel diodes conduct to feed the fault current. Economical fast DC switches have been used to isolate faulted DC line [9]. A protection strategy in [10] utilizes voltage chopper and overcurrent limitation controller to suppress overvoltage and overcurrent of the DC side of the VSCs. On the other hand, some faults can happen to converter itself and power electronic devices like IGBT misfiring. The behavior of overcurrent and differential relays has been investigated under different internal fault conditions [11]. Also, protection of high voltage capacitors has been studied in [12]. For protection of multi-terminal DC distribution systems, an overcurrent-based scheme has been suggested [13].

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http://dx.doi.org/10.1016/j.ijepes.2015.04.014
0142-0615/

A DC fault current can be cleared by AC circuit breakers on the AC side of the VSC. This is called handshaking method. A handshaking method for locating and isolating faulted DC line without telecommunication is analyzed in [14]. Majority of the suggested protection schemes for the VSC-HVDC systems which are current-based methods are reviewed in [15]. Wavelet transform is also proposed to detect DC faults in multi-terminal VSC-HVDC system [16]. None of aforementioned protective studies used detailed XLPE cable model for HVDC connection in their studies. A protection design against DC faults for multi-terminal DC wind farm is offered and fault analysis is discussed in [17,18]. Although some useful discussions are represented in [18], the protection scheme is just carried out for a small-scale system. However, lack of a fast and reliable method for identifying DC faults and distinguishing them from AC faults can be perceived in these systems.

In this paper, an innovative strategy based on using the sheath voltage is presented to diagnose wide range of DC faults consisting of positive cable to negative cable faults, positive cable ground faults, negative cable ground faults and DC capacitor unbalancing. Under normal operating condition, the magnitude of the sheath voltage is equal to zero while this magnitude increases under faulty conditions. Transient voltage of the cable sheath as new criterion and Wavelet analysis are used to detect the faulty situations. Simulation of a 400-MW OWF connected to the main grid via the XLPE HVDC cable is carried out. Obtained results show that the proposed method is effective and reliable.

This paper is organized as follows: in section 'VSC-HVDC transmission system for OWF and different faults scenarios', model of studied system and possible AC and DC faults are explained. Section 'The proposed concept' describes the concept of the proposed method. In section 'The performance evaluation', performance of the proposed method is evaluated by the simulation results. Finally, conclusions are discussed in section 'Conclusions'.

VSC-HVDC transmission system for OWF and different faults scenarios

The area of the OWF transmission system can be categorized into three sections as shown in Fig. 1: (1) wind generation section (OWF), (2) HVDC transmission section, (3) the main grid section.

The first section contains high power wind turbines at sea. Type of the wind generator used in the OWF can be Permanent Magnet Synchronous Generator (PMSG), Doubly Fed Induction Generator (DFIG) or Squirrel Cage Induction Generator (SCIG).

The OWF transmits its power by the HVDC transmission system. The second section is the HVDC transmission section consisting of marine substation, long submarine HVDC cable and onshore substation. Pulse Width Modulation (PWM) or Spatial Vector Pulse Width Modulation (SVPWM) techniques are used in order to control IGBTs in the VSCs.

Two parameters can be controlled independently by applying the PWM technique to the VSCs. Those are the magnitude and the phase angle of the AC voltage generated on the AC side of the VSC. DC link power and AC system voltage are adjusted by phase shift and magnitude control respectively. In fact, DC link voltage magnitude and reactive power which are directly related to the DC link power and the AC system voltage will be controlled. Topologies of converters can be three-level neutral point clamped VSC or two-level VSC [19,20]. These kinds of the topologies have similar behaviors under faulted conditions [21]. A two-level topology is used in the simulated system. There are other topologies such as Modular Multilevel Converters (MMC) that have different behaviors in case of faults and can be more tolerant of faulted conditions [22,23].

Finally, the third section is the AC main grid. Usually, there is a power transformer to adjust the voltage magnitude of the inverter for connecting to the main grid which is called converter transformer.

Faults may happen in each mentioned sections of the system. Types of faults may happen in the first and the third sections are AC faults. On the other hand, DC faults may occur in the second section. Moreover, converters inner faults that are related to power electronic devices can happen to the VSCs like the IGBT misfiring. The Power electronic devices have their own protections which are significantly faster than transmission system protections [24,25]. Detection of the converter inner faults is not included in this paper.

DC faults

The DC faults in the second section can be classified as follows:

1. Pole to pole fault (Positive cable to negative cable fault).
2. Positive cable ground fault.
3. Negative cable ground fault.
4. Unbalancing of positive pole capacitor bank.
5. Unbalancing of negative pole capacitor bank.

The submarine DC cables are almost immune to the pole to pole faults as insulation and conduit set the positive and negative cables apart. On the other hand, the cable ground faults are more common. This kind of the DC faults is due to the insulation failure (insulation breakdown). Cable aging and exposure to wet environment can be the reasons of the insulation failure. In this case, fault current will loop through grounding points of the system. In order

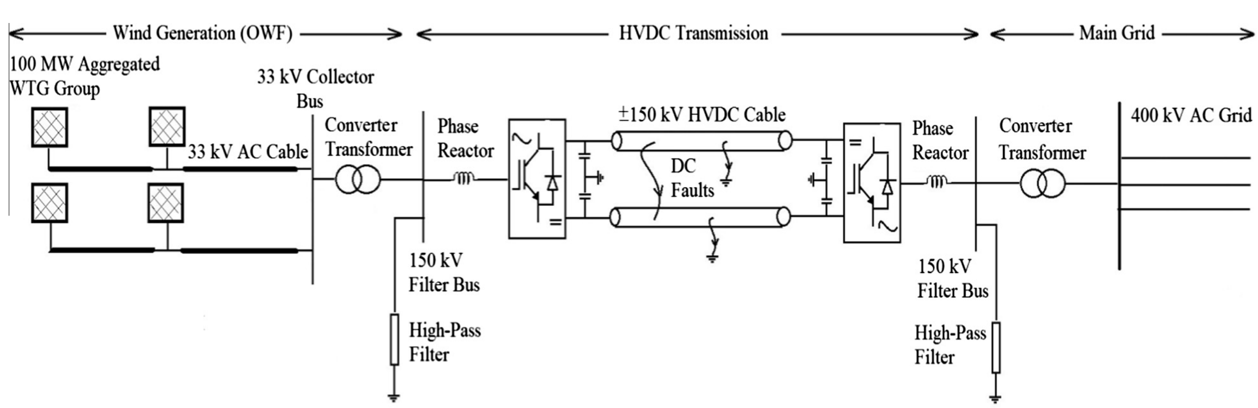

Fig. 1. Single line diagram of the simulated system.