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Analyzing Impact of Different Mother Wavelets on Power Swing and Fault Detection

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Abstract

Wavelet Transform represents the improved form of Fourier Transform of the signal having wide range in signal processing and pattern re-cognition. This paper studies application of discrete wavelet transform detection of two commonly existing abnormalities in power system including different fault types and power swings. This paper proposes four mother wavelet types namely: Battle Lemarie (Piecewise Linear Spline), Beylkin, Daubechies and Symlet for differentiating faults from power swing by extracting voltage and current signals and evaluating signal wavelet energy. Comparison study is commented at the end for varied fault locations. The proposed study is implemented on a 400 kV, 50 Hz parallel transmission line network developed in MATLAB software.

Keywords: Distance Relay, Power Swing, Wavelet –Transform, Mother Wavelet.

INTRODUCTION

When there is a sudden increase or decrease in load, a fault occurs, or any transmission line/generator is disconnected from supply, there is a transitory phenomenon known as power swing, which is also experienced by the relay positioned near the bus. Because of this transient condition, the generators at both ends of the line either speed up or slowdown in response to a loss of connected load or an increase in demand. In the case of an unstable swing, the situation is exactly reversed. Essentially, there are two forms of swings: steady and unstable swing. In the case of stable swing, the change in relative rotor angles among two generators is within the limitations, resulting in no loss of synchronism. Power swing causes significant changes in system voltages and currents. The frequency of swing can range from 1 Hz to 7 Hz [1], which also depends on the severity of the transitory condition.

During power swing condition, it is studied in literature that the calculated impedance of distance relay may be less than the zone setting impedance and hence it will be treated as a fault for the relay because impedance relays operates when the calculated value is less than the set value of impedance. In earlier literature, various signal processing techniques are proposed for detection of t power swing and fault during power swing. These include Wavelet Transform [1-13], Negative Sequence Current [14], Support Vector Machine [17], Adaptive Neuro- Fuzzy Inference System (ANFIS), Auto-regression technique [19] etc

In above context, Yamen R. Alsyoufi and Ammar A. Hajjar used Piecewise Linear Spline Wavelet from Battle Lemarie family with multi resolution analysis for fast detection of faults and power swings [1]. In author’s perceptive, wavelet transform is the most suitable signal processing tool as it perfectly works in time frequency localization. Ammar A. Hajjar also preferred wavelet transform tool for calculation of spectral energies of the extracted voltage and current signals to form two discriminating signals of the relay to make it operative/inoperative in case of transmission line protection [2]. The relay measures impedance as the ration of sensed voltage to current at the related bus which decides zone of protection for particular relay setting. Real-time detection of the fault-induced transients using the wavelet coefficient energy with consideration of border effects of the sliding window leads to faster fault detection [3]. This technique covers those faults which do not induce transient energy such as LG fault. In [4], Sukumar M. Brahma has used wavelet transform block along with the digital relay whose output decides presence of a power swing condition whereas digital relay output gives output related to 3 phase fault condition. Logical AND circuit is used to indicate fault during power swing condition. High frequency information from three phase voltage signals is extracted using discrete wavelet transform in [5] using travelling wave theory. The detection of symmetrical faults during power swing is studied using Daubechies dB4 wavelet in [6] using thirteen wavelet coefficients. The author stated in [7] that the WT uses short windows at high frequencies and long windows at low frequencies whereas Fourier transform uses a single window for analysis. R. Nandi and B.K. Panigrahi analyzed a hybrid power system with wind generation in [9] using wavelet transform that can detect and classify various types of faults. Wavelet transform tool is also used in previous literature [10,11,12] to detect faults during power swing. In [10], symmetrical fault detection during power swing is achieved using Daubechies-8 (Db8) wavelet. Ratio of energies of forward and backward travelling waves is considered for symmetrical fault detection as these waves exist during fault condition only. Daubechies 4 (dB4) mother wavelet is used by Prakash K. Ray in [11] for fault detection analysis along with independent component analysis. Symmetrical fault detection and out-of-step blocking during power swing is detailed in [12] by Rahul Dubey and Subhransu Ranjan Samantaray using wavelet transform (dB4). In [13], Nan Zhang and Mladen Kezunovic studied decomposition of current signal using WT and singular values related indicators are calculated to differentiate between stable and unstable power swing and also fault detection during power swing. Authors implemented wavelet transform with multi resolution analysis and neural network for detection of fault type and whether fault is internal or external so that there is no distance relay mal-operation. In [14], Jitendra Kumar1 and Premalata Jena proposed fault detection during asymmetrical power swing by calculating phasor difference between fault and pre fault negative sequence currents. The stable and unstable power swings is detected in [15] using wavelet transform of angular velocity signal of the synchronous machine. A supervisory algorithm with dynamic threshold value improves the immunity of the distance relaying during power swing condition and symmetrical faults. The wavelet synchro-squeezing transform is utilized by the authors

With reference to above literature survey, it may be concluded that work is not yet reported for implementation of various types of mother wavelets for a typical power system network for detection of transient condition such as power swing and fault by applying similar fault parameters. Hence, this paper proposes four different types of wavelet families namely: Battle, Beylkin, Symlet and Daubechies for extraction and decomposition of voltage and current signals present at relay end. Total eight levels of decomposition are obtained (d1- d8) using wavelet transform. After extraction of signals, energy calculation of detail coefficient d1 of voltage signal and d8 of current signal is used for detection of power swing and fault during power swing respectively in a typical double circuit transmission line network.

The rest of the paper includes theory of wavelet transform in section-II, detailed system description in section-III, result and discussion in section IV followed by conclusion in section-V.

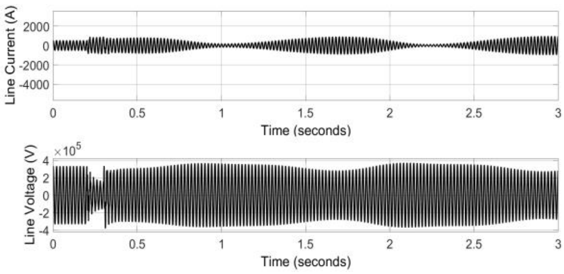


Figure 1 Current (upper) and voltage (lower) signal during slow power swing.

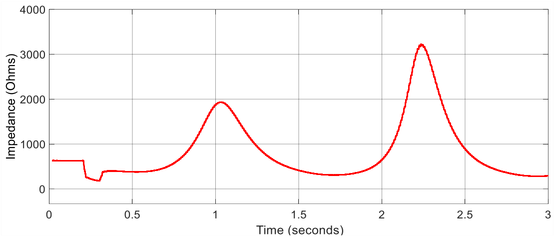


Figure 2 Impedance observed by the relay during slow power swing.

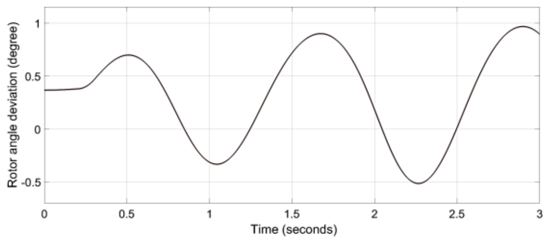


Figure 3 Rotor angle deviation during slow power swing.

THEORY OF WAVELET TRANSFORM (WT)

Apart from its application in speech and image processing, wavelet transform is used in electrical power system applications for transient signal analysis in which case signal frequency considerably varies over the time. The most significant applications of wavelet transform (WT) related to power system include power quality analysis and power system protection [36]. The process includes decomposing given signal into approximation coefficients capturing low frequency components and detail coefficients capturing high frequency components. Another set of approximation and detail coefficients is created by further decomposing approximation coefficients. The process is then repeated and the successive stages of decomposition are known as level-1, level-2, etc. The high frequency information of the signal is contained in the detail coefficient of level 1 (D1), while the low frequency information is retrieved in approximatively coefficients (cA). The mother wavelet which is also called as a windowed function and possesses a significant role in the signal analysis with DWT. In the reported literature, many authors have used mother wavelet from Daubechies wavelet family with different vanishing moments.

Discrete wavelet transform

The mathematical expression for continuous wavelet transform is given in eq. (1) in terms of scaled and shifted wavelets whose combination in terms of coefficients gives original mother wavelet.

$$C\ (scale, position) = \int_{-\infty}^{+\infty} f(t)\ \psi\ (scale, position, t)\ dt \quad (1)$$

In Discrete Wavelet Transform the wavelets are discretely sampled. It returns the data vector of length equal to that of an input. The basic difference between continuous wavelet transform (CWT) and the discrete wavelet transforms (DWT) is in terms of decreasing the scale parameter. The former has the exponential scales with a base smaller than 2 while later with the base equal to 2. The mathematical expression of DWT is given by the following equation:

$$(t, k) = \sum_t \sum_k x(k) \frac{1}{\sqrt{2}} \psi^{\frac{(n-k)}{2}} \quad (2)$$

where, $\Psi\ (k)$ is the mother wavelet.

Multi resolution analysis

A discrete wavelet transform can be very efficiently implemented with multi resolution analysis consisting of low pass and high pass filters breaking the signal into various components. It produces details and approximate coefficients of various levels as D_1, D_2, D_3 etc. for further analysis and thus allows ease of analysis by separating the signal into components at different resolutions (multi-resolution) where a time dependent signal $x(t)$. is passed through successive pairs of high pass filters (HPF) and low-pass filters (LPF). Approximations (cA) are the terms for representing each pair's high-scale low-frequency signal components, while details are the terms for the signal's low-scale high-frequency components (cD). After each filtering stage, every second data point is thrown away, this is the notion of down sampling, according to Nyquist's rule, to avoid redundant data [26,27]. Fig. 4 depicts a two-stage filtering process of signal $x(t)$. After sampling, signal data that cD1 records at a sampling frequency of (f_s) will fall within the range [$f_{s/4}$-$f_{s/2}$]. The information in the band [$f_{s/8}$-$f_{s/4}$] will be captured by cD2, while the remaining information in the band [0-$f_{s/8}$] will be retained by cA2.

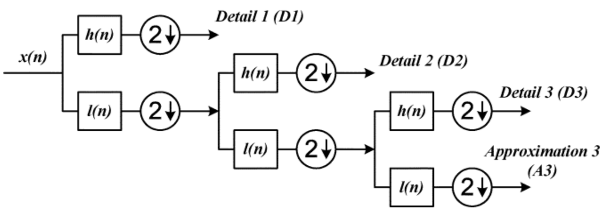


Figure 4 Three stage filtering process of a signal f (t).

Discrete Filter Banks in Discrete Wavelet Transform :

Signal filtration refers to the arithmetic operation upon convolution of signal to its impulse response. This convolution operation represented in discrete time with filter length 'n' and having impulse response hn is represented by following Equation

$$xn * hn = \sum x[k] * h[n-k] \quad (3)$$

The STFT overcomes the problem faced in Fourier transform by using concept of a sliding window w(t−u) which is non zero for only a short duration of time. The long duration signal is converted into small sections to perform Fourier transform of these small portions. The transformed coefficient has two independent parameters. One is the time parameter 'τ' and other is the frequency parameter ξ, just like that in the Fourier transform.

$$Sf(u,\xi) = \sum_{-\infty}^{+\infty} f(t)\ \omega(t-u)\ \exp(-j\xi t)\ dt \tag{4}$$

The main function of wavelet transform is to work in time domain having measurable length along with frequency domain having finite bandwidth. When we perform dilation and translation for the mother wavelet, very low frequency components are represented by large's' while very high frequency component are located at small 's' where 's' parameter is inversely proportional to the frequency.

$$Wf(s,u) = \sum_{-\infty}^{+\infty} f(t)\ \frac{1}{\sqrt{s}}\ \Psi^{*}\frac{(t-u)}{s}\ dt \tag{5}$$

Different Types of Wavelet Families

- ***Haar wavelet***: The Haar wavelet is the simplest and oldest wavelet. It is discontinuous and resembles a step function. The Haar wavelet is useful for detecting sudden changes in a signal.
- ***Daubechies wavelets:*** The Daubechies wavelets are a family of orthogonal wavelets that are compactly supported. They are smooth and have good localization properties. The Daubechies wavelets are widely used in signal and image processing.
- **Symlets:** The Symlets are a family of nearly symmetrical wavelets that are also compactly supported. They are similar to the Daubechies wavelets, but they have better symmetry properties. The Symlets are also widely used in signal and image processing.
- ***Morlet wavelet***: The Morlet wavelet is a complex-valued wavelet that is not compactly supported. It is useful for analyzing signals that have both amplitude and phase information.
- ***Biorthogonal wavelets:*** The biorthogonal wavelets are a family of wavelets that are not orthogonal, but they are still useful for signal and image processing. They have the advantage that they can be designed to have linear phase, which is important for some applications

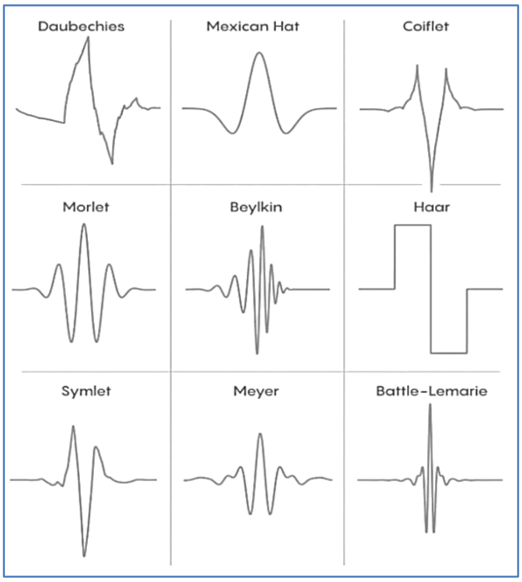


Figure 5. Natures of various mother wavelets.

Calculation of threshold value

The spectral energy of any signal means the distribution of signal energy in terms of required frequency range. The developed algorithm based on wavelet transform in this paper calculates spectral energy of the details coefficient (d_1) of the voltage signal and the details coefficient (d_8) of the current signal for power swing and fault detection respectively. The spectral energy calculation can be performed using eq. (6) below:

$$E = \sum_{i=1}^{N} [d(i)]^2 \quad (6)$$

Here, 'N' is the total number of samples for the selected window and 'd(i)' is the i^{th} detail coefficient. The threshold value is decided using calculated energy level.

Choice of suitable mother wavelet

Wavelet analysis is a popular time-frequency analysis method applied in various researches for analysis and features extraction of a wide range of signals including biological signals, vibration signals, acoustic and ultrasonic signals, image processing and transient signal analysis in power system. Choosing the best mother wavelet for the specified tasks is the key problem when using the wavelet transform tool since different mother wavelets applied to the same data can provide different outcomes. Common characteristics of mother wavelets include orthogonality, compact support, symmetry, and vanishing moment.

SYSTEM DESCRIPTION

The system under study developed in MATLAB software consists of 400 kV doubly fed parallel transmission line network with synchronous generator modeled in dq rotor reference frame. Line-1 is divided into two sections, each of 140-km length, and Line-2 is 280 km long. Lines are modeled with distributed parameters and distance relay R1 is considered for voltage and current signal extraction during fault and power swing condition respectively. The data for simulation study is detailed in the Appendix A at the end. When a three-phase fault occurs in lower line, the circuit breakers associated with relays R5 and R6 open up which results into a power swing event whose frequency depends upon fault conditions. This event is experienced by the distance relay R1 which the main focus of study.

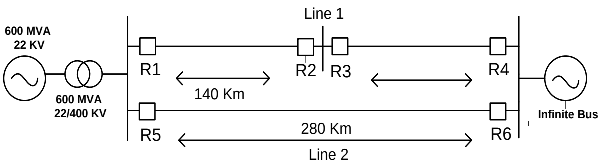


Figure 6 System under study.

SIMULATION RESULTS AND DISCUSSION

The results for voltage signal wavelet energy for fault and power swing condition are depicted below in Fig. 7 and Fig. 8 respectively. Here, first decomposition level of voltage signal is considered for fault detection and eighth decomposition level of current signal is considered for power swing condition. The later condition is created at 3.0 sec. and three-phase fault is created at 9.5 sec. as well as 3.45 sec.

TABLE-I: FREQUENCY BAND OF DETAILS COEFFICIENTS

Different details coefficients	Corresponding frequency bands (Hz)
Level $d1$	5000 to 10000
Level $d2$	2500 to 5000
Level $d3$	1250 to 2500
Level $d4$	625 to 1250
Level $d5$	312.5 to 625
Level $d6$	156.25 to 321.5
Level $d7$	78.125 to156.25
Level $d8$	39.1 to 78.125

The results for simulation work are obtained by varying fault distance from relay R1, fault resistance and type of fault. The reason is that the impedance seen by the relay increases with increase fault resistance and fault distance but decreases with increase in fault severity. The results for calculated energy are depicted in Fig. 7 and 8 below.

Case-I: **Voltage signal spectral energy for symmetrical fault detection**

The wavelet energy is extracted for different types of faults for all four types of mother wavelets under consideration. It is clearly seen that Battle Lemarie wavelet detects fault condition with lower decomposition energy.

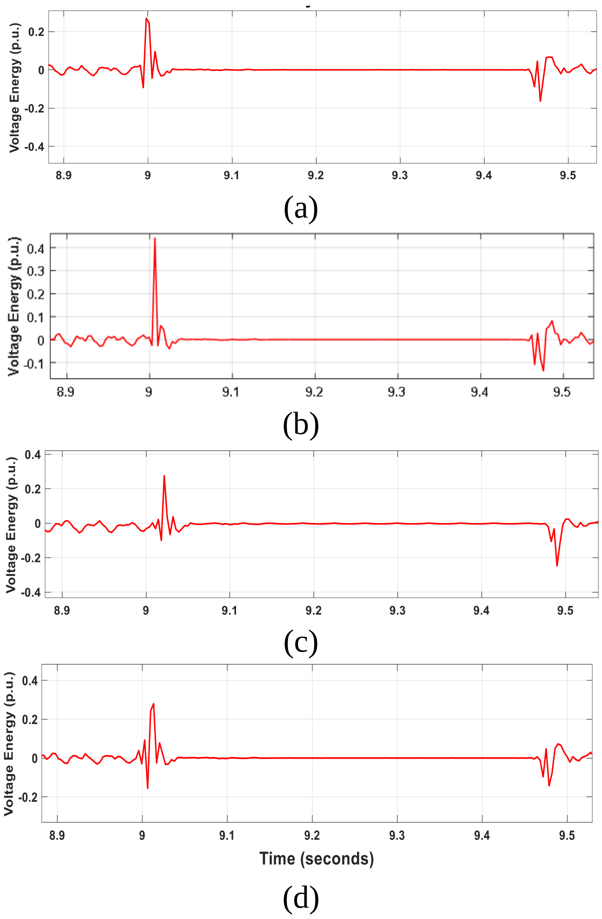
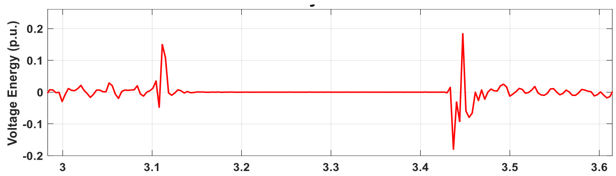
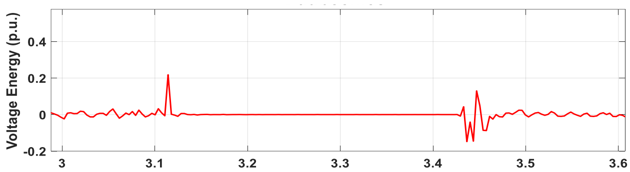


Figure 7 Voltage signal spectral energy for different wavelets for 3 phase fault in Line 1.

Case-II: Current signal spectral energy for power swing detection



(a)



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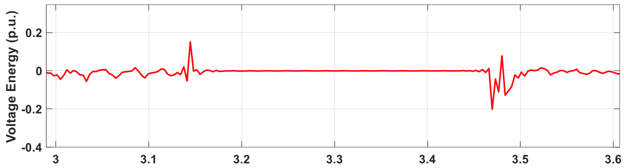
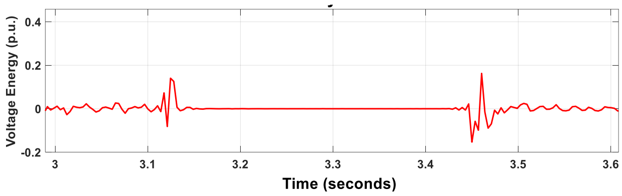


(c)



(d)

Figure 8 Voltage signal spectral energy for different wavelets for 3 phase fault at 140Km distance

Summary of Simulation Work:

The relative amount of wavelet decomposition energy calculated using wavelet transform decides whether the wavelet type is better or poor for signal analysis. Wavelet decomposition energy is observed for different fault types with change in fault resistance and fault location. The comparison of various mother wavelets is presented in Table 1 below and wavelet decomposition energy of voltage and current data using all four mother wavelets for varied fault locations is depicted in Table 2 provided in APPENDIX-B at the end.

Table 1: Comparison of different mother wavelets for varied fault parameters

Type of wavelet	Variation in Fault Type	Variation in Fault Resistance	Variation in Fault Distance	Detection time (sec.)
Symlet	Good	Average	Good	0.011
Piecewise Linear Spline	Good	Better	Good	0.014
Daubechies	Good	Good	Good	0.011
Beylkin	Average	Average	Good	0.011

CONCLUSION

This research contributes to a wavelet transform-based approach for detecting power swings and faults while using the MATLAB environment. Four types of wavelets are used: Symlet, Piecewise Linear Spline, Daubechies, and Beylkin. A comparative analysis is performed on several fault metrics such as fault distance, fault resistance, fault type, and detection time. Simulation results show that, in addition to the Daubechies wavelet, which has been widely employed in previous research, the Beylkin wavelet from the Battle Lemarie family performs the essential task with high precision. The findings may be valuable to future scholars for selecting wavelet in the case of any form of transient..

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