Transmission Line Fault Detection Using Time-Frequency Analysis

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Abstract — A new approach for fault detection in power system network using time-frequency analysis is presented in this paper. The S-transform with complex window is used for generating frequency contours (S-contours), which distinguishes the faulted condition from no-fault. Here the fault current data for one cycle back and one cycle from the fault inception is processed through S-transform to generate time-frequency patterns with varying window. The generated time-frequency patterns clearly distinguishes the faulted condition from un-faulted.

Keywords — Fault detection, time-frequency analysis, S-contours.

I. INTRODUCTION

Different types of transient phenomena occur on the transmission line. From these transient phenomena, faults on transmission lines need to be detected and classified accurately, and cleared as fast as possible. In power transmission line protection, faulty phase identification is very important 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 current data at the relaying point are used to detect and classify the fault involving the line with or without fault resistance present in the fault path.

Another pattern recognition technique based on wavelet transform [1,2] 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. Another powerful time-frequency analysis known as S-transform has [3-5] found applications in geoscience and power engineering. 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 is decreasing 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 [6].

When the fault occurs on the power system, the fault current is captured at the relaying point. After the signal is retrieved, it is processed through S-transform with complex window [7] to produce the time-frequency contours known as S-contours to which distinguishes faults from un-faulted one. As s-transform is obtained by multiplying the real window with fourier sinusoid and the fourier sinusoid has time-invariant frequency, s-transform is unsuitable for resolving waveforms whose frequency changes with time. This problems can be overcome by using complex gaussian window with a user designed complex phase function. The phase function modulates the frequency of the fourier sinusoid to give better time-frequency localization of the time series. That means if the time series contains a specific sinusoidal waveform that is expected at all scales, then the complex gaussian window can give better time-frequency resolution of event signatures than the un-modulated, real valued gaussian window of the original signal.

II. S-TRANSFORM WITH COMPLEX WINDOW

The original S-transform is defined as

$$S(t, f, p) = \int_{-\infty}^{\infty} h(t) \{w(t - \tau, f, p) \times \exp(-2\pi if\tau)\} d\tau,$$

(1)

where $w$ is the window function of the S-transform and $p$ denotes the set of parameters that determines the shape and property of $w$. The alternative expression of (1) with Fourier transform can be given as:

$$S(t, f, p) = \int_{-\infty}^{\infty} H(\alpha + f) W(\alpha, f, p) \times \exp(+2\pi i\alpha t) d\alpha$$

(2)

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Where

\[ H(f) = \int_{-\infty}^{\infty} h(t) \exp(-2\pi ft) dt \]  

(3)

\[ W(\alpha, f, p) = \int_{-\infty}^{\infty} w(t, f, p) \exp(-2\pi i\alpha t) dt \]  

(4)

The variable \( \alpha \) and \( f \) having same units. For S-transform to converge to \( H \) given by:

\[ \int_{-\infty}^{\infty} S(t, f, p) dt = H(f) \]  

(5)

For \( w \) to the window of S-transform, the following condition must be satisfied

\[ w(t - t, f, p) \exp(-2\pi ft) = A(t - t, f, p) \exp\{-2\pi i\phi(t - t, f, p)\} \]  

(6)

where \( A \) and \( \phi \) are the amplitude and phase of \( w \). If both sides get multiplied by Fourier sinusoids, \( w \) becomes:

\[ w(t - t, f, p) \exp(-2\pi ft) = A(t - t, f, p) \exp\{-2\pi i\phi(t - t, f, p)\} \]  

(7)

As \( A \) and \( \phi \) are known, the instantaneous frequency can be defined as the time derivative of the total phase. Then the instantaneous frequency can be given as:

\[ F = f + \frac{\partial}{\partial t} \phi(t - t, f, p) \]  

(8)

The S-transform gives the best localized spectrum when the analyzing function matches with the shape of the time series of the signal. The analyzing function is defined by multiplication of the Fourier sinusoid with the Gaussian window with phase modulation through an appropriate complex factor and normalization. This gives to complex Gaussian window [9]

\[ w_{CG}(t - t, f, \sigma) \]

\[ \begin{cases} \rho \exp\left[-2(t - t)^2\right] \exp(-2\pi f(t - t)) & t \leq t + \sigma |f|, \\ +2\pi i\text{sign}(f)\rho \log\left[+\frac{|f|}{t - t}\right] & t \geq t + \sigma |f|, \\ 0 & t < t + \sigma |f|. \end{cases} \]  

(9)

The pre-factor \( P \) is defined as

\[ p^{-1} = \int_{-\sigma / |f|}^{\infty} \exp\left\{\frac{f^2}{2} - 2\pi ft + 2\pi i\text{sign}(f) \times \log\left[+\frac{|f|}{t + \sigma / |f|}\right]\right\} dt, \]  

(10)

where the positive parameter \( \sigma \) controls the degree of phase modulation. When \( w_{CG} = 0 \) the instantaneous frequency becomes

\[ F = \frac{\sigma f}{\sigma + |f|} \]  

(11)

The discrete S-transform is obtained by sampling (2) in the frequency domain and given by:

\[ S_{\alpha} = \left[ jT, \frac{n}{MT}, P \right] = \sum_{m=-\frac{M}{2}}^{\frac{M}{2} - 1} \int_{-\infty}^{\infty} H(\frac{n + m}{MT}) \right] \times W_{\alpha}\left[\frac{m}{MT}, \frac{n}{MT}, P\right] \times \exp\left(+2\pi imj\right) \]  

(12)

where \( T \) is the sampling interval, \( M \) is the numbers of sample points and \( j \) is the discrete time index. \( m \) and \( n \) are discrete frequency indices. The discrete window function is obtained by

\[ W_{\alpha}\left[\frac{m}{MT}, \frac{n}{MT}, \sigma\right] = P \sum_{k=\max(-\frac{M}{2}, |m|), -\frac{M}{2}}^{\frac{M}{2} - 1} \exp\left[-\frac{n^2}{2M^2} - 2\pi i\frac{nk}{M}\right] \times \exp\left(-2\pi i\frac{nk}{M} - \sigma \text{sign}(n) \times \log(\sigma + |\frac{n}{M}|)\right) \]  

(13)

where \( P \) is defined as:

\[ P^{-1} = P \sum_{k=\max(-\frac{M}{2}, |m|), -\frac{M}{2}}^{\frac{M}{2} - 1} \exp\left[-\frac{n^2k^2}{2M^2}\right] \times \exp\left(-2\pi i\frac{nk}{M} - \sigma \text{sign}(n) \times \log(\sigma + |\frac{n}{M}|)\right) \]  

(14)

where \( k \) is the discrete time index.
III. SIMULATION STUDY AND RESULTS

The 400 KV, 3-phase, 300 km power transmission studies is shown in Fig. 1. A cycle-to-cycle comparison of currents and thresholds are used to detect any abnormality due to the occurrence of a fault. Once a deviation is observed, the S-transform is applied to the data one cycle back and the one cycle data from the point of occurrence of the deviation in the current amplitudes. The sampling rate chosen is 6.4 kHz. The parameters are chosen as: L(1)=0.9337e-3 H/km, L(0)=4.1264e-3 H/km, R(1)=0.01273 Ohms/km, R(0)=0.3864 Ohms/km, C(1)=12.74e-9 F/km, C(0)=7.751e-9 F/km.

Fig. 2 through Fig. 12 depict the results for different fault condition with various operating mode. Fig.2 shows the S-contours for a-ph (a-g) fault at 20% of line with 20 ohm fault resistance (Rf). Similarly the Fig.3 shows the S-contours for b-ph at (a-g) fault at 20% of line with 20 ohm fault resistance ohm. It clearly seen that in case of faulted phase the S-contours are at higher frequency scale compared to un-faulted phase where S-contours are at lower frequency scale. Fig.5 and Fig.6 depict the fault patterns for Line-Line (a-b fault) at 45% of the line with 50 ohm fault resistance. Similarly Fig.7 through Fig.9 show the S-contours resulted from S-transform in case of Line-Line-Ground fault at 65% of the line with 80 ohm fault resistance. It is clearly seen that in case of faults the S-contours are at higher values compared to S-contours generated for phase without fault. For Line-Line-Line faults at 80% of line with Rf=100 ohm, the generated S-contours are shown in Fig.10 and Fig.11. Fig.12 depicts the S-contours for Line-Line-Line-Ground fault at 90% of the line with 150 ohm fault resistance.

From the above results the fault is recognized by pattern recognition approach where faults and no-faults are clearly distinguished from the position of the S-contour levels in the generated time-frequency patterns. In case of faults the S-contours are concentric at higher frequency scales where as in un-faulted condition the S-contours are concentric about Lower frequency scale.

Fig. 1. Transmission Line Model

Fig. 2. S-contours for a-ph (a-g) fault at 20% of line with Rf=20 ohm.

Fig. 3. S-contours for b-ph (a-g) fault at 20% of line with Rf=20 ohm.

Fig. 4. S-contours for c-ph (a-g) fault at 20% of line with Rf=230 ohm.
V. CONCLUSION

This paper presents a pattern recognition approach for fault detection using time frequency analysis. The fault current is processed through the S-transform with complex window and
it generates time-frequency patterns or S-contours. The S-contours are concentric at higher frequency scales for faulted condition but in case of un-faulted phase the S-contours are concentric about lower frequency scales, which clearly distinguishes faults from no-fault condition. As S-transform is very less sensitive to noise, the proposed method is very accurate and robust for protection of transmission line.

REFERENCES