A fast protection scheme for VSC based multi-terminal DC grid

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**A B S T R A C T**

This paper proposes a novel protection scheme for voltage source converter based multi-terminal direct current (VSC-MTDC) grid, in which DC line pilot protection applies polarity comparison of initial current travelling wave and DC busbar protection is based on sampled value current differential theory. This DC line protection utilizes modulus maximum of wavelet transform to get the polarity of initial current travelling wave on two ends of DC lines to distinguish internal faults from external faults. Current differential protection based on sampling values is adopted as DC busbar protection, which has the characteristics of fast operation speed and less computation compared to conventional current differential protection. A two-level voltage source converter (VSC) based four-terminal DC grid is built on the PSCAD platform and each VSC is equipped with resistive superconducting fault current limiters (R-SFCLs) to limit the short circuit current. Thus, DC circuit breakers can be used to break the DC fault current. The simulation results verify the validity and feasibility of the proposed VSC-MTDC grid protection scheme.

1. Introduction

Multi-terminal direct current (MTDC) transmission system is one of the valid approaches to resolve the integration problems of increased penetration of renewable energy sources. Unlike a line commutated converter (LCC) based high voltage direct current (HVDC) link, reversal of power flow can be achieved with the DC side voltage polarity fixed in a VSC-HVDC link. Thus, the VSC technology is the better choice for MTDC grids [1,2]. In a DC grid, the rise rate of fault current is very high and DC circuit breakers are yet to be commercially available for high power ratings currently. Therefore, protection and fault current interruption in VSC-MTDC grids are key research problems at present [3–5].

One method to clear a DC side fault is to open the mechanical circuit breakers on the AC side of VSCs. In [6], the authors describe a solution based on AC CBs and the handshaking method to locate and isolate the faulty DC line. The drawback of this method is that it leads to the de-energization of the whole DC grid and, requires quite a long time to clear a DC side fault and restore the DC grid. Depending on the DC CBs to isolate only the faulty line while continuing to operate the rest of the DC grid as usual is the future research direction [7–11]. Therefore, DC CBs are key apparatuses for DC grids. At present, ABB has tested devices with maximum breaking currents up to 9 kA and operating time less than 5 ms [12]. In December 2014, a 200 kV DC breaker prototype was developed successfully in China, whose maximum breaking current is 15 kA and the breaking time is 3 ms in [13]. Though DC CB technology has been gradually improved, their wide application in actual engineering still needs a long time. To solve this issue of fast rising rate of DC side fault current, fault current limiting methods are proposed based on inductor-capacitor-inductor (LCL) circuit or resistive superconducting fault current limiter (R-SFCL) in [14–17]. Owing to fault current limited, available DC circuit breakers of relatively low power ratings can be used to break the fault currents in the event of a DC fault.

A protection strategy based on fault-tolerant LCL VSCs and differential currents is presented in [18], but its operation time of dozens of milliseconds is too long for DC grid. There are a number of differential type schemes proposed in [19–21], such as a protection algorithm based on differential voltage measurement and the utilization of supplementary inductors placed at each end of the lines is proposed in [19], which does not need communication link. However, the parameter selection is complex. The two-level VSC based HVDC has shunt large capacitor on both sides of DC transmission lines, based on which, several DC line protection schemes are proposed in [22–24]. Nevertheless, these protection methods are only applied in two-end DC transmission system, for MTDC grid fault, their adaptability should be further analyzed.

As mentioned above, fault current limiter and DC CB combined with...
fast protection are a promising solution to MTDC grid fault. In actual, MTDC grid DC side faults include DC line fault and DC busbar fault. Therefore, on the basis of R-SFCL and DC CB, this paper proposes a fast protection scheme for two-level VSC-MTDC grid, which involves current travelling wave based DC line protection and sampled value current differential based DC busbar protection. To verify the correctness, several DC fault scenarios are simulated in a four-terminal DC grid in PSCAD. The simulation results show that the proposed VSC-MTDC grid protection scheme can fast and correctly identify whether the DC line or DC busbar is fault or not, and it is basically immune to fault type, fault resistance and fault locations.

2. Travelling wave based DC line protection principle

2.1. Current travelling wave characteristic analysis

For a VSC based three-terminal DC grid as shown in Fig. 1, assuming the positive current direction is from busbar to the DC line. When a fault at $F_1$ occurs inside the DC line MN or outside the DC line MP and line NP, the current travelling wave will be generated by the fault, as shown in Fig. 2, where, $F_1$ is the fault point; $U_f$ represents the fault superimposed voltage source; $I_{MN}$ and $I_{MP}$, $I_{NM}$ and $I_{PM}$ are the initial current travelling waves observed at terminals M, N and P, respectively.

As the black dotted line shown in Fig. 2, for a fault occurring on positive pole, the polarity of $U_f$ is negative. Thus the polarities of $I_{MN}$ and $I_{NM}$ are both positive for a fault inside the line MN, while the polarities of $I_{MP}$ and $I_{PM}$ are opposite for the fault outside the line MP. Similarly, for a fault occurring on negative pole (the red line shown in Fig. 2), the polarity of $U_f$ is positive. Thus the polarities of $I_{MN}$ and $I_{NM}$ are both negative for the internal fault and the polarities of $I_{MP}$ and $I_{PM}$ are opposite for the external fault.

In AC system, when a fault occurs on one of double circuit lines or a ring network, the initial current travelling waves on two ends of the healthy line may be with the same polarity, consequently, the healthy line may be identified as the faulty line. In the same way, in a ring DC grid, the initial current travelling waves on two ends of the healthy line may be with the same polarity in the event of a DC fault.

The difference is that there are only two poles in a DC grid: the positive pole and the negative pole. For faults on a certain pole, the polarity of fault superimposed voltage source is fixed no matter what the fault time is. Therefore, as shown in Fig. 3, for a ring DC grid, when a fault occurs on the positive pole of line MN, the polarities of initial current travelling waves on two ends of the healthy lines MP and NQ are all opposite. But for the healthy line PQ, their polarities may be opposite or the same, even if the polarities are the same (as the black dotted line in Fig. 3), they are both negative in theory. However, the polarities of initial current travelling waves on two ends of the faulty line MN are both positive. Similarly, for a fault on the negative pole, the polarities of initial current travelling waves on two ends of the healthy line may be opposite or the same, if the polarities are the same, they must be positive, while the polarities on both ends of the faulty line are negative. Obviously, the polarity characteristics are different for the faulty line and healthy line.

According to the aforementioned analysis, the following conclusions can be made:

1. When a DC fault occurs on the positive pole, the polarities of initial current travelling waves on two ends of the faulty line are all positive, while the polarities of initial current travelling waves on healthy line are opposite or both negative.
2. If a DC fault occurs on the negative pole, both the polarities of initial current travelling waves on two ends of the faulty line are negative, while the polarities of initial current travelling waves on healthy line are opposite or both positive.

2.2. Wavelet transform and theory of modulus maximum

As a powerful signal processing method, the wavelet transform can
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