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A new fault detection and fault location method for multi-terminal high voltage direct current of offshore wind farm

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HIGHLIGHTS

- This paper presented the solution to promote the HVDC system for offshore wind farm.
- A novel fault detection, classification and location for the MTDC is proposed.
- The new method is fault resistance independent so that to avoid high fault impedance effects.
- A three-terminal HVDC test system of offshore wind farm is simulated including converter control.

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ABSTRACT

This paper proposes a novel protection scheme for multi-terminal High Voltage Direct Current (MTDC) systems incorporating offshore wind farm based on high-frequency components detected from the fault current signal. This method can accurately detect the fault on each line and classify the fault types. Using the post-fault current time series, both single-ended measurements (detection and classification) and double-end measurements (location), the frequency spectrum is generated to measure the gaps between the contiguous peak frequencies giving a robust and comprehensive scheme. Unlike the previous travelling wave based methods, which must identify the travelling wavefront and require a high sampling rate, the new gap-based approach is able to give accurate fault detection and fault location using any appropriate range of post-fault signals. Furthermore, the proposed method is fault resistance independent and thus even a very high fault impedance has no effect on the fault location detection. By immediately tripping the faults, the fault-caused disturbance to the offshore wind farm is minimized. A three-terminal voltage sourced converter HVDC (VSC-HVDC) system connection of offshore wind farm is modelled in PSCAD/EMTDC (Power Systems Computer Aided Design/Electro-Magnetic Transients including DC) software, which is used for obtaining the fault current data for the transmission line terminal. The algorithm is verified by studying a range of cases, by varying the fault resistance fault locations and also including external faults. The results show that the proposed method gives an accurate and reliable fault detection, classification and location on the test MTDC system.

1. Introduction

The development of power system technology and the increasing penetration of renewable energy has led to interconnected national grids, resulting in increasingly economic and sustainable electrification worldwide [1]. Consensus on climate change mitigation in Europe has led to the large of penetration renewable sources [2–4] and electrical vehicles [5–7]. Sources of renewable energy will produce substantial changes in the technological and organizational environment of the global energy system [8,9], which are often available in remote locations, and so must be transported over long distances to supply load centres [10]. The recent technological advancement in wind turbine makes offshore wind generation a promising technology. Integrated and reliable networks for distributed generations are a crucial prerequisite [11]. Developing the technology of power transmissions will improve the robustness of the energy infrastructure, improve the security of system and enhance the penetration of renewable energy sources [12]. The current development of the offshore wind power plants have resulted in a demand for new transmission systems [13]. One of the solutions to promote the renewable generation may be HVDC super-grids

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[14] that could connect large numbers of offshore wind farms [13,15] in Europe.

The power electronics and circuit breakers evolution make MTDC transmission a promising technology [16]. Some novel VSC technologies have been introduced in paper [13,17]. In particular the advantages of VSC-based HVDC technology increase the feasibility of multi-terminal systems [18]. However, many challenges remain in the evolution from point-to-point HVDC to multi-terminal HVDC, especially for the system featuring offshore wind farms. In order to reduce the destructive influence caused by DC side transmission line fault, the protection scheme should keep the wider system stable by de-energising and isolating the minimum possible plant, leave as much of the healthy network still in operation [19] and minimize the influence to offshore wind farm. In typical HVDC point-to-point links, the circuit breakers reside on the AC side, and in the event of a fault, the entire link is de-energised [20]. In the multi-terminal case, however, it is more desirable to isolate only the faulted link rather than trip the entire DC grid to transfer the power generated from offshore wind farm with the healthy lines. Therefore, DC circuit breakers have been developed to isolate the faulted line, but their operation must be controlled by DC protection relays. A robust protection strategy for transmission system is essential for both the distributed generation and power system security operation [21].

Currently, travelling wave based methods as introduced in [1], are the most common HVDC and MTDC transmission line protection. Based on travelling wave principle, the fault location can be achieved as introduced in paper [22,23]. Such approaches are very fast and reasonably accurate and work through detecting initial wave front of the voltage or current fault surge. The discrete wavelet transform (DWT) is usually chosen over pure frequency or time-domain based methods, because of its fast computational time and straightforward implementation [24]. For example in [25] two out of three of the fault criteria are determined with the DWT and used together with a time domain method. However, the travelling-wave principle must make use of a high sampling rate and relies completely on accurate wave front detection. Boundary protection has been proposed in [26]. Based on boundary characteristics, another transient harmonic current protection method is introduced in [27]. Differential protection is also applied to HVDC transmission lines but relies on two terminal measurements and a communication link between them. Other specific methods have been developed such as fault location using the similarity of voltage signals [28]. Extracting the natural frequencies is introduced in [29], which uses the natural frequency generated by travelling wave, although a higher resolution spectra estimation tool is required. Sheath voltage can be used as criteria for fault detection and classification. ANN based methods can be also applied in HVDC and multi-terminal HVDC systems [30]. However, all such aforementioned methods have at least one of the following drawbacks, such as, relying on two-terminal measurements, slow operation, poor robustness (for example, dependability with high impedance faults) or lack of proven generality.

The speed of operation has a strict requirement for a DC protection system, with fault clearing times within several milliseconds. The fault must therefore be cleared quickly to avoid damage to the sensitive power-electronic equipment and to keep the fault current below the maximum interruptible current of DC breakers [31]. As proposed in [32], the frequency spectrum of voltage and current is a useful source of information for protection purposes. As introduced in [33], the high-frequency component is a good criterion for fault detection and fault location. This paper presents a new frequency domain method using features in the transient fault current spectra. Fault detection and classification is achieved quickly and robustly using a one terminal measurement and fault location is then achieved reliably using two terminal measurements. By using these high speed signal processing tools, the proposed method can meet the speed requirement. The method can also robust detect and locate the fault in a three-terminal system.

2. Theory of proposed method

2.1. High-frequency component

When a fault causes a step change in the circuit, a wave travels out from the fault point close to the speed of light in a vacuum and is reflected at the discontinuities in the line, causing high-frequency components. Travelling waves measured at the relaying point are seen as high-frequency oscillations. Such generated travelling waves consist of natural frequencies, which can be regarded as a series of frequency components with equal distance. Unlike existing research [29,34], which relies on the dominant frequency component, this paper presents an approach using the characteristic of equal distance between the high-frequency components in the post fault spectra [35].

The frequency content during a fault on the transmission line is observed to change depending on the fault characteristics, and thus can be used to obtain information about the fault. Due to the large DC component, frequencies higher than 700 Hz are used in the new scheme. This is extracted from the fault current signals using the Fast Fourier Transform (FFT). Unlike travelling wave methods which rely on the detection of the wave-front, the new fault detection and location can use any parts of the post fault signal which contain features due to the propagation of the travelling waves. Additionally, the high-frequency contents have features at locations on spectra that vary with fault location, but are importantly independent of fault resistance [30].

2.2. Travelling wave principle

A fault on the transmission line will result in travelling waves on both current and voltage signals, and will travel in both directions originating from the fault position. The propagation of the wave and subsequent reflections can be clearly analysed in space and time using a Bewley Lattice diagram. At any point on the transmission line, the current and voltage at point x can be described with the partial differential Eq. (1).

$$\begin{cases} \frac{\partial e}{\partial x} = -L\frac{\partial i}{\partial x} \\ \frac{\partial i}{\partial x} = -C\frac{\partial e}{\partial x} \end{cases} \tag{1}$$

where L is the line inductance, C is the capacitance, e and i represent the voltage and current at the location x.

The current signal, which has both a time and distance dependency, is described by (2).

$$i(x,t) = \frac{1}{Z}[e_i(x-vt) + e_r(x+vt)] \tag{2}$$

where $Z = \frac{1}{\sqrt{L/C}}$ that Z is the characteristic (surge) impedance of the transmission line, $v = \frac{1}{\sqrt{LC}}$ is the velocity, e_i and e_r are two arbitrary functions of $(x-vt)$ and $(x+vt)$, which refer to the incident and reflected travelling wave.

Assuming the fault occurs at t_0, the initial travelling wave is generated by the fault, so the superimposed voltage is:

$$e_k = -\frac{1}{Z}e_f\sin(\omega t) \tag{3}$$

where e_f is the amplitude of the superimposed voltage.

The propagation of the fault travelling wave is described by (4):

$$\begin{cases} i_a(t) = \frac{1}{Z_C}\begin{bmatrix} -e_k(t-\tau_a) + K_a e_k(t-\tau_a)+ \\ K_a^2 e_k(t-3\tau_a)-K_a^2 e_k(t-3\tau_a)... \end{bmatrix} \\ i_b(t) = \frac{1}{Z_C}\begin{bmatrix} -e_k(t-\tau_b) + K_b e_k(t-\tau_b)+ \\ K_b^2 e_k(t-3\tau_b)-K_b^2 e_k(t-3\tau_b)... \end{bmatrix} \end{cases} \tag{4}$$

where K_a and K_b is reflection co-efficient, $\tau_a = \frac{t_{a2}-t_{a1}}{2}\tau_b = \frac{t_{b2}-t_{b1}}{2}$, t_a and t_b is the wave travel time from the fault to the end of the line, Z_C is the