Electric Power Systems Research 130 (2016) 78–88

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A differential protection technique for multi-terminal HVDC

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ARTICLE INFO

Article history:
Received 7 February 2015
Received in revised form 29 May 2015
Accepted 26 August 2015
Available online 12 September 2015

Keywords:
Multi-terminal HVDC
Protection
Wavelet transform
Wind farm

ABSTRACT

This paper presents a technique for differential protection of Multi-terminal High Voltage Direct Current (MTHVDC) transmission lines. The proposed technique depends on the electrical current data at both ends of each line section. Discrete Wavelet Transform (DWT) is used to detect DC faults as well as filter out the high frequency transients superimposed on the current signals. An operating signal and a restraining signal are used in this technique to discriminate between internal faults and external faults through their ratio in each section of the MTHVDC. The operating and restraining signals depend on energy contents of the de-noised current signals at both ends of each line section. MTHVDC modeling and relay design are carried out in the MATLAB environment. The results demonstrate the high reliability of the proposed relay in the zonal protection of MTHVDC.

1. Introduction

Voltage source Converter (VSC)-HVDC installations are promising power transmission methods for transmission of bulk power over long distances. The deployment of offshore wind power generation is expected to contribute a major portion of the world's future energy portfolio due to the expected depletion of fossil fuels along with the climate changes introduced by CO_2 emissions. Offshore wind power generates a large amount of power that can be collected and transmitted to different onshore grids via HVDC systems. Different wind farms can be ultimately interconnected to multiple grids by means of multi-terminal HVDC (MTHVDC). Moreover, MTHVDC enables the transmission of high power levels, which can contribute to the realization of the future super grids such as the European super grid [1–3].

Many research articles discuss the protection of a two-terminal HVDC system such as the research reported in [1,4–8]. However, these methods are suitable only for two-terminal HVDC systems. Some of these methods cannot be extended to MTHVDC while others have not been tested for operation in MTHVDC. Generally, the design of protection systems for MTHVDC grids is considered in its early stages. Limited research has tackled the protection problems of MTHVDC [9–14].

The research carried out in [9] has presented a thorough discussion concerning the DC-fault current and voltage waveform shapes, but it did not present a complete protection scheme for MTHVDC systems. The employment of circuit breakers (CBs) on the AC side of the converter for protection of MTHVDC was introduced in [10]. In case of faults inside the DC grid, all CBs on the AC sides of all terminals isolate the DC grid, then the faulted section is identified by means of a handshaking method [10]. The faulted section is isolated and the DC grid is restored afterwards. This method avoids using DC CBs, however, it takes a long time for isolation, fault zone identification, and system restoration. Moreover, the MTHVDC system is completely shut down unnecessarily. Alternatively, the use of DC CBs is now recommended to avoid unnecessary shutdown of healthy DC lines, isolate the fault quickly, and increase the DC system reliability [2,3,9,11,12,15]. The research relevant to DC CBs is promising and several architectures of DC CBs have been developed in literature [2,3,9,11,12,15]. With proper design of a protective relay, the DC CBs can isolate the faulted section quickly without the need to trip the whole DC system.

Yang et al. simulated the DC faults in MTHVDC including wind farms in [11] and proposed a distance protection scheme in [12] to be used in MTHVDC. However, this method did not address large systems with a high fault resistance. The largest rate of change of current is taken as a discrimination feature to identify the faulty line in [13]. However, it depends on system topology, where in some DC fault cases, the healthy line may have a larger rate of change of fault current. Moreover, this method avoids the deployment of DC

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http://dx.doi.org/10.1016/j.epsr.2015.08.021
0378-7796/

CB; therefore, it takes a relatively long time for isolation. The work done in [14] presents three criteria to identify the faulted cables in meshed MTHVDC systems. These criteria are voltage Wavelet coefficients, current Wavelet coefficients, and voltage derivative and magnitude. Nevertheless, the authors did not consider the non-zero resistance fault case. Moreover, the proposed method depends on the initial change of voltage and current Wavelet coefficients, which may be confusing to the relay especially during the initial transient period of the fault. Furthermore, a combination between overhead lines and underground cables is not considered in this paper, which is the existing case in practical systems.

The proposed protection algorithm in this paper presents a differential protection method for protection of MTHVDC with different configurations of DC sections (overhead lines and underground cables). The method depends on calculating an energy index for the de-noised versions of positive and negative pole currents at both ends of a line to discriminate between internal and external faults. Pole to ground, pole to pole, and pole to pole to ground faults are simulated to test the proposed method. Various fault resistances were simulated to prove the reliability of the proposed method in low resistance and high resistance faults. The paper is organized as follows. Section 2 presents the MTHVDC model used to test the protection algorithm. Section 3 introduces the main concept of the proposed method. Protection functions and the design steps of the proposed algorithm are explained in Section 4. Section 5 presents the simulation results, and finally, Section 6 concludes the work presented in this paper.

2. Power system model

The most common voltage source-based HVDC converters are two-level (2L-VSC), three-level (3L-VSC), and Modular Multilevel Converters (MMC). The MMC can be classified into half-bridge MMC (HBMMC), full-bridge MMC (FBMMC), and clamped double sub-module based MMC (CDSM-MMC). The latter two types of MMC are out of the focus of this work, as they do not need DC CBs due to their current suppression capability during DC side faults, but operate with lower efficiency compared to the half-bridge MMC in conjunction with a DC CB [16]. It has to be noted that 2L-VSC, 3L-VSC, and HBMMC have the same nature during DC side faults, and they require DC CB for clearing the DC fault current. So this work targets these types of converters, whose behavior during a DC side fault will be identical. The presented results in this work use the 3L-VSC Neutral point clamped (NPC). Most of the worldwide VSC-HVDC projects are based on conventional 2L-VSC and 3L-VSC NPC [17].

A three-terminal bipolar HVDC model is considered for this study. The three-terminal system contains three sections. Section 1 is connected to AC grid 1 via a 3L-VSC. Section 2 is connected to AC grid 2 via a 3L-VSC, and section 3 is connected to a 3L-VSC fed from an offshore wind farm. Sections 1 and 2 are overhead bipolar HVDC lines and section 3 is a bipolar undersea cable connecting the offshore wind farm with the overhead lines. The system configuration is shown in Fig. 1. This model is suitable for implementation in the European super grid, in which, the MTHVDC is used to transmit electrical power from an offshore wind farm to two different AC grids. Nevertheless, the proposed algorithm can be typically implemented on other MTHVDC configurations including meshed configurations. However, meshed networks need complicated control systems which are outside the scope of this research. The bipolar HVDC system, shown in Fig. 1, is operating at a nominal voltage of ±250 kV. The rated power of the wind farm is 1000 MVA at a unity power factor. The nominal power flow is considered from the wind farm toward the two AC grids. The lengths of section 1, section 2, and section 3 are 200 km, 300 km, and 60 km, respectively.

Table 1
MTHVDC parameters.

Section	Resistance (Ω/km)	Inductance (μH/km)	Capacitance (nf/km)
Overhead line 1	0.028	553	20.2
Overhead line 2	0.028	553	20.2
Undersea cable	0.007	200	226

A relay is placed at each end of each section with a sampling frequency of 100 kHz, which corresponds to a sampling time of 10 μs. A SIMULINK/MATLAB model is built to simulate the whole system. 3L-VSCs are used throughout the whole system. The converters' switching frequency is set to 1 kHz, a switching frequency of (1–2 kHz) is recommended for VSC in HVDC applications [18]. The DC-link capacitor of each converter is 1 mF. The grid side converters' controllers control the DC-link voltages based on the well-known droop control [19], and the wind-turbine side converter controllers are set to active and reactive power (PQ) control mode [20]. The droop gains are adjusted based on line impedances as given in [19]. The MTHVDC parameters are shown in Table 1.

3. Concepts of the proposed algorithm

In MTHVDC, when a fault occurs in any section, all converters contribute to the fault current; VSC control is able to block the operation of the IGBT switches. DC fault in a line section fed from a VSC can be represented by three equivalent circuits representing three operational stages as shown in Fig. 2 where L and R are the line equivalent inductance and resistance from VSC to fault position. In order to analyze the short circuit current, the short circuit is decomposed into 3 different stages of operation: Converter DC-link capacitor discharge stage, equivalent inductor discharge stage, and AC grid feeding stage.

In the capacitor discharge stage shown in Fig. 2(a), the converter DC-link capacitor voltage can be expressed as follows, assuming underdamped performance [21]

$$v_C = \frac{v_C(t_0)\omega_o}{\omega} e^{-\delta t} \sin\left(\omega t + \beta\right) - \frac{i_L(t_0)}{\omega C} e^{-\delta t} \sin(\omega t) \quad (1)$$

and the inductor current is [21]

$$i_L = C\frac{\mathrm{d}v_C}{\mathrm{d}t} = -\frac{i_L(t_0)\omega_o}{\omega} e^{-\delta t} \sin\left(\omega t - \beta\right) + \frac{v_C(t_0)}{\omega L} e^{-\delta t} \sin(\omega t) \quad (2)$$

where t_0 is the fault inception time, $\delta = R/2L$, $\omega = \sqrt{\left(1/LC\right) - \left(R/2L\right)^2}$, $\omega_o = \sqrt{\delta^2 + \omega^2}$, and $\beta = \arctan\left(\omega/\delta\right)$.

This response continues until the full discharge of the converter DC-link capacitor [21]. Solving (1), the time at which the capacitor voltage drops to zero can be found.

$$t_1 = t_0 + \frac{(\pi - \gamma)}{\omega} \quad (3)$$

where γ can be calculated as follows [21]

$$\gamma = \arctan\left(\frac{v_C(t_0)\omega_o C \sin\left(\beta\right)}{v_C(t_0)\omega_o C \cos\left(\beta\right) - i_L(t_0)}\right) \quad (4)$$

For positive pole to ground fault 50 km from BB3, the values of L, R, and C according to Table 1 are 0.01 H, 0.35 Ω, and 1 mF. The values of $i_L(t_0)$, and $v_C(t_0)$ are 2000, and 250 kV. For this fault, values of ω, δ, ω_o, β, and γ are 315.74, 17.5, 316.22, 1.515, and 1.5406, respectively. As a result, $t_1 = t_0 + 5.071$ ms. Fig. 3(a) shows the positive pole current of converter 3 during positive pole to ground fault.

At $t = t_1$, the second stage starts as shown in Fig. 2(b). The circuit inductor starts to discharge through the VSC freewheeling diodes.