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Chapter

Wavelet Transform Analysis to Applications in Electric Power Systems

Mario Orlando Oliveira, José Horacio Reversat and Lucas Alberto Reynoso

Abstract

The wavelet transform has received great importance in the last years on the power system analysis because the multi-resolution analysis presents proprieties good for the transient signal analysis. This chapter presents a review on main application of wavelet transform in electric power systems. The study areas have been classified as power system protection, power quality disturbances, power system transient, partial discharge, load forecasting, faults detection, and power system measurement. The areas in which more works have been developed are the power quality and protections field, where both cover 51% of the articles analyzed.

Keywords: electric power systems, wavelet transform, signal processing, transient events

1. Introduction

Electromagnetics transients in electric power systems (EPS) are generally caused by lightning discharges and/or certain operating conditions, such as faults in equipment and transmission lines, switching of electric power system devices, voltage sags, capacitor switching, and transmission line energization and de-energization. Faulted EPS signals are associated with fast electromagnetic transients and are typically nonperiodic with high-frequency oscillations. These characteristics present a problem for traditional Fourier analysis because it assumes a periodic signal and a wide-band signal that require denser sampling and longer time periods to maintain good resolution in low frequencies. Wavelet transform (WT), on the other hand, is a powerful tool in the analysis of transient phenomena in power systems. It has the ability to extract information from the transient signals simultaneously in both time and frequency domains and has replaced the Fourier analysis in many applications. This ability to tailor the frequency resolution can greatly facilitate the detection of signal features that may be useful in characterizing the transient cause or the state of the postdisturbance electrical system.

On the other hand, the waveforms associated with fast electromagnetic transients are typically nonperiodic and contain both high frequency oscillations and localized superimposed impulses on power frequency and its harmonics. These characteristics present problems for traditional Fourier analysis because the latter assumes a periodic signal that needs longer time periods to maintain good resolution in the low frequency. In this sense, WT has received great attention in power

community in the last years because they are better suited for the analysis of certain types of transient waveforms than the other transform approaches.

Many books and papers have been written that explain WT of signals and can be read for further understanding of the basics of wavelet theory. The first recorded mention of what we now call a "wavelet" seems to be in 1909, in a thesis by A. Haar. The concept of wavelets in its present theoretical form was first proposed by J. Morlet, a Geophysicist, and the team at the Marseille Theoretical Physics Center working under A. Grossmann, a theoretical physicist, in France. They provided a way of thinking for wavelets based on physical intuition. In other words, the transform of a signal does not change the information content presented in the signal [1].

Thus, in the first part, this chapter presents an overview of the main characteristic of wavelet transform for the transient signal analysis and the application on electric power system. The property of multiresolution in time and frequency provided by wavelets allows accurate time location of transient components while simultaneously retaining information about the fundamental frequency and its low-order harmonics. This property of the wavelet transform facilitates the detection of physically relevant features in transient signal to characterize the source of the transient or the state of the postdisturbance system.

Initially, we will discuss the performance, advantages, and limitations of the WT in electric power system application, where the basic wavelet theory is presented. Additionally, the main publications carried out in this field will be analyzed and classified by the next areas: power system protection, power quality disturbances, power system transient, partial discharge, load forecasting, faults detection, and power system measurement. Finally, a comprehensive analysis related to the advantages and disadvantages of the WT in relation to other tools is performed.

2. Wavelet transform (WT)

The wavelet transform theory is based on analysis of signal using varying scales in the time domain and frequency. Formalization was carried out in the 1980s, based on the generalization of familiar concepts. The wavelet term was introduced by French geophysicist Jean Morlet. The seismic data analyzed by Morlet exhibit frequency component that changed rapidly over time, for which the Fourier Transform (FT) is not appropriate as an analysis tool. Thus, with the help of theoretical physicist Croatian Alex Grossmann, Morlet introduced a new transform which allows the location of high-frequency events with a better temporal resolution [2].

Faulted EPS signals are associated with fast electromagnetic transients and are typically nonperiodic and with high-frequency oscillations. This characteristic presents a problem for traditional Fourier analysis because it assumes a periodic signal and a wide-band signal that require more dense sampling and longer time periods to maintain good resolution in the low frequencies [3]. The WT is a powerful tool in the analysis of transient phenomena in power system. It has the ability to extract information from the transient signals simultaneously in both time and frequency domains and has replaced the Fourier analysis in many applications [4].

2.1 Continuous wavelet transform (CWT)

The short-time Fourier transform (STFT) of the continuous signal $x(t)$ can be seen as the Fourier Transform (FT) of the signal with windowed $x(t).g(t - \tau)$ or also as a signal decomposition $x(t)$ into basis functions $g(t - \tau).e^{-jwt}$. The functions

based term refers to a complete set of functions that, when combined on the sum with specific weight can be used to then construct a certain sign [5].

In the FT case, the base functions are complex sinusoid e^{-jwt} with a windows centered on the τ time. The WT is described in terms of its basic functions, called wavelet or mother wavelet, and variable frequency w is replaced by an ever-escalating variable factor a (which represents the swelling) and, generally, to variable displacement in time τ, is represented by b.

The main characteristic of the WT is that it uses a variable window to scan the frequency spectrum, increasing the temporal resolution of the analysis. The wavelets are represented by:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \cdot \psi\left(\frac{t-b}{a}\right) \tag{1}$$

In Eq. (1), the constant $1/\sqrt{a}$ is used to normalize the energy and ensure that the energy of $\psi_{a,b}(t)$ is independent of the dilation level [6]. The wavelet is derived from operations such as dilating and translating the mother wavelet, ψ, which must satisfy the admissibility criterion given by [7]:

$$C_\psi = \int\limits_{-\infty}^{+\infty} \frac{|\widehat{\psi}(y)|^2}{|y|} dy \leq \infty \tag{2}$$

where $\widehat{\psi}(y)$ is the FT of the $\psi(t)$. This means that if $\widehat{\psi}$ is a continuous function, then C_ψ is finite only if $\psi(0) = 0$, i.e., [7]:

$$\int\limits_{-\infty}^{+\infty} \psi(t)\,dt = 0 \tag{3}$$

Thus, it is evident that WT has a zero rating property that increases the degrees of freedom, allowing the introduction of the dilation parameter of the window [8].

The continuous wavelet transform (CWT) of the continuous signal $x(t)$ is defined as:

$$(CWT)(a,b) = \int\limits_{-\infty}^{+\infty} x(t) \cdot \psi_{a,b}(t)\,dt = \frac{1}{\sqrt{a}} \int\limits_{-\infty}^{+\infty} x(t) \cdot \psi\left(\frac{t-b}{a}\right) dt \tag{4}$$

where the scale factor a and the translation factor b are continuous variables.

The WT coefficient is an expansion and a particular shift represents how well the original signal $x(t)$ corresponds to the translated and dilated mother wavelet. Thus, the coefficient group of CWT(a,b) associated with a particular signal is the wavelet representation of the original signal $x(t)$ in relation to the mother wavelet [9].

2.2 Discrete wavelet transform (DWT)

2.2.1 DWT definition

The redundancy of information and the enormous computational effort to calculate all possible translations and scales of CWT restricts its use. An alternative to this analysis is the discretization of the scale and translation factors, leading to the

DWT. There are several ways to introduce the concept of DWT, the main are the decomposition bands and the decomposition pyramid (or Multi-Resolution Analysis -MRA), developed in the late 1970s [10]. The DWT of the continuous signal $x(t)$ is given by:

$$(DWT)(m,p) = \int\limits_{-\infty}^{+\infty} x(t) \cdot \psi_{m,p} \, dt \tag{5}$$

where $\psi_{m,p}$ form bases of wavelet functions, created from a translated and dilated of the mother wavelet using the dilation m and translation p parameters, respectively.

Thus, $\psi_{m,p}$ is defined as:

$$\psi_{m,p} = \frac{1}{\sqrt{a_0^m}} \psi\left(\frac{t - pb_0 a_0^m}{a_0^m}\right) \tag{6}$$

The DWT of a discrete signal $x[n]$ is derived from CWT and defined as [9]:

$$(DWT)(m,k) = \frac{1}{\sqrt{a}} \sum_n x[n] \cdot g\left(\frac{k - nb_0 a_0^m}{a_0^m}\right) \tag{7}$$

where $g(^*)$ is the mother wavelets and $x[n]$ is the discretized signal function.

The mother wavelets may be dilated and translated discretely by selecting the scaling and translation parameters $a = a_0^m$ and $b = nb_0 a_0^m$ respectively (with fixed constants $a_0 > 1$, $b_0 > 1$, m and n belonging the set of positive integers).

2.2.2 Multi-resolution analysis (MRA)

The problems of temporal resolution and frequency found in the analysis of signals with the STFT (best resolution in time at the expense of a lower resolution in frequency and vice-versa) can be reduced through a multi-resolution analysis (MRA) provided by WT. The temporal resolutions, Δt, and frequency, Δf, indicate the precision time and frequency in the analysis of the signal. Both parameters vary in terms of time and frequency, respectively, in signal analysis using WT. In the STFT, a higher temporal resolution could be achieved at the expense of frequency resolution. Intuitively, when the analysis is done from the point of view of filters series, the temporal resolution should increase increasing the center frequency of the filters bank. Thus, tax is that Δf is proportional to f, i.e.,

$$\frac{\Delta f}{f} = c \tag{8}$$

where c is constant.

The main difference between DWT and STFT is the time-scaling parameter. The result is geometric scaling, i.e., 1, $1/a$, $1/a^2$, ...; and translation by 0, n, $2n$, and so on. This scaling gives the DWT logarithmic frequency coverage in contrast to the uniform frequency coverage of the STFT, as compared in **Figure 1**.

The CWT follows exactly these concepts and adds the simplification of the scale, where all the impulse responses of the filter bank are defined as dilated versions of a mother wavelet [10]. The CWT is a correlation between a wavelet at different scales and the signal with the scale (or the frequency) being used as a measure of similarity. The CWT is computed by changing the scale of the analysis window,
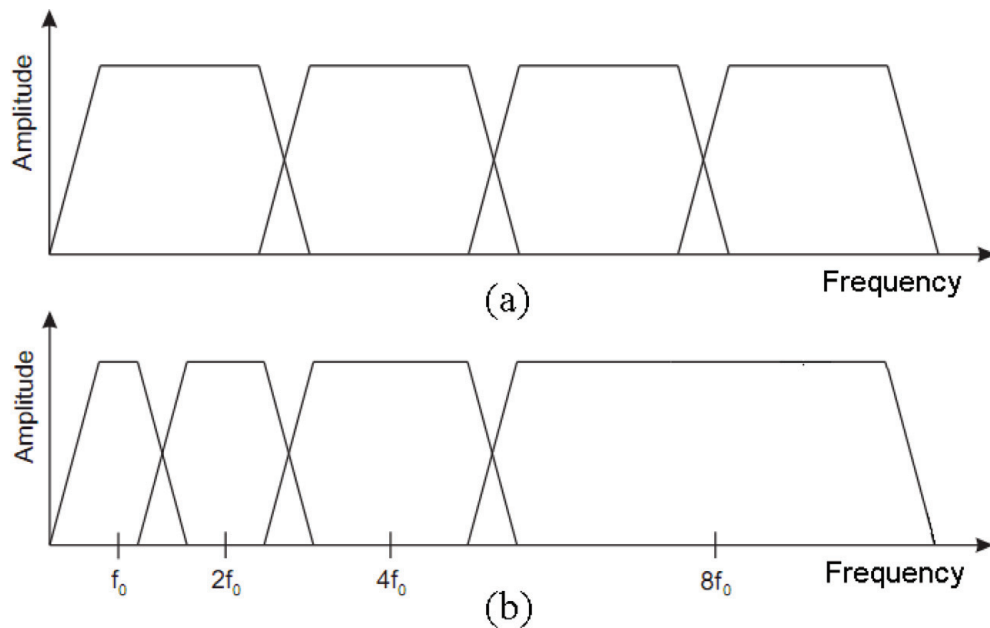
Figure 1.
Comparison of (a) the STFT uniform frequency coverage to (b) the logarithmic coverage of the DWT.
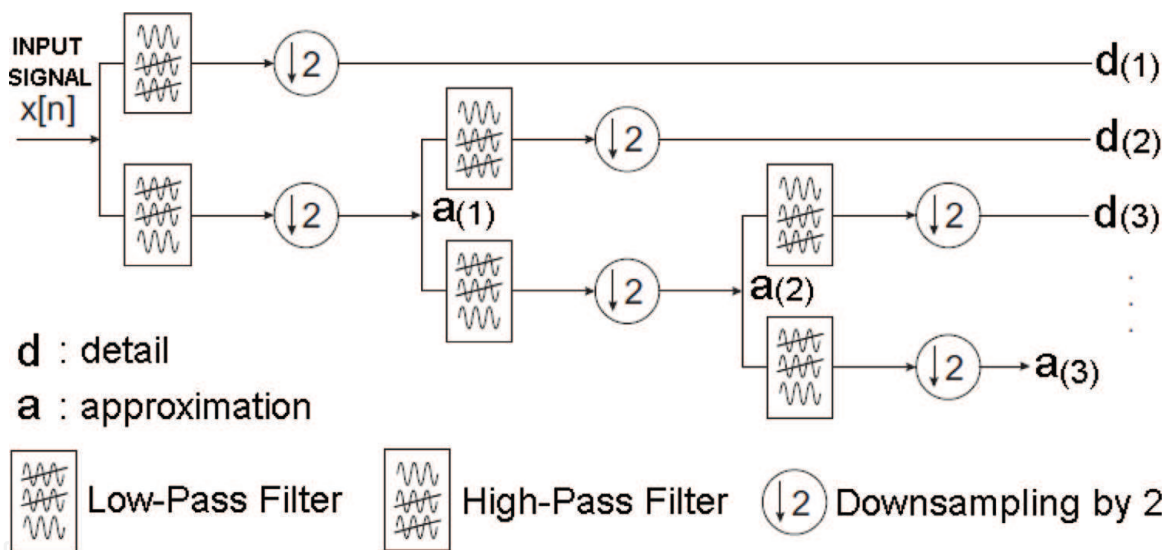
Figure 2.
DWT filter bank framework.

shifting the window in time, multiplying by the signal, and integrating over all times. In the discrete case, filters of different cut-off frequencies are used to analyze the signal at different scales. The signal is passed through a series of high-pass filters to analyze the high frequencies, and it is passed through a series of low-pass filters to analyze the low frequencies. Thus, the DWT can be implemented by multistage filter bank named MRA [11], as illustrated on **Figure 2**. The Mallat algorithm consists of series of high-pass and the low-pass filters that decompose the original signal $x[n]$ into approximation a(n) and detail d(n) coefficient, each one corresponding to a frequency bandwidth.

The resolution of the signal, which is a measure of the amount of detail information in the signal, is changed by the filtering operations, and the scale is changed by up-sampling and down-sampling (sub-sampling) operations. Sub-sampling a signal corresponds to reducing the sampling rate or removing some of the samples of the signal. For other hand, up-sampling a signal corresponds to increasing the sampling rate of a signal by adding new samples to the signal.

The procedure starts with passing this signal $x[n]$ through a half band digital low-pass filter with impulse response $h[n]$. Filtering a signal corresponds to the mathematical operation of convolution of the signal with the impulse response of the filter. The convolution operation in discrete time is defined as follows [2]:

$$x[n] * h[n] = \sum_{k=-\infty}^{\infty} x[k] \cdot h[n-k] \tag{9}$$

A half band low-pass filter removes all frequencies that are above half of the highest frequency in the signal. For example, if a signal has a maximum of 1000 Hz component, then half band low-pass filtering removes all the frequencies above 500 Hz. However, it should always be remembered that the unit of frequency for discrete time signals is radians.

After passing the signal through a half band low-pass filter, half of the samples can be eliminated according to the Nyquist's rule. Simply discarding every other sample will subsample the signal by two, and the signal will then have half the number of points. The scale of the signal is now doubled. Note that the low-pass filtering removes the high frequency information but leaves the scale unchanged. Only the sub-sampling process changes the scale. Resolution, on the other hand, is related to the amount of information in the signal, and therefore, it is affected by the filtering operations. Half band low-pass filtering removes half of the frequencies, which can be interpreted as losing half of the information. Therefore, the resolution is halved after the filtering operation. Note, however, the sub-sampling operation after filtering does not affect the resolution, since removing half of the spectral components from the signal makes half the number of samples redundant anyway. Half of the samples can be discarded without any loss of information.

This procedure can mathematically be expressed as [2]:

$$y[n] = \sum_{k=-\infty}^{\infty} h[k] \cdot x[n-k] \tag{10}$$

The decomposition of the signal into different frequency bands is simply obtained by successive high-pass and low-pass filtering of the time domain signal. The original signal $x[n]$ is first passed through a half band high-pass filter $g[n]$ and a low-pass filter $h[n]$. After the filtering, half of the samples can be eliminated according to the Nyquist's rule, since the signal now has a highest frequency of $p/2$ radians instead of p. The signal can therefore be sub-sampled by 2, simply by discarding every other sample. This constitutes one level of decomposition and can mathematically be expressed as follows [2]:

$$y_{high}[k] = \sum_{n} x[n] \cdot g[2k-n] \tag{11}$$

$$y_{low}[k] = \sum_{n} x[n] \cdot h[2k-n] \tag{12}$$

where $y_{high}[k]$ and $y_{low}[k]$ are the outputs of the high-pass and low-pass filters, respectively, after sub-sampling by 2.

3. Wavelets theory advantage

In [12], an application of WT and its advantages compared to Fourier transform is presented. One of the main advantages of wavelets is that they offer a

simultaneous localization in time and frequency domain. The second main advantage of wavelets is that, using fast wavelet transform, it is computationally very fast. Wavelets have the great advantage of being able to separate the fine details in a signal. Very small wavelets can be used to isolate very fine details in a signal, while very large wavelets can identify coarse details. A wavelet transform can be used to decompose a signal into component wavelets. In wavelet theory, it is often possible to obtain a good approximation of the given function *f* by using only a few coefficients, which is a great achievement when compared to Fourier transform. Wavelet theory is capable of revealing aspects of data that other signal analysis techniques miss like trends, breakdown points, and discontinuities in higher derivatives and self-similarity. It can often compress or de-noise a signal without appreciable degradation [12].

The Fourier transform shows up in a remarkable number of areas outside classic signal processing. Even taking this into account, we think that it is safe to say that the mathematics of wavelets is much larger than that of the Fourier transform. In fact, the mathematics of wavelets encompasses the Fourier transform. The size of wavelet theory is matched by the size of the application area. Initial wavelet applications involved signal processing and filtering. However, wavelets have been applied in many other areas including nonlinear regression and compression. An offshoot of wavelet compression allows the amount of determinism in a time series to be estimated [12].

4. Wavelets transform application in electric power system

Refs. [1, 13, 14] conducted studies related to this chapter. These authors also present a literature review on the application of WT in power electrical systems.

By means of the bibliographic review, it is possible to highlight certain topics of interest for researchers:

- Power quality

- Partial discharges

- Transient in electrical systems

- Power system protection

- Load forecasting

- Power system measurement

Figure 3 shows the percentage of publications in each area. The areas in which more works have been developed are the power quality and protection field. The next section presents a general description of wavelet application in the selected areas of power systems. There are more works in these areas; however, no details will be entered due to space issues and that the approach to the topic used WT is similar.

4.1 Partial discharges

Partial discharges are difficult to detect because of their short duration, high frequency, and low amplitude. However, the use of WT can not only detect them
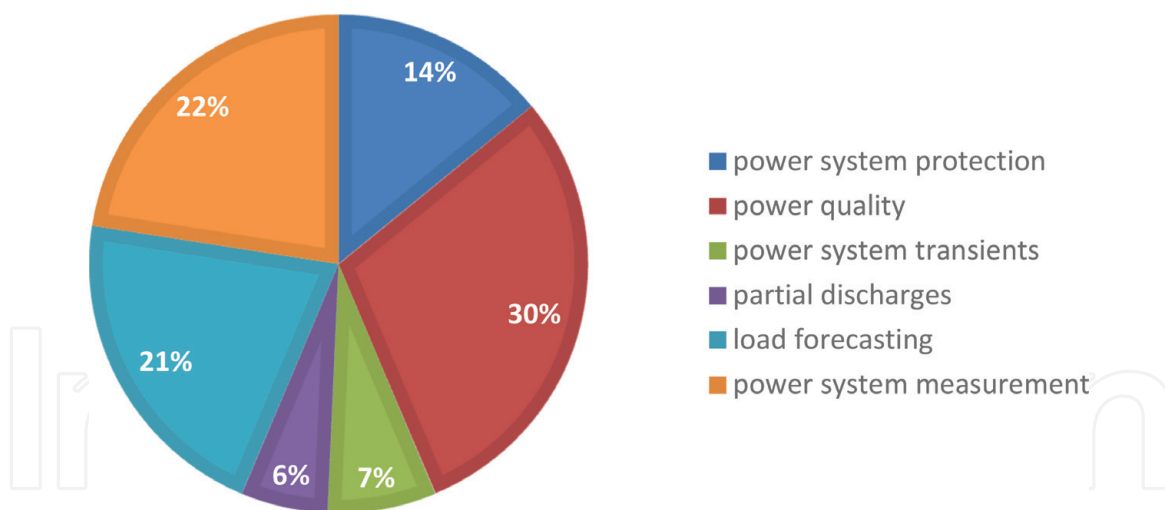
Figure 3.
Wavelet publication percentage in different power system areas.

but also isolate them by frequency bands for their study, performing a multi-resolution analysis. An important study is the filtering of noise in PD signals. In this sense, [15, 16] propose the recognition and categorization of PDs, for the study of transformer failures.

In [15], an adaptive filter is used to obtain PD without noise or interference for online studies. In [16], it is posed by means of a sophisticated equipment to obtain the currents and through WT to filter the PD and to be able to carry out its later study. If we follow the line of online monitoring, it can be seen in [17] that using a high-frequency transducer, the PD can be extracted to obtain analysis in transformers in service. We talked about how to get them and how to remove the noise in the signals, we just need to locate them. Ref. [18] proposes a PD injection method in preestablished nodes to obtain the plant model to measure at separate points.

4.2 Transient in electrical system

This section could be assembled considering different places of application of the WT, from generation to service transformers. In the generation, [19] shows us a study in the transients of the generation turbines where they perform an exhaustive analysis using a wavelet neural network to obtain the output values to adjust the turbine and obtain a correct operation.

Works [20–22] propose the use of WT for applications in high voltage lines (EHV) and the power system. In [20], WT used for the study of the electric field in the conductors can obtain the waveform of the current and voltage that facilitates the study of faults with which a filter for the study of harmonics can be designed. In [21], using the entropy energy, it is possible to obtain parameters of systems that change with certain sensitivity and design a protection that can reduce the capacitive effects in the bars and in the high-frequency traps. Ref. [22] proposes to use several scales of different frequencies to decompose the harmonics for the detection, localization, and segmentation of them. With this, we can estimate the energy and overvoltage caused and discern between impulsive and oscillatory transients. Ref. [23] presents an analysis on which is the best wavelet mother for the measurement of harmonics in electrical systems. Ref. [24] proposes an empirical wavelet transform for harmonic detector under dynamism conditions of the system. Ref. [25] presents a method for detecting and classifying faults in transmission lines by combining DWT and neural networks.

Finally, the characteristic impedance of a transformer can be obtained through its transient response [26]. With this, we can easily make a verification of the state of the transformer using the WT coefficients.

4.3 Power system protection

In the search for shorter downtimes and the maximization of the life time of the energy system equipment, it repeats itself to increasingly finer methods for analysis. In the recent years, we have begun to analyze the protections of voltage transformers (TT) and current transformers (CT) by WT [27]. This was done previously in the use of the Fourier Transform (FFT) and the current protections of the internal fault current. Refs. [28–31] study the differentiation of these currents by theoretical methods. This means that the test in the field is not done but the results of the simulations give positive results, an exception of [31] where the methods are applied to a test TT. For the development of differential protections, [30, 32–34] analyze the transients and extract the predominant signal from the internal fault; the method has been tested with different faults and an efficient algorithm for online analysis has been obtained. In [33–41], WT is used for fault diagnostic and transient event identification in transformer operation.

There has been a great effort in different works to evaluate the different mother wavelet. Thus, [33, 34] present a comprehensive analysis involving an important number of wavelets to prove the efficiency in power transformer protection.

Another important part is between disruptive currents and fault currents in the earth, where the results were analyzed with computer programs [42, 43].

The bus zone protection scheme is considered for the detection of transient current in [44]. In the electric machine area, [45] proposed the use of the WT for fault diagnostic using current signal. The transmission line fault detection with WT in the presence of wind power generation is studied in [46, 47] approach, a study on fault detection in compensated transmission line (TCSC technology). In [48], wavelet analysis is used for fault detection in hybrid energy source.

4.4 Power quality

With the increase of the use of electronic equipment, it has become a necessity to study the quality of energy. The loads, having a stationary or non-stationary state, are no longer easily analyzed, so we resort to mathematical tools capable of classifying and characterizing these states. In this network, transient disturbance occurring in the network can be classified as voltage drops, voltage increases, momentary interruptions, harmonics, and transients, among others.

The main topics of study are the harmonics; these are present in the waves and are common to see in the electrical networks, and so the first step would be to identify them and isolate their behavior in order to eliminate these disturbances. Ref. [49–51], using WPT, perform a method in which the fundamental harmonic and higher order harmonics can be extracted, which is a method applicable to energy networks for monitoring them. For the same application [52], they have formulated using CWT, an algorithm used to identify the variations of frequency, harmonics, sub harmonics, and inter harmonics.

A practical application of the CWT is the real-time monitoring of voltage and current signals for the rapid detection and elimination of transient events that may worsen the quality of the electric service. Previously, the first subject of study in terms of energy quality was established, but this is only a small part of the faults found in the energy system. Faults must be identified in order to perform an efficient analysis and be able to act on them as soon as they occur.

In the papers presented in [42, 53–61], their main theme coincides and is to classify the faults that can be obtained from the analysis of the voltage wave through WT. Broadly speaking, it can be highlighted that they obtain the range of frequency, amplitude, time of action, waveform, etc. Although their methods differ in the application of the WT, the essence of the study is the same. One step beyond performing fault classification studies is to achieve a practical application for the in-service power network. In [62], it implements a DSP for the continuous study of energy. Ref. [63] uses an FPGA for continuous analysis of system disturbances. In [42], through a wavelet neural network and a self-organizing arrangement system, it obtains automatic equipment for the detection and suppression of multiple faults in the network.

Other areas of power quality are studied using the WT characteristic. In [64, 65], the power quality events are characterized and classified using wavelet transformation. The power quality disturbance detection in grid-connected wind energy system is development with wavelet and S-transform. In [66] is presented a comparative analysis of power quality event using wavelet for real time implementation and [67] tested measurement system to electric energy quality together digital signal processor.

The voltage variation is a usual problem in electric system which affects the quality power. Ref. [68] addresses this problem from distributed energy resources.

4.5 Load forecasting

This analysis is the key to a correct distribution of energy in the electricity grid. Basically, a prediction is made of how the loads will behave in short- or medium-term horizons. In this sense, the behavior of the load can refer to disconnections of large equipment, circuits that have transients in start, devices with low power factor, etc. This analysis can be done through WT and some complement to make the prediction.

We have cases like [69] that use a linear correlation for the load forecast. This is a more conventional method compared to the other two. In recent years, there is much talk of NN and machine learning to such a point that [70–79] use machine learning to train a WT-based neural network. The load forecasting in the short-term used WT theory is presented in [80, 81]. Thus, it can be observed that this application is widely studied.

From another point of view, we have a prediction system based on fuzzy logic in [82], and finally, in the current year, a neural network with fuzzy logic based on WT is launched for the short-term study, which may be the foot to what is coming to the future.

4.6 Power system measurements

Mainly, the WT is used in power systems and RMS measurements, both voltage and current. As for the measurement systems of active, reactive, or apparent power, a decomposition and classification of those waves present in the fundamental are achieved. In [83], it analyzes how the variations of the loads influence the tension, as much as it falls as in descents or in blinking. Then in [23], it approximates the RMS value of the harmonics present in the voltage and current waves by means of statistics; with this purpose, the improvement of harmonic detection and measurement systems is sought. In [84], a method for determination and correction of measurement anomaly based in WT is proposed.

5. Conclusion

Wavelet transform is a powerful signal processing tool that transforms a time-domain waveform into time-frequency domain and estimates the signal in the time and frequency domains simultaneously. So, it is mostly used in electric power systems analysis.

This chapter carries out an approach on the WT application in EPS in order to facilitate the search for information in this area. Therefore, a classification of the different fields of EPS applications was made. A summary description for each WT application area is presented with the main objective of showing the applications of this tool in the resolution of typical problems of the energy system.

The works analyzed show that the Daubechies family was used in most of the applications in power systems analysis, especially in protection area. However, the type of mother wavelet and the decomposition level number may be changed and therefore may not be generalized to all the cases.

The use of WT together with artificial intelligence tools (neural networks, fuzzy logic, genetic algorithms, etc.) was presented as a promising methodology to diagnose faults in electrical systems.

Most of the works analyzed results of computational simulations. It is expected that in the short term, the functionality of WT it is will comprobed in real situations.

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