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A fault location criterion for MTDC transmission lines using transient current characteristics

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ABSTRACT

Multi-terminal DC (MTDC) transmission system is applied in modern power systems due to its technical features. In an MTDC system, the converter stations are generally connected in parallel. To smooth the DC current output from the converter, the smoothing reactors are integrated in the converter outputs, instead of in the DC transmission line. When a fault occurs on the DC transmission line of the MTDC system, the fault current will flow along the whole DC line. As a result, the protection scheme may not locate the fault accurately. Based on the characteristics of DC filter, this paper analyzes the impedance characteristics of the combinational circuits, and proposes a method to identify the fault location by the characteristic harmonic. A protection criterion of the non-integer harmonics comparison is composed with phase-frequency characteristics curve derived from complex wavelet transform. The inevitable blind zone is analyzed in theory which exists on the terminal of transmission lines just like distance protection in AC systems. The algorithm is successfully tested and compared with other techniques.

Introduction

The electric power transmission of large capacity and long distance is an indispensable need of modern power system. Considering the separate distribution of the sending end power source and the stability of the receiving end power system, multiple distributed sending ends transmit power to multiple distributed receiving ends by Ultra High Voltage DC Transmission Line (UHVDC) becomes a feasible method. Currently, Multi-terminal DC (MTDC) has been applied in engineering, such as the NEA800 Project in India and the MTDC Project in Quebec-New England [1–3]. Meanwhile, the VSC-based MTDC has been researched and proposed for applications [4–7]. However, LCC-based MTDC system is more economical and reliable than VSC-based MTDC system which is still in development.

Recently, VSC-based MTDC transmission line faults locating method and its protection are studied in [8,9]. Some faults locating method is involved in the DC fault current direction, but it cannot identify the fault location in the circumstance of AC/DC conductor contact fault or power reversal caused by the control system action after fault.

HVDC transmission line fault location methods are presented in [10–12]. However, they are mainly for two-terminal transmission lines. The key factor is the characteristics of the boundary phenomenon. The smoothing reactor is usually applied to smooth the ripples of the DC current. Meantime, to prevent the shock wave generated by the DC line or the switch station from entering into valves, smoothing reactor is often positioned at the outlets of the converter in MTDC as shown in Fig. 1. (i.e., closer to the converter side in the T connection composed by the converter outgoing line and the DC transmission line). The traveling wave caused by the DC line fault will flow along the whole DC line since it cannot be suppressed by the smoothing reactor effectively, and the identification of which line the fault occurs fails. Therefore, the method based on the traveling wave boundary information cannot work in MTDC system. In addition, the method based on the distributed parameter line model in [11] and that based on the symmetrical component in [12] may be influenced by the noise of the DC transmission lines and the differences of the attenuation coefficients.

The DC line protection of MTDC system based on Line Fault Location (LFL) has been applied in engineering already [1]. This protection compares the arrival times of the initial traveling waves on each terminal by the synchronizing clock function of the GPS system to determine the exact location of the fault on the DC line. In [13,14], the same method is also adopted. Since the fault

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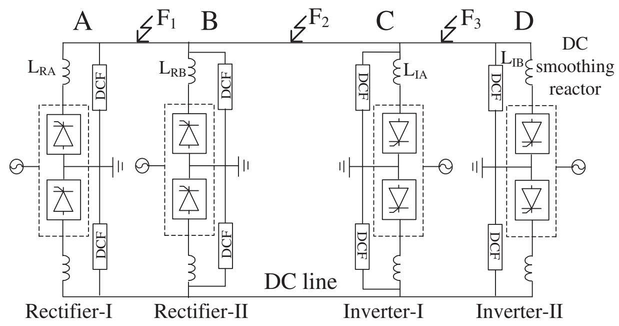

Fig. 1. A schematic of a bipolar MTDC system.

traveling wave transmits slightly slower than light at fixed speed, the difference of the arrival times of the traveling waves to every station is not significant when the stations are not far away from each other in distance, and the GPS time errors are not taken into account. Moreover, this scheme only utilizes the information in the limited time of the wave front, so the protection cannot work reliably if this information is not captured. In [15], the fault impedance used by fault locating scheme is unstable due to the variation in power system frequency.

The protection methods based on wavelet transform is presented in [16,17]. Hilbert–Huang transform methods are also mentioned in [18]. There are advantages to detect the surge of the transient currents in these methods, but they could not be extended to detect the phase information. The fault location method contains two parts. The first part is the fault distance measurement which is presented in [19]. The second part is to detect the faulted transmission line. For MTDC control strategy, detecting the fault line section is more important.

The fault line section selection is important to the MTDC control strategy. The characteristics of the DC filter are used in this paper for the fault locating of MTDC transmission lines. By analyzing the differences between the harmonics at the characteristic frequency and that at the other frequency when internal or external faults happen, a fault locating criterion based on complex wavelet transform is proposed. The inevitable one-end protection blind zones are deduced in the distributed parameter model. The algorithm is successfully tested and the results are compared with those from other algorithms.

MTDC system structure and its control strategy after fault

Take a four-terminal MTDC system as an example (as shown in Fig. 1). Four-terminal system is a paralleled extension of two-terminal system. The control strategy of CIGRE DC transmission test system is taken from [20].

In Fig. 1, traveling wave will flow along the whole line between Rectifier-I (point A) and Inverter-II (point D) when a fault happens on DC transmission line. The smoothing reactor in Rectifier-II (point B) and Inverter-I (point C) cannot be taken as the boundaries for the traveling wave after fault.

The structure of NEA800 is similar to Fig. 1 and the control strategy is provided in [1]. When fault happens on line BC, the rectifiers will be retarded for about 205 ms for deionization of the fault followed by a restart attempt. If the fault on line BC remains, it has three attempts to restore operation [1]. When fault happens on line AB, only one restart attempt is proposed. If the first restart attempt fails, the REC-I will control the DC line current to zero, and will be disconnected from the MTDC system by high speed switch. Therefore, the fault control logics at different location on the DC transmission line are different. The correct control strategy must be chosen by identifying the fault location.

Fault analysis of MTDC transmission line

Fault zones of DC transmission line

Assume a line-to-ground fault happens to the positive pole of the DC transmission line. Fig. 1 shows the line fault is divided into three fault conditions denoted by F_1 (between AB), F_2 (between BC) and F_3 (between CD). According to the analysis above, the MTDC system cannot work when a fault occurs in F_2. When faults happen in F_1 or F_3, the rest of the MTDC system can maintain the power transmission after the fault part is disconnected. Therefore, this paper mainly analyzes the difference between the faults F_2 and F_1 (or F_2 and F_3).

DC protection configuration and DC filter characteristic Analysis

Fig. 2 shows the smoothing reactor and the DC filter (DCF) which are installed in the output of the converter. The DC filter is composed of a set of three-tuned filter. The DC transmission line protection zone is denoted by the area c.

The impedances of the smoothing reactor and the DCF are respectively expressed as

$$Z_L = j\omega L_D \tag{1}$$

$$Z_{DCF} = \frac{1}{j\omega C_1} + j\omega L_1 + \frac{\frac{j\omega L_2}{j\omega C_2}}{j\omega L_2 + \frac{1}{j\omega C_2}} + \frac{\frac{j\omega L_3}{j\omega C_3}}{j\omega L_3 + \frac{1}{j\omega C_3}} \tag{2}$$

At the initial of fault happening, fault currents on DC line are varying in different frequencies due to the nonlinear effect of the fault arc and the circuit parameters. In AC system, fault analysis is involved in the symmetrical components of the steady-state circuit. Similarly, the steady-state circuit is also applicable to the DC fault analysis approximately.

The fault current discharging path is shown in Fig. 3. The fault current can circulate not only through the DCF but also through the converter valves. The AC system commutation inductance L_C and the smoothing inductance L_D are in the same branch of the converter valves. The high-frequency current of this branch is small because of the characteristic of L_D.

Assuming the parameters of smoothing reactor, DCF and AC commutation inductance are the same in every converter station, the impedance of the whole converter station is:

$$Z_{eq} = (j\omega L_D + j\omega L_C)//Z_{DCF} \tag{3}$$

The amplitude-frequency characteristic of Z_{eq} is shown in Fig. 4, which adapts some practical engineering parameters.

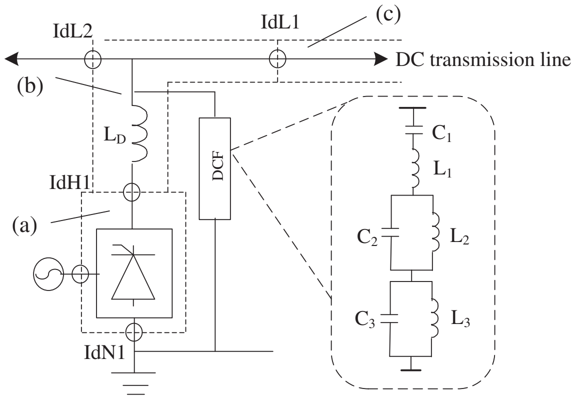

Fig. 2. The configuration of DC filter and the protections in converter station. (a) Converter protection. (b) DC bus bar protection. (c) DC transmission line protection.