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Fault Detection Algorithm for Multi-terminal LCC HVDC Interconnected Grid

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Abstract--The protection of Multi-terminal DC (MTDC) system is not straightforward. This paper proposes a novel protection technique for the proposed configuration topology of interconnection project between Egypt and Saudi Arabia. The proposed scheme depends on the second derivative of dc line current with the time which represents the acceleration of dc current with the time. A model of three-terminal Line Commutated Converter (LCC) MTDC with polarity reversing availability is used to study fault behavior and apply the proposed algorithm to detect and classify the fault. The proposed scheme is evaluated via an extensive simulation study for 500kV dc transmission network using Matlab©/Simulink©. The suggested algorithm detects a dc fault without communication link between the relays and can respond to different fault resistances and different fault distances in few milliseconds.

1. Introduction
Multi-terminal DC (MTDC) refers to an HVDC system that consists of more than two converter stations, and it is more complex compared to that of a two-terminal point-to-point system.

HVDC transmission can be based on two alternative technologies: Line Commutated Converter (LCC) using thyristors, and Voltage Source Converter (VSC) using IGBT. The most of the HVDC transmission systems used today in the world are based on the LCC, which is a quite mature technology and it has been in operation for more than thirty years with little maintenance. Many papers proposed different techniques for fault detection and fault location in LCC and VSC HVDC systems for two terminals HVDC and especially for multi-terminal HVDC (MTDC). These techniques can be categorized into magnitude processing techniques and signal processing techniques.

In the magnitude processing techniques, the protection technique is set up based on direct measurement of voltage (V) and current (I) signals and their derivatives (dV/dt) and (dI/dt) or signals derived from both voltage and current as power (P) and energy (E). In the signal processing techniques, the protection technique is set up based on the changes that occur in the wave shape of the electrical quantities immediately after fault occurrence, these techniques aim to extracting a unique characteristic which exists in the wave shape due to a certain fault type. These techniques as ABC to dq0 transformation, wavelet transform techniques, traveling waves, and artificial intelligence techniques as Neural Network. A fault detection technique is developed for HVDC transmission lines based on transient energy (∆E) [1] it depends on a communication channel between relays at both sides. In [2], a protection technique is proposed based on the pilot principle, it also requires a communication channel to be built. A backup protection scheme based on the integral of reactive power for HVDC systems is proposed in [3]. In [4], a proposed method of limiting fault current in a...
meshed HVDC grids is presented, this method depends on the superconducting fault current limiters (SFCLs) in the protection of HVDC system. Another magnitude processing techniques are presented in [5], [6].

Although the magnitude processing techniques are straightforward and don’t require any complicated processing, but they are subjected to noise and incorrect data samples and require a communication channel for accurate detection of fault which leads to increase the cost of the protection system.

Wavelet analysis for fault detection and fault location is discussed in different papers as in [6] and [7]. In [8], a fault location on multi-terminal DC systems is presented based on traveling wave. Although the signal processing techniques are advanced and accurate methods for fault detection and fault location, but these techniques require more sophisticated mathematical equations, long processing time, and some artificial intelligence techniques need training. In this paper, a stand-alone protection algorithm is proposed based on the second derivative of dc line current which represents the acceleration of dc current according to the time to detect the fault based on local measurements without communication channel.

2. MTDC system description and modeling

Matlab®/Simulink® has been successfully applied for modeling and simulation of the three terminals HVDC system for studying the protection of multi-terminal of HVDC system. The simulated system represents one operating case of the network with two rectifiers and one inverter as shown in figure 1.

2.1 AC supply

The AC supply of the two rectifiers and inverter is modeled as a thevenin equivalent voltage with equivalent source impedance. The voltages of AC side of three terminals are 500kV, 50Hz, and 380kV, 60Hz, and 380kV, 60Hz.

2.2 Converter

The 12-pulse converter station for rectifiers and inverter are constructed by two universal bridge blocks connected in series.

2.3 Filters and DC Lines

Filters are provided for 11th, 13th, and 24th harmonics at each converter station. The DC side of the rectifiers and inverter consist of smoothing reactors, DC filter and DC circuit breakers (DC CB).
3. The proposed protection algorithm

The concept of the relay which is applied in the protection system is based on obtaining the second derivative of the DC current which represents the acceleration of DC current.

The acceleration of DC current with time can be calculated digitally as follow:

\[
\frac{\Delta^2 I_d}{\Delta t^2} = \frac{\Delta}{\Delta t} \left( \frac{\Delta I_d}{\Delta t} \right)
\]

(1)

\[
\frac{\Delta I_d}{\Delta t} = \frac{I_d(k) - I_d(k-1)}{t(k)-t(k-1)}
\]

(2)

Where:

\( \frac{\Delta I_d}{\Delta t} \) : the first derivative of the DC link current.

\( I_d \) : the DC link current.

\( K \) : the most recent sample.

The acceleration of DC current can differentiate between fault case and transient case. As the DC current is constant value during normal operation and has zero rate of change with the time, so any disturbance that may occur in the DC system will lead to producing a change of current with the time so it is so difficult to make a protection decision in a DC system based on the rate of change of the DC current (First derivative) but the second derivative of the DC current which represents the acceleration of DC current with the time can be applied to discriminate between fault case and any other transient case.

The protection system consists of four relays located at two terminals of transmission lines as shown in figure 2, each relay applies the second derivative on its terminal current to determine the acceleration of current with time to detect the fault based on the polarity of the first spike of \( \frac{\Delta^2 I_d}{\Delta t^2} \) and its value.

For relay (1), faults in line (1) (internal faults) and faults in line (2) (external faults) will lead to a huge increase of current detected by relay (1), and the first spike of the acceleration will be positive. But the magnitude for external faults is lower than the internal one because the equivalent impedance which seen by relay (1) for faults in line (2) will be greater than the equivalent impedance for faults in line (1) due to existing of rectifier (2).

For relay (2), faults in line (1) (internal faults) will lead to a huge increase of current in the same direction of measurement of relay (2) the polarity of the first spike of the acceleration is positive. But faults in line (2) (external faults) will lead to a huge increase of current but in the reverse direction of measurement of relay (2), so the polarity of the first spike of the acceleration is negative.

For relay (3), faults in line (2) (internal faults) will lead to a huge increase of current in the same direction of measurement of relay (3), so the polarity of the first spike of the acceleration is positive. But faults in line (1) (external faults) will lead to a huge decrease of current flowing through relay (3), so the polarity of the first spike of the acceleration is negative.

For relay (4), faults in line (2) (internal faults) and faults in line (1) (external faults) will lead to a huge increase of current detected by relay (4), and the first spike of the acceleration will be positive. But the magnitude for external faults is lower than the internal one because the equivalent impedance which seen by relay (4) for faults in line (1) will be greater than the equivalent impedance for faults in line (2) due to existing of rectifier (2).

The principle of the protection technique which is set up in the digital relay can be summarized in the following flow chart shown in figure 3.
4. Threshold selection
Comprehensive test studies for different cases such as normal case, switching case, effect of source impedance, AC fault case and DC faults at different distances with different fault resistances are simulated. There are many case studies are taken and the threshold boundary is selected as follows; 4.4 MA/ms$^2$ for relay (1), 10.5 MA/ms$^2$ for relay (2), 9.5 MA/ms$^2$ for relay (3) and 5.2 MA/ms$^2$ for relay (4).

5. Simulation results
The simulation set-up shown in figure 4 has been used to implement the transient protection technique for multi-terminal HVDC lines with various disturbances, such as DC faults (internal and external) with different fault resistances, different fault distances are applied.

5.1 Effect of fault position
Response of relay (1) for DC fault (F3) in line (1) and DC fault (F5) in line (2) is shown in figure 5. A fault resistance ($R_f$) of zero Ω is included. The polarity of the first spike of acceleration of the both faults is positive, but its value for (F5) is lower than the threshold.
Another case study is performed to test the response of relay (2) for DC fault (F1) in line (1) and DC fault (F4) in line (2) is shown in figure 6. A fault resistance (R_f) of zero Ω is included. The polarity of the first spike of acceleration of the DC current the acceleration for (F1) is positive and its value is greater than the threshold, but for (F4) the polarity is negative.

![Figure 6](image)

**Figure 6.** Response of relay (2) for DC faults (F1) and (F4) with R_f=0Ω. (a) DC current of relay (2) (b) Acceleration of DC current processed by relay (2).

Another case studies are performed to test the responses of relay (3) and relay (3) for internal and external faults with fault resistance (R_f) of zero Ω as shown in figure 7 and figure 8 respectively.

5.2 **Effect of fault resistance**

Another case studies are performed to test the responses of relay (1), relay (2), relay (3) and relay (4) for internal and external faults with fault resistance (R_f) of 50 Ω as shown in figure 9, figure 10 figure 11 and figure 12 respectively.

![Figure 7](image)

**Figure 7.** Response of relay (3) for DC faults (F2) and (F4) with R_f=0Ω. (a) DC current of relay (3) (b) Acceleration of DC current processed by relay (3).

![Figure 8](image)

**Figure 8.** Response of relay (4) for DC fault (F2) and (F4) with R_f=0Ω. (a) DC current of relay (4). (b) Acceleration of DC current processed by relay (4).

![Figure 9](image)

**Figure 9.** Response of relay (1) for DC faults (F3) and (F5) with R_f=50Ω. (a) DC current of relay (1). (b) Acceleration of DC current processed by relay (1).

![Figure 10](image)

**Figure 10.** Response of relay (2) for DC faults (F1) and (F4) with R_f=50Ω. (a) DC current of relay (2). (b) Acceleration of DC current processed by relay (2).
6. Conclusion
A novel protection algorithm based on the acceleration of fault current is proposed for the multi-terminal HVDC system, this technique is straightforward, doesn’t require any complicated processing, it requires one electrical quantity to detect the fault in MTDC system and doesn’t require a communication channel. The performance of the proposed in-dependably algorithm of protection is satisfied and can discriminate between internal and external faults in a few milliseconds without communication link between the relays.

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