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Wavelet-based analysis and detection of traveling waves due to DC faults in LCC HVDC systems

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ABSTRACT

This paper presents qualitative and quantitative analysis of the traveling waves induced by faults on direct current (DC) transmission lines of line-commutated converter high-voltage direct current (LCC HVDC) systems for detecting the wavefront arrival times using the boundary wavelet coefficients from real-time stationary wavelet transform (RT-SWT). The qualitative analysis takes into account the steady-state operation and the detection of the inception times of both first and second wavefronts at the converter stations. The behavior of the boundary wavelet coefficients in DC transmission lines is examined considering the effects of the main parameters that influence the detection of the traveling waves, such as mother wavelets, sampling frequency, DC transmission line terminations, electrical noises, as well as fault resistance and distance. An algorithm designed to run in real-time and able to minimize the factors that hamper the performance of traveling wave-based protection (TWP) methods is proposed to detect the first and second surge arrival times. Quantitative results are achieved based on the accuracy of one- and two-terminal fault location estimation methods, and indicate the proper operation of the presented algorithm.

1. Introduction

High-voltage direct current (HVDC) technology has been widely applied in transmission systems due to the advantages presented for bulk-power delivery, asynchronous alternating current (AC) power networks interconnection, long distance transmissions, etc. [1]. The line-commutated converter (LCC) is one of the main technologies used in HVDC transmission systems and has been extensively employed in HVDC projects around the world [1,2]. Due to the commonly extensive length of LCC HVDC transmission lines and the fact of half of faults in these systems takes place on the lines [3], it is important to analyze the transient behavior in order to detect and locate direct current (DC) faults as fast as possible.

Several methods capable to detect and locate faults on DC transmission lines have been developed, since a fast and accurate detection speeds up the maintenance process, which reduces the energy supply interruption time and increases the HVDC transmission system reliability. For instance, the analysis of the rate of change of DC reactor voltage is employed in [4], support vector machines are used in [5], and a scheme for fault detection based on the compensation of the distributed capacitive current is depicted in [6]. However, the speed of the protection system is essential to mitigate the system damage and most of these schemes are not as fast as the traveling wave-based protection (TWP) methods [7]. Therefore, the TWP has become essential for the HVDC transmission line protection [8,9], and has been successfully applied to fault detection and location [10,11]. However, some factors limit the performance of TWP methods, such as fault distance [12], fault resistance [13], and the flexible operation modes (which require adaptable thresholds) [12]. Consequently, there is a demand for detection methods capable to solve or minimize these factors in order to improve the TWP performance.

Diverse mathematical tools have been employed in TWP methods [10,12]. However, pure frequency-domain-based tools, such as the Fourier transform, are not suitable for detecting the traveling wave arrivals due to the time-varying transients [14], and pure time-domain-based ones, such as the DC current and/or voltage derivative methods, are usually influenced by noise [15]. Therefore, several wavelet transform versions have been commonly used to analyze the high-frequency components presented on fault-induced transients due to its multi-resolution properties of time and frequency [14–17].

The continuous wavelet transform (CWT) has been used to detect the arrivals of the traveling waves in DC lines [14]. However, CWT is a highly redundant transform and is usually applied for an offline analysis. The discrete wavelet transform (DWT) has also been applied to

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detect DC fault-induced transients [17]. However, the DWT presents shift-sensitivity due to the downsampling, undermining its application to the real-time [18]. The real-time stationary wavelet transform (RT-SWT) overcomes these drawbacks, and has been employed to detect singularities in the real-time due to its translation-invariance property [18].

In spite of the SWT wavelet coefficients be better than the DWT to detect fault-induced transients, both DWT and SWT are highly affected by the choice of the mother wavelet and present time delay for long wavelets in the real-time analysis. In addition, the wavelet coefficients face problems to detect overdamped fault-induced transients. Nevertheless, the wavelet coefficients of the real-time boundary SWT (RT-BSWT) overcome all these drawbacks, providing an accurate fault-induced transient detection in AC lines [18,19]. However, to the best of the authors knowledge, the wavelet coefficients of the RT-BSWT were not used for wavefront arrival time detection of traveling waves, which is for the first time verified in this paper considering DC lines.

A fast protection and an accurate fault location estimation on DC transmission lines depend on the correct and fast detection of the surge arrival times. Important parameters, such as DC line terminations, fault resistance, and fault distance influence the wavefronts and their detection. The adopted sampling frequency and mother wavelet, as well as the noise level can also impact in the identification of the DC fault-induced transients. Therefore, the effects of all these parameters have to be evaluated in distinct situations: steady-state operation, and at the first and second wavefront arrival times. Despite all these possible effects, most of the papers define their wavelet-based methods to detect the transients induced by faults on DC lines without a deep analysis. For instance, simple trial-and-error study and observation have been employed to define mother wavelet and threshold values.

In this paper, all the aforementioned parameters are appropriately evaluated through a wavelet-based qualitative analysis of DC line voltages and currents during the steady-state operation (important for automatic thresholding establishment), and at the inception times of the first and second surges (important for automatic fault detection and location). The wavelet coefficients of both RT-SWT and RT-BSWT are considered. The depth of the provided analysis regarding the effects of DC filter (line termination), fault parameters, sampling frequency, and mother wavelet in transient behavior is essential in order to support fault detection methods and, due to this, consists in a great contribution of this work. For instance, in this analysis it is verified that the DC signal to be analyzed, voltage or current, depends on the DC line terminations, and the adoption of Haar mother wavelet (the shortest one) is necessary to detect the second wavefront when it arrives few samples after the first one.

Based on the characteristics presented on qualitative analysis, an algorithm based on the wavelet coefficients of the RT-BSWT is also proposed to detect the inception times of the first and second wavefronts, and represents a second contribution of this paper. This algorithm was designed to run in real-time and minimize the main factors that can affect the TWP method operation. For instance, the threshold values used to identify the first and second wavefront inception times are self-adaptive and, due to this, the proposed method can be employed for LCC HVDC systems with flexible operation modes, which may imply different levels of voltage and current. The performance assessment of the proposed algorithm is evaluated considering different DC line terminations, sampling frequencies, and noise levels. Multiple fault distances and resistances, which traditionally limit the TWP methods performance [12,13], are also addressed. The results obtained with the proposed algorithm are compared with those acquired using the RT-SWT Haar wavelet coefficients, which present a performance equivalent to the derivative methods for detecting the wavefront inception times. The proposed method using the db(4) boundary wavelet coefficients presented the best performance.

2. Wavelet coefficients of the RT-SWT and RT-BSWT

The first level RT-SWT wavelet coefficients associated to the actual sample time k/f_s ($w(k)$) are computed through inner products between L coefficients of the wavelet filter (h) and L samples of the time-domain signal (x), as follows [20]:

$$w(k) = \frac{1}{\sqrt{2}} \sum_{n=0}^{L-1} h(n)x(k-L+n+1), \tag{1}$$

since $\exists\ [x(k-L+1),\ ...,x(k-1),\ x(k)]$.

The first level RT-BSWT wavelet coefficients associated to the actual sample time k/f_s are defined as follows [19]:

$$w(l,k) = \frac{1}{\sqrt{2}} \sum_{n=0}^{L-1} h(n)\mathring{x}(k-L+n+1+l), \tag{2}$$

where $0 \leqslant l < L; L \leqslant \Delta k; k \geqslant \Delta k-1; \mathring{x}(k+m) = x(k+m)$ if $-\Delta k < m \leqslant 0$ and $\mathring{x}(k+m) = x(k-\Delta k+m)$ if $0 < m \leqslant L$ (periodized signal x in Δk samples); k is the actual sample; f_s is the sampling frequency.

According to (2), x is decomposed in L wavelet coefficients: 1) $w(0,k) = w(k)$, which is exactly the wavelet coefficient of the conventional SWT adapted to the real-time, as defined in (1), and 2) $w(l,k)$ with $l \neq 0$, which are $L-1$ coefficients termed as boundary wavelet coefficients (coefficients with circular border distortions). Therefore, (2) incorporates the RT-SWT and provides additional $L-1$ boundary wavelet coefficients.

In AC signals, [19] demonstrated that $\Delta k = f_s/f$ (samples in one cycle. E.g., the last 400 samples of x need to be stored for f_s = 20 kHz and f = 50 Hz). However, in the case of DC signals, this paper suggests $\Delta k = L$ (the shortest window. E.g., just 4 samples need to be stored by using db(4) wavelet) for any sampling rate.

3. Equivalence between derivative methods and RT-SWT Haar wavelet coefficients

The rate of change of DC voltage and/or current (dv/dt and di/dt, respectively) has been employed for DC fault detecting [21,22], and its definition in a time-discrete signal is, as follows:

$$\frac{dx(k)}{dt} = \frac{x(k)-x(k-1)}{1/f_s} = f_s[x(k)-x(k-1)], \tag{3}$$

where x represents a DC voltage or current signal. Therefore, the derivative method is the difference between two consecutive samples (high-pass filter) with a gain f_s.

The Haar wavelet coefficients of the RT-SWT are defined, from (1), as follows:

$$w_{Haar}^{x}(k) = \frac{1}{\sqrt{2}}[h(0)x(k-1) + h(1)x(k)], \tag{4}$$

where $h(0) = 1/\sqrt{2}$ and $h(1) = -1/\sqrt{2}$. Therefore:

$$w_{Haar}^{x}(k) = \frac{x(k-1)-x(k)}{2} = -0.5[x(k)-x(k-1)]. \tag{5}$$

According to (3) and (5), the only difference between RT-SWT Haar wavelet coefficient and the derivative methods is the factor that multiplies $[x(k)-x(k-1)]$. In the context of the traveling waves, both derivative and RT-SWT Haar wavelet coefficients use thresholds with both positive and negative values to detect the wavefront arrival times. Therefore, there is a relationship between the thresholds, and the same threshold methodology applied for both methods will provide the same results. This equivalence is considered in the remainder of this paper.

4. LCC HVDC test system description

Fig. 1 depicts the HVDC test system, which was modeled by using