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A novel traveling-wave-based directional protection scheme for MTDC grid with inductive DC terminal

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ABSTRACT

This paper presents a new rapid and reliable directional protection scheme for Multi-Terminal DC (MTDC) grid with an inductive DC terminal. The proposed method determines an internal or external fault easily by comparing the transient energy polarities of traveling waves measured at both ends of each line section. Compared with the conventional direction principle based on traveling waves, the proposed method performs more reliably in the case of an inductive terminal. Moreover, the double-end fault location method based on traveling waves is integrated into the protection scheme to predict the accurate fault location. The effectiveness of the proposed method is verified by a meshed DC grid modeled in PSCAD/EMTDC software. Extensive simulation results show the proposed method is able to determine internal or external faults correctly under conditions of different fault types, fault distances and fault resistances. Furthermore, the proposed method is also insensitive to the sampling frequency and noises.

1. Introduction

Voltage-source converter (VSC) based Multi-Terminal DC (MTDC) grid has been envisioned as a viable solution to the integration of the growing offshore wind farms [1–3]. This advanced technology provides distinct advantages over AC and traditional HVDC technologies in the areas of interconnection flexibility, economic efficiency and power supply reliability [3]. However, the fast and reliable protection scheme has become a knotty problem hindering the development of MTDC grid [4].

For conventional point-to-point HVDC grid, the protection can clear the fault by the ac-side circuit breakers (ACCBs), while the MTDC grid should only isolate the faulty section so that the healthy part of the system can keep continuous operation [5]. Thus, protection schemes in conventional HVDC are hardly extended to MTDC system due to lack of selectivity. With the development of DC circuit breakers (DCCBs), they will be regarded as the indispensable technique for achieving the selective protection for MTDC grid, although their performances still need to be improved in terms of speed and on-state losses for further application [6–8].

Another intractable problem of protection in MTDC grid is the operation speed. When a fault, especially a close-in pole to pole fault, occurs on the dc line, the fault currents will attain quite high rate of rising and very large steady-state values within a few milliseconds, leading to serious damages to the power electronics devices in the converter stations [9]. Therefore, fault identification and clearance must be achieved in the transient phase of DC fault. The fundamental-components-based methods in traditional ac systems are difficult to meet the requirements of speed [10], and new transients-based principals, such as traveling waves, should be developed for MTDC grid.

Some solutions to line protection for MTDC grid have been proposed in recent years. Previous investigation in Ref. [11] proposes "handshaking method" that uses ac CBs to interrupt dc fault currents and then isolates faulty line by fast dc switches. However, this method will result in the outage of all the dc system for a period of time until the whole system is successfully restarted. In Refs. [12–14], the current limiting reactor, which is placed at the end of each dc line, is used to realize the fault identification based on the characteristic that reactor can limit the rate of change of DC current and voltage. Therefore, voltage derivative and current derivative are used to achieve the fault discrimination, whereas these criteria are susceptible to incorrect data samples and noises. Moreover, it is worth mentioning a large inductance will largely affect the fault behavior and may result in undesired oscillation of dc voltages [6,15]. A methodology of differential protection for multi-terminal HVDC system is presented in Ref. [16], in which discrete wavelet transform is used to detect faults and filter out high frequency transients of currents. Nevertheless, in order to guarantee the reliability of the protection, the data window is up to 10 ms.

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Ref. [17] uses the differences of transient energy between the two ends of the dc line to discriminate internal and external fault reliably and swiftly in conventional HVDC grid, whereas this method is still hardly extended to MTDC grid in terms of protection speed.

In the literature, traveling waves (TWs) principal is also to be a good solution to the protection of MTDC systems. In Refs. [18–21], the identification of fault section and location can be accurately determined by calculating the time interval between any two terminals. However, these methods mainly focus on the precise fault location, and the local measurements need to receive the surge arrival times at all the terminals. Thus, these methods used as the system protection are restricted by the communication delay. In Ref. [22], fault identification for MTDC system is achieved by installing a shut capacitor at the joint point which is used to filter out the high-frequency components of traveling wave. However, additional protection devices must be installed to protect the shunt capacitor because a fault on the capacitor may lead to all the lines connected to the joint point to be cut off.

In this paper, a directional protection algorithm is proposed for a meshed DC grid with inductive terminal. The possible adverse impacts of inductive terminal on the traditional travelling-wave-based directional principle [23] is analyzed, and then a more reliable criterion directional criterion, the transient energy, is proposed. By comparing the polarities of transient energies measured at both ends of line, an internal or external fault can be determined swiftly and reliably. The rest of this paper is organized as follows. Section 2 analyzes the effects of inductive terminal on the traveling-wave-based directional principle and illustrates the proposed method. Section 3 describes the specific process of the proposed scheme. Section 4 verifies the proposed algorithm with numerous simulations. Finally, Section 5 is the conclusion of the algorithm.

2. Protection principal

2.1. Transient power of forward and backward wave

To illustrate the protection principal more simply, a simple single-line system with a fault on transmission line is used to demonstrate a basic truth, first. As shown in Fig. 1, relay R_1 and R_2 that are placed at the end of transmission line, are used to detect TWs. u_f represents the amplitude of the initial fault wave, and ρ and γ are the reflection and refraction coefficient of voltage wave at bus M, respectively. The positive direction of current is defined as the current flowing outward from the bus. Moreover, waves traveling outward from the bus are called forward waves, while waves traveling inward to the bus are called backward waves.

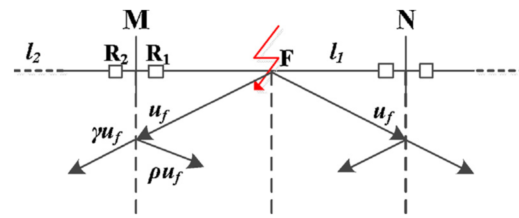

Fig. 1. The TWs path under a fault on the line.

Take the relay R_1 and R_2 as examples for analysis. According to the traveling wave principal, the voltage and current waves measured at R_1 and R_2 can be denoted as (1) and (2), respectively.

$$\begin{cases} \Delta u_1 = (1+\rho)u_f \\ \Delta i_1 = -(1-\rho)u_f/Z_{C1} \end{cases} \tag{1}$$

$$\begin{cases} \Delta u_2 = \gamma\Delta u_f \\ \Delta i_2 = \gamma u_f/Z_{C2} \end{cases} \tag{2}$$

In (1) and (2), Z_{C1} and Z_{C2} are the characteristic impedance of l_1 and l_2, Δu_k and Δi_k (k = 1,2) represent the voltage and current increments caused by TWs, which can be obtained by subtracting normal DC voltages and currents form the post-fault voltages and currents. The product of Δu and Δi represents the transient power of TWs, which is calculated by

$$\Delta P = \Delta u \times \Delta i \tag{3}$$

By inserting (1) and (2) into (3), the transient power at R_1 and R_2 can be obtained as

$$\begin{cases} \Delta P_1 = -\left(1-\rho^2\right)\Delta u_f^2/Z_C \\ \Delta P_2 = \gamma^2\Delta u_f^2/Z_C \end{cases} \tag{4}$$

It is known reflection coefficient ρ and refraction coefficient γ satisfy the condition: $|\rho| < 1$ and $0 < \gamma < 2$. Therefore, we can confirm that the polarity of ΔP_1 is negative and that of ΔP_2 is positive. Since the initial wave is considered as a backward wave for R_1 and a forward wave for R_2, then a basic truth is concluded as

$$\begin{cases} \Delta P < 0, \text{for the backward wave} \\ \Delta P > 0, \text{for the forward wave} \end{cases} \tag{5}$$

2.2. Directional principle in MTDC grid

A MTDC system based on modular-multilevel-converter, shown in Fig. 2, is considered in this study. In order to investigate the transient power in the meshed gird, a fault at point F is applied on link 13. Assuming the current limiting reactor which is usually placed

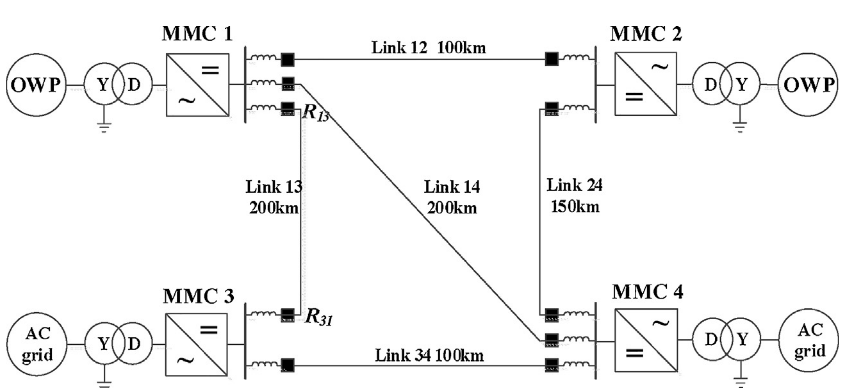

Fig. 2. The single-line diagram of the four-terminal test system.