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Transmission line distance relaying using a variable window short-time Fourier transform

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Abstract

This paper presents a new approach for transmission line protection using a variable window short-time Fourier transform known as S-transform. The S-transform (ST) is a time–frequency spectral localization method, similar to short-time Fourier transform (STFT), but with a Gaussian window whose width scales inversely, and whose height scales linearly with the frequency. The change in spectral energy of the ST of the current and voltage signals provide the information regarding fault detection. After the fault detection, the impedance to the fault point is calculated using the estimated phasors of the faulted current and voltage signals which provide accurate results even with noisy conditions. Also, the fault location is calculated using polynomial curve fitting technique with a devised index obtained from the ratio of spectral energy of the voltage and current signals, respectively.

Keywords: Curve fitting; Distance relaying; Impedance trajectory; Phasor estimation; S-transform; Spectral energy

1. Introduction

Faults on transmission lines need to be detected, classified, located accurately, and cleared as fast as possible. In power transmission line protection, faulty phase identification and location of fault are the two most important items which need to be addressed in a reliable and accurate manner. Distance relaying techniques based on the measurement of the impedance at the fundamental frequency between the fault location and the relaying point have attracted wide spread attention. The sampled voltage and current data at the relying point are used to locate and classify the fault involving the line with or without fault resistance present in the fault path.

The error caused by current and voltage transformers affects the measurements at the relaying end. The current transformer (I-transformer) causes error due to saturation and the secondary current disappears for a portion of the waveform. Even if the CT is not saturated to that extent, the secondary current is always in error due to small but non-zero magnetizing current required to set up the flux in the core. The CT error is kept low by proper choice of CT and its connected burden. Also in the computer relaying, the CT error can be computed and corrected in the computer relay if the CT characteristics and burden impedance are given as inputs to the computer relay. The voltage transformer (V-transformer) causes error as the primary voltage changes suddenly from its pre-fault value to post-fault value, the output voltage undergoes a subsidence transient before settling to it final steady state value. The subsidence transient magnitude depends upon the CVT parameters, burden impedance, power factor and angle of incidence of primary fault. Thus, the CVT transient response causes difficulties in those relaying tasks which require voltage as inputs. Special attention is given to relay algorithm while designing such systems, particularly if severe voltage collapse may be caused by a fault near a zone boundary. Short transmission lines fed from weak systems usually constitute difficult relay design problems due to transient CVT errors.

The accuracy of the fault classification and location also depends on the amplitude of the dc offset and harmonics in comparison to the fundamental component. Fourier transforms,

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differential equations, waveform modeling and Kalman filters are some of the techniques used for fault detection and location calculation.

In recent years, neural networks [1,2] are trained to recognize fault patterns associated with the voltage and current waveforms from the relaying point due to their superior ability to learn and generalize from training patterns. However, in the fault classification and location tasks, the neural networks cannot produce accurate results due to the inaccuracies in the input phasor data and the requirement of a large number of neural networks for different categories of fault.

Another pattern recognition technique based on wavelet transform [3–8] has been found to be an effective tool in monitoring and analyzing power system disturbances including power quality assessment and system protection against faults. Although wavelets provide a variable window for low and high frequency currents in the voltage and current waveforms during fault, they are subject to inaccuracies due to noise and the presence of harmonics [9]. Some of the recent papers in this area [6–8] have used only the sampled current values at the relaying point during faults for classification of fault types and distance calculations.

Another powerful time–frequency analysis known as S-transform has found applications in geoscience and power engineering [10–13]. The S-transform is an invertible time–frequency spectral localization technique that combines elements of wavelet transforms and short-time Fourier transform. The S-transform uses an analysis window whose width decreases with frequency providing a frequency dependent resolution. This transform may be seen as a continuous wavelet transform with a phase correction. It produces a constant relative bandwidth analysis like wavelets while it maintains a direct link with Fourier spectrum. The S-transform has an advantage in that it provides multi resolution analysis while retaining the absolute phase of each frequency. This has led to its application for detection and interpretation of events in a time series like the power quality disturbances [14].

The proposed protection scheme consists of three basic parts. The first part includes the fault detection from the change in energy content of the S-transform of the voltage and current signal. After the fault detection, the impedance to the fault point is calculated from the estimated current and voltage phasors. The phasors are estimated from the S-matrix generated from S-transform for respective fault current and voltage signal with and without noise. The S-transform provides accurate phasor estimation even with SNR 20 dB unlike wavelet transform, which is susceptible to noise. The last part includes the fault location determination using polynomial curve fitting with a devised index found out from the ratio of energy content of the faulted voltage and current signal.

The time taken for the fault detection is half cycle (10 samples from fault inception) and the time taken for the impedance trajectory to enter the relay operating zone, is within half cycle (6–10 samples). Thus, the total time taken for the fault detection and impedance trajectory to enter the relay operating zone is less than one cycle (20 samples) from the inception of the fault which shows the fastness of the proposed protection scheme.

2. Generalized S-transform

The S-transform [11], is an extension to the idea of the Gabor transform and wavelet transform, and is based on a moving and scalable localizing Gaussian window. The interesting phenomenon in the ST is that it is fully convertible both forward and inverse from time domain to frequency domain. This property is due to the fact that the modulating sinusoids are fixed with respect to the time axis while the localizing scalable Gaussian window dilates and translates. As a result the phase spectrum is absolute in the sense that the origin of the time axis is taken as the fixed reference point. The ST falls within the broad range of multiresolution spectral analysis, where the standard deviation is an inverse function of the frequency, thus reducing the dimension of the transform. The localizing Gaussian function $g(t)$ is defined as:

$$g(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp^{[-t^2 f^2/2\sigma^2]} \tag{1}$$

where σ is the standard deviation. The multiresolution ST is defined by

$$S(f, \tau, \sigma) = \int_{-\infty}^{\infty} h(t) g(\tau - t, \sigma)\, \mathrm{e}^{-\mathrm{i}2\pi f t}\, \mathrm{d}t \tag{2}$$

This falls within the definition of the multiresolution Fourier transform. The Gabor transform $\Gamma(f, \tau)$ is a particular case of $S(f, \tau, \sigma)$ with σ held constant. The primary purpose of the dilation (or scaling) parameter is to increase the 'width' of the window function $g(t, \sigma)$ for lower frequency and vice versa, and is controlled by selecting a specific functional dependency of σ with the frequency f. Thus, the width of the window is inversely proportional to the frequency and by varying the width of the window; the required spectral (frequency) components can be picked up. Also we have chosen the width of the window to be proportional to the period of the cosinusoid being localized. Thus, the width the window is given as

$$\sigma(f) = T = \frac{\alpha}{|f|} \tag{3}$$

where 'T' is the time period. The choice of α is important as a small α means improved time resolution and loss of frequency resolution. The vice versa is true for large value of α which improves the frequency resolution, but reduces time resolution. Consequently, identification of the whole event can be compromised with $\alpha < 1$. A choice of $\langle\alpha\rangle = 0.4$ is good enough for fault detection and identification, keeping both time and frequency resolution into consideration.

ST may be written as

$$S(f, \tau) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}}\, \mathrm{e}^{-(\tau-t)^2 f^2/2}\, \mathrm{e}^{-\mathrm{i}2\pi f t}\, \mathrm{d}t \tag{4}$$

For the discrete ST, $h(t)$ can be written in discrete form as $h[kT]$, where k varies from 0 to $N-1$ and is known as discrete time series of the signal $h(t)$. Discrete Fourier transform of the sam-