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Speed and security improvements of distance protection based on Discrete Wavelet and Hilbert transform

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ABSTRACT

In order to maintain power system stability, modern transmission networks demand a high fault detection speed. At the same time, a high level of protection security is required, since each protection maloperation might lead to a system blackout and high economic loss. The protection speed and security represent conflicting requirements fundamentally limited by the Heisenberg's Uncertainty Principle. Traditional line protection approach relies on fundamental frequency phasor estimation based on Discrete Fourier Transform. There are also various Discrete Wavelet Transform algorithms, typically based on Daubechies wavelet families, which may be used to estimate phasors. In this paper wavelet families other than Daubechies are evaluated as methods for estimating phasors. Two new algorithms based on Reverse Biorthogonal mother wavelets are presented and compared to the previous solutions. The protection speed and security are evaluated via a very demanding test formed on the basis of several thousands of fault simulations, as well as on 60 fault records from 400 kV and 220 kV transmission networks.

1. Introduction

Transmission line protection is of critical importance in power systems since near 85% of faults at High-Voltage (HV) and Ultra High-Voltage (UHV) levels occur in transmission lines. The most important feature of line protection is security. A protection device operates securely if it does not trip the circuit breaker in case of faults outside of the protected line, or in case of other non-faulty disturbances [1]. False tripping, or maloperations, are unacceptable in HV and UHV grid, as they can lead to system blackouts with high economic loss [2].

Distance relays (DR) have been widely used for transmission line protection since they provide a high level of protection security with low hardware requirements (sampling frequencies of several kHz, protection algorithms with low computational burden) and with no demands for fast communication between the line terminals. Relying on the fundamental frequency component, the algorithms are capable of achieving a high level of security due to their immunity to harmonics, DC components and noise in measured signals. The robustness is accomplished through the use of the full-cycle data window, however the price for robustness is low fault detection speed (long tripping time). The protection speed is mainly limited by the length of data window used for the signal processing in each sampling period. For the algorithms that use the full-cycle data window, the tripping time is around one fundamental cycle or 20 ms in the case of 50 Hz systems.

Due to the growth of complexity and interconnectivity modern power systems demand faster (sub-cycle) protection tripping times, in order to maintain the system stability [3,4]. The main problem is that protection speed and security are connected at the fundamental level by Heisenberg's Uncertainty Principle (HUP). Protection speed is related to signal localization in the time-domain (determine the time interval when a fault occurs), while security is related to signal localization in the frequency-domain (distinguish the fundamental component from harmonics and noise in order to avoid maloperation, in the given time interval) [5]. A faster

Abbreviations: DR, distance relay; HUP, Heisenberg's Uncertainty Principle; DWT, DR algorithm based on Maximum Overlap Discrete Wavelet Transform (MODWT); DbFL, DR algorithm based on Fourier-like (FL) DWT utilizing Daubechies wavelet; DbHT, DR algorithm based on combination of DWT and the Hilbert transform (HT) utilizing Daubechies wavelet; RBioFL, DR algorithm based on Fourier-like (FL) DWT utilizing reverse biorthogonal wavelet; RBioHT, DR algorithm based on combination of DWT and the Hilbert transform (HT) utilizing reverse biorthogonal wavelet; TW, Traveling Wave based protection; CT, current transformer; CVT, capacitive voltage transformer.

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tripping time implies that a fault is detected within a shorter time interval (shorter data window), but according to the HUP, shortening the data window increases the uncertainty in the frequency domain (making it difficult to distinguish whether the signal is affected by other frequency components, which might lead to a false fault detection and maloperation). For this reason, there is always a trade-off between protection security and speed.

The Traveling Wave (TW) approach has been developing for several decades as the fastest possible solution for fault detection. The TW approach does not rely on the fundamental frequency component, as the main source of information, so it does not require the full-cycle data window for the fundamental component estimation. The TW approach is based on the analysis of transient components generated at the location of a fault that travel to the line terminals with a speed close to the speed of light. In theory, it is possible to detect faults in milliseconds even for very long transmission lines [6]. Since the faults are detected by the high-frequency signals (instead of the fundamental frequency components), they are localized in the time-domain with the high certainty. As a consequence, according to the HUP, the uncertainty in the frequency domain is high. The information is spread through the wide frequency range which means that many events, such as operation of surge-arresters, series capacitors, lightning strikes and parallel line faults might be mistakenly recognized as the line faults and consequently lead to a maloperation. The security assessment in case of a TW based protection approach requires the consideration of all these different phenomena and different models of the power systems. For this reason, despite TW being superior in speed, it is not possible to compare directly its security level with the traditional distance relays based on the fundamental component.

The fault detection speed of phasor domain algorithms can be improved to some extent through the use of DWT rather than DFT. At the same time, a high level of robustness to different transients from the rest of the system is preserved due to the long data window. A phasor calculation based on a DWT filter with respect to the reference sinusoidal signal using the basic vector mathematics is presented in Refs. [7,8], while a Maximum Overlap DWT approach with non-orthogonal pair of filters is presented in Ref. [9]. Orthogonal MODWT filters (Fourier-like filters and combination of Wavelet and Hilbert transform) are presented in Ref. [10]. A time domain algorithm based on a full-cycle data window is presented in Ref. [11]. All the mentioned approaches rely on *Daubechies* mother wavelet (Db). In this paper the potential of different wavelet families to be used as a part of phasor estimation based distance relays is assessed. An overview of the algorithms is given in Section 2. The algorithms are explained in more detail in Section 3 where two new algorithms, the Fourier-like reverse biorthogonal wavelet (RBioFL) and the reverse biorthogonal wavelet and Hilbert transform based algorithm (RBioHT), as well as two algorithms from literature, the Fourier-like Db wavelet (DbFL) and Db wavelet and Hilbert transform based algorithm (DbHT), are selected for further testing. The assessment methodology is given in Section 4, while the results are presented in Section 5.

2. Phasor domain based distance relay algorithms

2.1. General scheme of a distance relay

A simplified scheme of a distance relay is shown in Fig. 1. The inputs are measured phase voltages and currents, while the output is the tripping signal that opens the circuit breaker in the case that a fault at the protected line is detected. A DR consists of two main blocks:

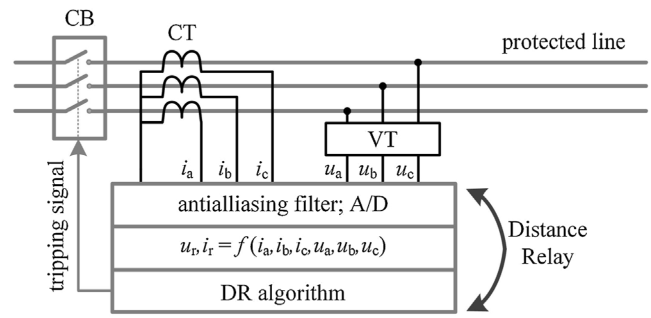

Fig. 1. Simplified scheme of a distance relay (DR), CB—circuit breaker, CT—current transformer, VT—voltage transformer, A/D—analog to digital convertor.

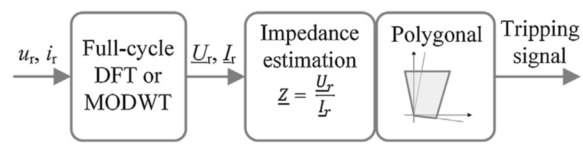

Fig. 2. Block diagram of impedance estimation based distance relay algorithm.

Table 1
Inputs to a distance relay.

Type of fault	$\underline{U}_r$	$\underline{I}_r$
a-g	$\underline{U}_a$	$\underline{I}_a + \underline{k}_0\,\underline{I}_0$
b-g	$\underline{U}_b$	$\underline{I}_b + \underline{k}_0\,\underline{I}_0$
c-g	$\underline{U}_c$	$\underline{I}_c + \underline{k}_0\,\underline{I}_0$
a-b	$\underline{U}_a - \underline{U}_b$	$\underline{I}_a - \underline{I}_b$
b-c	$\underline{U}_b - \underline{U}_c$	$\underline{I}_b - \underline{I}_c$
c-a	$\underline{U}_c - \underline{U}_a$	$\underline{I}_c - \underline{I}_a$

a,b,c—phases; g—ground; $\underline{k}_0$ is a relay setting called residual compensation factor.

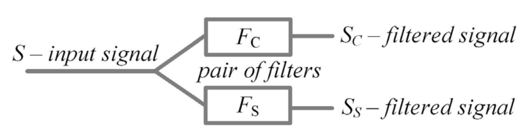

Fig. 3. DFT filters.

- Measurement and preprocessing (antialiasing filtering, sampling process, analog to digital conversion, samples scaling and storage, preparation of input signals for DR algorithm);
- Distance relay algorithm (in this paper the phasor domain approach used is as given in Fig. 2).

In order to achieve a correct correlation between the measured impedance and fault location DR algorithms use the voltage u_r and current i_r that are calculated differently for each type of fault, as shown in Table 1.

2.2. Discrete Fourier Transform (DFT) as a reference phasor estimator

The traditional approach for calculating the fundamental frequency phasors ($\underline{U}_r$, $\underline{I}_r$ from u_r, i_r) is based on DFT, which consists of a pair of orthogonal filters (Fig. 3). The impulse and frequency responses of these filters are shown in Fig. 4. A sampling frequency of 32 samples per a fundamental period (fs = 1600 Hz) has been used. The fundamental phasor magnitude M and angle θ are calculated from the filtered signals S_S and S_C:

$$M = \sqrt{S_C^2 + S_S^2}, \tag{1}$$

$$\theta = \arctan(S_S/S_C). \tag{2}$$