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Improved traditional directional protection by using the stationary wavelet transform

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ABSTRACT

This paper proposes a directional protection with phase, positive sequence, negative sequence, and zero sequence units by using the scaling coefficients of the real-time stationary wavelet transform (RT-SWT). As directional protection activators, the wavelet coefficients are used for fast detection of the fault inception time, whereas the scaling coefficients are used to provide backup activators in accordance with the overcurrent protection. Evaluations prove the feasibility to rebuild the traditional directional protection by using RT-SWT. However, the proposed wavelet-based directional protection provided better performance and faster operating time than the conventional one based on the discrete Fourier transform (DFT). As new functionalities, the wavelet-based negative sequence unit can be used to detect three-phase faults, even with severe voltage sags without memory strategies, which is not possible with the conventional protection. In addition, the proposed protection was implemented in hardware in order to demonstrate its practical feasibility.

1. Introduction

Directional elements are fundamental in both transmission and distribution protection systems. In transmission lines, directional elements are essential for enhancing the selectivity of the distance protection [1], and can be used in association with the overcurrent backup protection [2]. In distribution systems with distributed generation, the overcurrent protection is unable to identify the fault directionality [3], and the directional protection is necessary to overcome this drawback.

Conventionally, directional elements are integrated to the overcurrent protection yielding the directional overcurrent protection referred as the code 67 by the ANSI standard device numbers [4]. The directional overcurrent protection is divided in phase (67A, 67B, and 67C), positive sequence (67P), negative sequence (67Q), and zero sequence (67N) units. These protection units compare the operating current with the polarizing voltage using fundamental phasors computed by the Fourier transform, resulting in trip for forward faults [5]. The performance of the conventional (Fourier-based) directional protection is usually very reliable. However, Fourier-based algorithms present well-known issues such as the computational burden and the influence of the DC exponential decay. Despite available solutions for overcoming these problems, Fourier-based algorithms cannot provide a high-speed protection and they are usually suitable for low-sampling rates.

The forthcoming smart grids will require both conservative and innovative protections. The conventional directional protection in association with overcurrent or distance protections attends properly the conservative protection system. Conversely, improved directional protection in association with new protection strategies or new activator procedures has to be proposed for faster protection in specific cases, attending the innovative tendency of the power system. In this context, both conventional and non-conventional protective functions should work together.

Regarding the non-conventional directional protection, traveling wave-based directional protection is one of the fastest ways to identify the fault direction according to the traveling wave polarities [6,7]. Protection methods based on travelling waves have been proposed to both AC and DC transmission lines [8–11] with a quite acceptable reliability in long lines. However, these methods present several limitations: the first wavefront cannot be identified accurately for faults near the line terminals; the required high-sampling rate in the order of MHz; limited bandwidth of conventional transducers; fault-induced transients can be overdamped in specific fault inception angles, the effect of noise [7,10,12,13]. Conversely, most distribution systems are composed mainly by short lines, yielding several reflected and transmitted waves in a short time, making these methods impracticable [14]. Therefore, the conventional directional protection must continue strong in both transmission and distribution systems.

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The discrete wavelet transform (DWT) and its variants such as the stationary wavelet transform (SWT) have been properly used for accurate and fast fault diagnosis in the real-time (fault detection, classification, and location) [15,16] as well as for the protection of power transformers [17,18], transmission lines [19–22], distribution systems [23], and busbars [24] in agreement with different protection principles such as directional and differential. However, regarding the directional protection, to the best of the authors knowledge, the DWT/SWT has been only used in accordance with either the travelling waves principles or the fault-induced transient content, whose limitations were aforementioned.

Other types of non-conventional directional protections have been also proposed, such that based on artificial neural network (ANN) [25], which treat the fault direction problem as a pattern classification problem. However, an ANN needs an expert knowledge in order to build a representative database to the training for each power system [26].

The DWT/SWT decomposes a sampled signal into scaling and wavelet coefficients. Most of wavelet-based fault diagnosis and protection functions are based on the wavelet coefficients/wavelet coefficient energies in order to propose non-conventional methods [13,17,18,23,24]. However, recently, the conventional overcurrent protection was recreated by using the scaling coefficient energies successfully [23]. However, this wavelet-based overcurrent protection is unable to identify the fault direction as required in most practical applications.

This paper proposes an improved conventional directional protection based on the real-time SWT (RT-SWT). By using only the first level, the scaling coefficients are used in replacement of the Fourier transform in order to recreate the conventional directional protection, and four conventional-based protection units were developed (wavelet directional units): phase (67WA, 67WB, and 67WC) and positive (67PW), negative (67QW), and zero (67NW) sequences. To do that, the torque equations were mathematically redefined in the wavelet domain by using sampled voltages and currents, i.e., with no need of phasors. Regarding the protection activation, the wavelet coefficients are used for fast detection of fault-induced transients (wavelet activators) in order to reduce the relay operating time, whereas the scaling coefficients are used for backup activation in accordance with the overcurrent protection (wavelet overcurrent activators). Therefore, the proposed method presents an original application of the wavelet transform in the directional protection in order to attend both conservative and innovative trends of the protection system.

The proposed method was assessed with representative and extensive simulations, and better performance than the conventional directional protection was obtained, i.e., the conventional directional protection was recreated successfully. In addition, the proposed method presented the lowest computational burden, could be properly used at medium sampling rates in the order of few kHz, and presented the fastest directional operating time by combining all the units due to the additional wavelet-based triggering unit. As additional functionality, the wavelet-based negative sequence unit worked properly under three-phase faults, even with severe voltage sags without the use of voltage memory strategy, which is not possible with the conventional method. A wavelet-based directional relay was implemented in a DSP (digital signal processor) in order to prove its practicability. The performance of the directional methods was assessed alone, without the combination with overcurrent or other associated protections, which is out of scope of this paper.

2. Conventional directional protection

The torque, at the current sampling k, is given by [27]:

$$T(k) = |V_{pol}(k)||I_{op}(k)|\cos(\angle V_{pol}(k) - \angle I_{op}(k)), \tag{1}$$

where V_{pol} and I_{op} are fundamental phasors of the polarizing voltage and operating current, respectively, estimated through the Fourier transformer; the underscripts {pol, op} represent phase or line quantities as well as positive, negative, or zero sequences (Table 1). For instance: I_A, I_B and I_C are phase current phasors; V_{BC}, V_{CA}, and V_{AB} are line voltage phasors; I_1, I_2 and I_0 are positive, negative and zero sequence current phasors, respectively; V_1, V_2 and V_0 are positive, negative and zero sequence voltage phasors, respectively; Z_1 and Z_0 are positive and zero sequence line impedance, respectively.

Table 1
The conventional operating and polarizing quantities.

Directional Protection	Quantities I_{op}	V_{pol}
Phase A (67A)	I_A	V_{BC}
Phase B (67B)	I_B	V_{CA}
Phase C (67C)	I_C	V_{AB}
Positive sequence (67P)	I_1	$V_1(1\angle Z_1)$
Negative sequence (67Q)	I_2	$-V_2(1\angle Z_1)$
Zero sequence (67N)	I_0	$-V_0(1\angle Z_0)$

The fault directionality is defined through the torque sign of (1): positive sign for forward fault and negative sign for reverse fault, obtained through the normalized torque ($\widetilde{T}(k) = T(k)/(|V_{pol}(k)||I_{op}(k)|)$), termed as torque factor in this paper. Therefore, a forward fault is identified when:

$$\widetilde{T}(k) = \cos(\angle V_{pol}(k) - \angle I_{op}(k)) > \epsilon, \tag{2}$$

where $-1 \leqslant \widetilde{T} \leqslant 1$; the threshold $\epsilon > 0$ is used to enhance the reliability.

2.1. The directional unit selection and triggering

The directional protection is usually activated through the overcurrent function [28]. In this paper, for the sake of simplicity, it is enabled when the operating current is higher than a pickup value (I_{51}) of the time-delay overcurrent (lowest threshold), which is X_{51} times a reference current (I_r):

$$I_{op}(k) > I_{51}, \tag{3}$$

where

$$I_{51} = X_{51} I_r, \tag{4}$$

where X_{51} is a constant related to the overcurrent protection sensibility according to the system requirements, i.e., it defines the pickup current of time-delay overcurrent units. Therefore, the directional units 67A, 67B, 67C, 67Q and 67N are properly activated when the overcurrent of the respective current I_A, I_B, I_C, I_2, and I_0 reaches the time-delay pickup value (intrinsic unit selection). The unit 67P is activated if any of the phase currents reach the time-delay pickup.

3. The real-time stationary wavelet transform

Based on the multiresolutional analyses [29], the DWT can be used to decompose a discrete signal into scaling and wavelet coefficients in j decomposition levels. However, the DWT is a time-variant transformation due to the down-sampling process by a factor of two in each decomposition level, which can limit the DWT in real-time signal evaluations required by a relay. Conversely, the SWT is a time-invariant transformation, overcoming some drawbacks of the DWT, which makes it more suitable for protection applications [30].

The RT-SWT decomposes a sampled signal (x) in the first level scaling (s_x) and wavelet (w_x) coefficients as follows [31]:

$$s_x(k) = \frac{1}{\sqrt{2}} \sum_{l=0}^{L-1} h_\phi(l) x(k + l - L + 1), \tag{5}$$