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Detection, classification, and location of faults in power transmission lines

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ABSTRACT

This paper presents a pattern recognition approach for current differential relaying of power transmission lines. The current differential method uses spectral energy information provided through a new Fast Discrete S-Transform (FDST). Unlike the conventional S-Transform (ST) technique the new one uses different types of frequency scaling, band pass filtering, and interpolation techniques to reduce the computational cost and remove redundant information. Further due to its low computational complexity, the new algorithm is suitable for real-time implementation. The proposed scheme is evaluated for current differential protection of a transmission line fed from both ends for a variety of faults, fault resistance, inception angles, and significant noise in the signal using computer simulation studies. Also the fundamental amplitude and phase angle of the two end currents and one end voltage are computed with the help of the new formulation to provide fault location with significant accuracy. The results obtained from the exhaustive computation show the feasibility of the new approach.

Introduction

Differential relaying has been already applied for a wide variety of protective systems for the generators, transformers, bus bars, transmission lines and provides high speed fault clearance [1–3]. For transmission lines both the current and power differential protection schemes [4–6] have been used for the detection and classification of faults in the protected zone. Further the implementation of Global Positioning System (GPS) based synchrophasors makes differential protection of transmission lines a practical idea [7,8], even for very long transmission lines [9] in a smart grid environment. A SONET architecture [8] that follows a redundant and reliable asymmetric communication scheme results in the end-to-end time delay of a few milliseconds. The speed of response of the differential scheme is hardly influenced by this communication delay. The concept of using synchrophasors for digital protection has already been attempted [10]. The use of phasor measurement units (PMU) have been suggested [11] for measuring current at the two ends of a transmission line and use these values for determining the restraining and operating quantities for differential protection. However, these schemes suffer from line charging current and CT saturation and thus time-frequency methods have been suggested for differential protection of transmission lines. Amongst the various time-frequency techniques, the discrete wavelet transform (DWT) has been introduced [12,13] for a variety of protection of power system elements including the differential energy based approach for differential protection of transmission lines.

Although the wavelet transform provides a variable window for low- and high-frequency components in the voltage and current waveforms during faults, special threshold techniques are needed under noisy conditions [14]. Also the wavelet transform uses high pass and low pass filters to splint the power signal into a detail and an approximation repeatedly until a required level of decomposition is achieved. As it only decomposes the signal approximations, it may fail in cases where certain informations belong to the high frequency regions. Thus for more accuracies wavelet packet transform is used for protection purposes [15]. Additionally, the detailed amplitude, instantaneous phase or frequency of the fundamental components, necessary for protection purpose cannot be obtained easily without a complex set of calculations [16]. In recent years S-Transform (ST) has been used for the protection of transmission lines [14] and power signal disturbance detection due to its superior properties of localizing the time-frequency components. However, unlike the DFT, the ST can vary the amount of time and frequency over which measurements are averaged, depending on the frequency under consideration. This is an important property that differentiates wavelets and the ST from the DFT. A further

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potential advantage of the ST over wavelets is that it utilizes sinusoidal basis functions so "phase" measurements are more directly related to the conventional concept of phase. The phase information associated with the ST makes it as an ideal candidate for the detection and classification of distorted signals, and thus it is used here to localize and detect any power system amplitude or phase changes in the power system signals [17–20].

The physical reality of power system signals is then better analyzed using mathematical methods like S-Transform. Although ST is a powerful tool for power signal disturbance assessment, it involves high computational overhead which is of the order of $O(N^2 \log N)$ using the entire data window for the signal. Thus there has been some attempts [21] to reduce the computational overhead for the calculation of discrete ST for biomedical signal processing, by using a dyadic frequency scaling which may not be suitable for power system protection due to the range and nature of harmonics generated during faults. This paper, therefore, presents intelligent scaling mechanisms which can make the computation of S- Transform faster and suitable for power system protection operations. The scaling techniques act as smart numerical filters for deciding the time domain localizations of significant frequencies. The digital relay based on such methods can intelligently and dynamically decide the online signal calculations for relay operations. Thus with the significant reduction in computational cost, the fast discrete ST (FDST) has a distinct advantage over DWT in giving an unified approach for both fault detection and fault location simultaneously to a very accurate extent. Further the new FDST based current differential protection scheme can include fault location function by simply measuring the differential current and voltage at one end, say the sending end relaying point [22,23].

The paper is organized as follows: Section 'Spectral energy computations' [24] describes the spectral energy computation scheme where the energy computations are triggered using a computationally light technique called CuSum algorithm. Section 'Fast Discrete S-Transform (FDST)' explains the FDST algorithm and the frequency scaling methods used. It also describes the application of the CuSum and FDST to detect and classify the various kinds of fault. Section 'Results and discussions' shows the results obtained from the simulation studies for a practical system taken from the literature. Section 'Conclusion' is the conclusion of the study.

Spectral energy computations

Using the differential current and its energy for operation and the average current and its energy for restraint, a DWT based spectral energy differential relay has been suggested [22] to overcome some of the sensitivity and stability problems of the conventional differential scheme and give suitable protection for both the internal and external faults. Parallel to DWT based protection schemes for power system elements, S-Transform has been used [14] for providing a pattern recognition approach for the protection of both compensated and uncompensated transmission lines. However, before processing the instantaneous difference or average values of the current samples it is necessary to detect any change in the differential current and the average current using the Cumulative Sum technique (CuSum). The CuSum algorithm is described below.

CuSum algorithm

The CuSum algorithm does cumulative summation of the differences between the reference cycle and the present cycle to detect any sudden change in the signal amplitude. It is useful in reducing the computational load on the digital relay's processor. It is excellent in change detection of periodic patterns, but it is not useful to confirm the occurrence of a fault or to perform further computations on the fault signal. Being computationally light, CuSum is suitable to be used as a trigger for initiating the Fast Discrete S-Transform.

A cumulated signal for a fundamental cycle is given by

$$\mathrm{CuSum} = \sum_{k=1}^{Ns}(S(k) - S(k - \lambda \cdot Ns)) \quad (1)$$

where $S(k)$ is the signal amplitude at the kth sample, Ns is number of samples per fundamental cycle and λ is the factor determining the time gap between the present amplitude and the reference amplitude. In on-line mode, CuSum is continually computed at each sample. CuSum for the kth sample is given by

$$\mathrm{CuSum}(k) = \mathrm{CuSum}(k-1) + S(k) - S(k - \lambda \cdot Ns) \quad (2)$$

λ is generally taken as 1 considering the simplicity of implementation. The time point at which CuSum(k) exceeds a preset value μ is taken as the CuSum Detection Point (CSDP). Effectively, CSDP = k such that CuSum(k) > μ for the first time. The CuSum status is cleared later after the detection of the occurrence of the change indicating the occurrence of a fault on the line. Upon the detection of CSDP the algorithm to obtain the time-frequency localized signal energies is initiated.

S-Transform Formulations

The ST provides a time frequency representation with frequency-dependent resolution while, at the same time, maintaining the direct relationship, through time-averaging, with the Fourier spectrum [15]. The Generalized S-Transform of a time varying signal $x(t)$ is obtained as

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t) \cdot w(\tau - t, f) \cdot \exp(-2\pi i f t) dt \quad (3)$$

where the window function $w(t, f)$ is chosen as

$$w(t, f) = \frac{1}{\sigma(f)\sqrt{2\pi}} \exp\left(\frac{-t}{(2\sigma(f)^2)}\right) \quad (4)$$

and $\sigma(f)$ is represented as $\sigma(f) = \frac{\alpha}{|f|}$ (5)

The window is normalized as

$$\int_{-\infty}^{\infty} w(\tau - t, f) d\tau = 1 \quad (6)$$

If the continuous time series $x(t)$ is sampled with a sampling period of T sec to obtain N samples, the expression for discrete ST becomes

$$S\left(jT, \frac{n}{NT}\right) = \sum_{k=0}^{N-1} x(kT) \cdot w\left((j-k)T, \frac{n}{NT}\right) \cdot e^{\left(-\frac{i2\pi kn}{N}\right)} \quad (7)$$

where $f = \frac{n}{NT}$, T = sampling interval, and the window function in the discrete domain is chosen as:

$$w\left(jT, \frac{n}{NT}\right) = \frac{a + b\left|\frac{n}{NT}\right|^c}{r\sqrt{2\pi}} \exp\left((jT)^2 \left(a + b\left|\frac{n}{NT}\right|^c\right)^2 \div 2r^2\right) \quad (8)$$

where $j = 0, 1, \ldots, N-1$ represents a time point index, $n = 0, 1, \ldots (N/2) - 1$ is a frequency point index of a given cycle, x is the discrete time domain signal, k is the time domain shift required for the convolutive operation with the window w, f is the frequency point computed from the frequency point index and time period NT of the signal. Further r and b are the scaling factors that control the number of oscillations in the window, and a, c are positive constants. When k is increased, the window broadens in the time domain, and hence, frequency resolution is increased in the