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Fast S-transform based distance relaying in transmission line

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ABSTRACT

The paper presents distance relaying of transmission line using Fast S-transform (FST). Basically distance relaying needs a faster and accurate phasor estimation of the fault current and voltage signals, which are used to compute apparent impedance for issuing the tripping signal in case of faulty situations. Originally developed conventional S-transform is an invertible time–frequency spectral localization technique that combines elements of wavelet and short-time Fourier transforms. However, the computational burden (processing time) of conventional S-transform is high and thus, not suitable for on-line applications such as digital protection of transmission lines. However, recent development of FST reduces the computational burden by utilizing downsampling. The FST is found to be accurate and faster compared to conventional S-transform while estimating the phasor and computing impedance trajectory. The accuracy in estimation with high DC off-set and performance in noisy environment ensures the robustness of the FST for relaying applications. The results from extensive study indicate that the FST can suitably replace the existing DFT based algorithm for on-line digital distance relaying task in large power transmission network.

1. Introduction

Fault is one of the important transient phenomena that occur on the power transmission line and needs to be detected, classified, located accurately and cleared as fast as possible. If not identified and removed quickly, it may lead to wide spread damage in the power system. Thus, a fast and accurate fault clearance technique is required in order to improve the system stability and reliability. To achieve this, the protective relays need to be faster and accurate in detecting the faulty events (within one or two cycles of power frequency from the event inception) to prevent the damage spreading to healthy part of the power network. This makes the issue more challenging as lesser data is provided to a digital filter to extract the desired signal frequency.

Most important issue in the digital relaying is to extract the fundamental frequency signal, quickly and accurately. The fault signal is normally composed of fundamental frequency component, harmonics and a decaying dc component. The task of the digital filters is to extract only the fundamental frequency signal by filtering all other unwanted signals. The time constant and amplitude of the decaying dc are unknown and are associated with the fault resistance, fault position and the fault beginning time. The most popular phasor estimation algorithms are the full and half cycle DFT-based algorithms [1–3]. It is well known that full cycle DFT filters have better frequency responses than half cycle DFT filters, because the former eliminate all harmonics, whereas the latter do not eliminate even harmonics. In addition, although the latter are faster than the former, they suffer from inaccuracies due to the decaying dc and off nominal frequency components [4]. Many improvements in DFT-based algorithms have been reported [5–8], and some of them use adaptive strategies to vary the window length after detecting the fault, resulting in better frequency responses. However, they are still slower and fail in presence of noise and high DC off-set.

In recent years, Discrete Wavelet Transform (DWT) [9,10] has been extensively used for fast digital relay algorithms. Although good results are reported on phasor estimation and relay decision, the DWT based phasor estimation suffers from many inaccuracies as it does not eliminate harmonics. The DWT provides the equivalent of finer time resolution at high frequencies and finer frequency resolution at low frequencies. However, the DWT does not measure frequency but only an analogue, called scale. Additionally, the DWT provides either no phase information, or phase measurements which are all relative to different local references. Further, performance of DWT is significantly degraded owing to the existence of noises riding high on the signal [11]. Thus there is a strong motivation to develop distance relaying algorithm based on a new time–frequency transform which is accurate in adverse situations where DFT and DWT fail.

The proposed research presents a fast and accurate digital relaying algorithm using Fast S-transform (FST). Conventional S-transform [12,13] is an invertible time–frequency spectral localization technique that combines elements of wavelet and

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short-time Fourier Transforms. The S-transform uses an analysis window whose width is decreasing with frequency providing a frequency-dependent resolution. This time–frequency transform may be seen as a continuous wavelet transform with a phase correction. This has found wide applications in power system protection [14], power quality [15], seismic signal processing [12], and other similar applications. However, S-transform usually is selected for off-line analysis as it is computationally highly demanding [16] and thus, translates to long computation time for phasor estimation, which is not suitable for on-line applications in distance relaying. To overcome the afore mentioned problem, the Fast S-transform [17,18] based digital relay algorithm is proposed which includes estimation of faulted voltage and current phasors to achieve an accurate and faster tripping decision making in transmission line distance relaying.

2. Fast S-transform (FST)

The S-transform can be derived as variable windowed Short Time Fourier Transform (STFT), where the window width depends upon the frequency or as phase correction to the mother wavelet transform. The S-transform uses sinusoidal basis functions like those of Fourier Transform (FT) and STFT. These are multiplied by Gaussian window functions that vary depending the frequency content. Moreover, the S-transform provides both the true frequency and the global referenced phase of FT and STFT and, progressive resolution of wavelet transform. These properties have made it useful for non-stationary signal analysis in various applications. The conventional S-transform can be defined as

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t) \cdot w(t-\tau, \zeta) \cdot e^{-i2\pi ft} \quad (1)$$

where $x(t)$ is the time domain signal to be transformed, $w(t-\tau, \zeta)$ is the window function centered at τ with a width that is inversely proportional to ζ, f is the frequency and $S(\tau, f)$ is the resulting S-spectrum. To realize the S-transform, the window function must satisfy $\int_{-\infty}^{\infty} w(t-\tau, \zeta)d\tau = 1$. The discrete version of the conventional S-transform (1) can be represented as

$$S\left(jT, \frac{n}{NT}\right) = \sum_{k=0}^{N-1} x(kT)w(kT, \zeta)\exp^{-(i2\pi nk/N)} \quad (2)$$

where as $t \to kT$, $\tau \to jT$ and $f = n/NT$ and $h(kT)$, $k[0, 1, \ldots, N-1]$ is the discrete time series with sampling interval of 'T'.

The S-transform provides the combined time–frequency resolution and the trade-off between time and frequency resolution depend upon the window width ζ. For higher frequencies, the window width decreases lowering the frequency resolution and for lower frequencies, window width is higher and thus, lowering the time resolution. Thus, the uniform sampling does not reflect the change in resolution. Further, for low frequencies, the original signal can be down sampled (by decreasing T) satisfying Nyquist criterion, resulting lesser signal samples that need to be used for computation. For higher frequencies, the window becomes narrower and thus, the length of the signal NT may be reduced, resulting fewer signal samples to be evaluated.

Thus, Fast S-transform [17,18] is the computation of S-transform with reduced computational burden using down sampling. This combines a dyadic sampling scheme with downsampling and signal cropping to produce a Fast S-transform (FST). Since this formulation uses a generalized window function, it is a fast algorithm for calculating the conventional S-transform. It has a computational complexity of $O(N \log N)$, compared to the conventional S-transform at $O(N^2 \log N)$ and thus, a faster method for calculating the S-transform. The algorithm is calculated from the time domain, so computation of the transform can proceed while data is being collected.

The steps involved in computing Fast S-transform using down sampling are given as follows:

1. Compute Fourier Transform of the signal $X(n/NT)$.
2. Compute the kernel functions

$$\Psi^{+} = e^{-(i2\pi kn/N)} \text{ and } \Psi^{-} = e^{(i2\pi kn/N)}$$

3. Compute the window functions $w\left(kT, \frac{n}{NT}\right)$,

$$\text{for} N = \left[\frac{N}{2}, \frac{N}{4}, \ldots 4, 2, 1\right]$$

4. Compute band pass filter $X(\kappa)$, where $\frac{N}{2} \le \kappa \le n$ and inverse Fourier Transform to obtain $x'(t)$.
5. Finally, compute the transformed samples for every point 'j' in '$x'(t)$'

$$S\left(jT, \frac{3n}{4NT}\right) = \sum_{k=0}^{N-1} x'(kT) \cdot w\left(kT - T, \left|\frac{3n}{4NT}\right|\right) \cdot \psi^{+}\left(kT, \left|\frac{3n}{4NT}\right|\right)$$

$$S\left(jT, -\frac{3n}{4NT}\right) = \sum_{k=0}^{N-1} x'(kT) \cdot w\left(kT - T, \left|\frac{3n}{4NT}\right|\right) \cdot \psi^{-}\left(kT, \left|\frac{3n}{4NT}\right|\right)$$

6. End of the process

Like S-transform, FST can be inverted, with their respective inverse transform algorithms, to recover the original signal. The inverse of FST can be given as follows

$$X\left(\frac{n+p}{NT}\right) = \frac{1}{M}\left[\sum_{j=0}^{M-1} S\left(jT, \frac{n}{NT}\right) \cdot e^{i(2\pi jp/M)}\right] \cdot \frac{1}{W(1/NT, \varsigma)} \quad (3)$$

where X is the Fourier Transform (FT) of the signal x, W is the FT of the window function w, p is the offset from the calculated frequency and M is the number of samples along the j-axis. Since the FST uses a dyadic sampling scheme, frequencies that are not directly calculated by the FST must be recovered. These "off-center" coefficients are generated by performing an FFT of the nearest calculated jT-line, correcting for the weighting effects produced by the window, and choosing the appropriate resulting coefficient. Since many choices of window will yield a nonorthogonal transform, many sampling schemes are possible. Even though the above mentioned algorithm does oversample the S-spectrum to some extent, however, it is conceptually simple and easy to implement.

After generating the S-spectrum using FST algorithm, the magnitude and phase of the signal [14] can be extracted as follows:

$$\text{Magnitude : mag}\left(S\left(jT, \frac{n}{NT}\right)\right) = \max\left(S\left(jT, \frac{n}{NT}\right)\right) \quad (4)$$

$$\text{Phase :} \quad \phi\left(jT, \frac{n}{NT}\right) = a\tan\left\{\frac{\text{imag}(S(jT, (n/NT)))}{\text{real}(S(jT, (n/NT)))}\right\} \quad (5)$$

3. Initial test system

The power system transmission network shown in Fig. 1 is simulated using SIMULANK (MATLAB) package. The relaying point is as shown in Fig. 1, where fault voltage and current signals samples (per unit) are retrieved for different fault situations. The power system network consists of S_1 and S_2 of 400 kV generation capacities and