Voltage Sag Detection through Wavelet Energy Coefficient

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***Abstract*—In this work, a new voltage sag detection method based on wavelet transform is developed. Voltage sag detection algorithms, so far have provided their efficiency and computational ability. Several windowing techniques take long durations for disturbance detection. Due to increasing power quality standards new high quality performance disturbance detection techniques are necessary to obtain high power quality standard. Also research has been carried out for the last decade to isolate voltage sag detection form other voltage disturbances. In this paper a novel approach of wavelet transform has been carried out to detect voltage sag duration and magnitude. Results show that, the new approach provides very accurate and satisfactory voltage sag detection.**

***Index Terms*—Power quality, voltage sag, wavelet transform, dyadic analysis.**

I. Introduction

Recent power quality (PQ) has become one of the most important issues in modern power industries. The origin of events affected quality of power is mainly electromagnetic transients, which are common phenomena in every electric power systems. A number of transient's causes can be identified: planned switching action in distribution and transmission system, lightning strokes, switching of end user equipments and self clearing faults or faults cleared through current limiting fuses. The increased use of nonlinear loads such as power electronics based devices, adjustable speed drives (ASD), uninterrupted power supplies (UPS), personal computers (PCs) and electric arc furnaces (EAFs) in the electric power system over the last decades; create distorted (non-sinusoidal) current even when supplied with purely sinusoidal voltage. These distorted currents cause voltage and current distortion throughout the system which deteriorates the quality of the electric power that is supplied to consumers owing sensitive devices to voltage and/or current variations. Recent advancement in signal analysis have led to the development of new methods for characterization and identifying various power quality problems. Today one of the most power quality problems is voltage sag [1]. Voltage sags are the 80% common problems for power quality issues. Voltage sag is a short time (10ms to 1 min) event during which a reduction in RMS voltage magnitude occurs [2]. Despite of a short duration, a small deviation from the rated voltage can result in lots of cost effective disturbances. Because of the effect of voltage sag, many times halt the production process and even for small duration sag (1 second) can several hours for restoration. For many power system equipments, the effect of voltage sag is the same as the effect of an interruption. The number of voltage sag is about 80 to 90 per year, where the number of interruptions is on average around one per year. So the consequences due to voltage sags are more significant than interruptions [2]. Voltage sag often sets only by two parameters, magnitude and duration [3]. Wavelet is a power full tool gives full information about duration and localization of voltage sag [4]. Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. By time series analysis of wavelet transform one can get the actual localization and variance of signal for a particular time [5].

Several studies have been done to show the identification and localization of power quality problems through wavelet transform where voltage and current waveforms are taken as sampled values as per Perseval's theorem [6]-[10].

This paper presents a new algorithm to detect the starting and ending points and the magnitude of the voltage sag. The discreted wavelet transform (DWT) is used to detect fast changes in the voltage signals, which allows time localization of differences frequency components of a signal with different frequency wavelets. A FPGA based system is used to test proposed algorithm in real time with ALTERA FPGA.

II. From Fourier Analysis to Wavelet

Drawbacks of signal processing techniques used in power quality disturbances:

1) RMS is major tool used in signal processing techniques. The RMS of signal is not an analysis technique but it gives some basic information about an electrical system. The main disadvantages of this algorithm are its dependence on size of sample window [11]. As a result of small window RMS parameter becomes less relevant and loses meaning of mean value of power.
2) Another most widely used tool in signal processing is Fourier analysis. It helps in analysis of harmonics and essential tool for filter design. The DFT and FFT are essential tools for estimation of fundamental amplitude of signal. The DFT importance in area of frequency (spectrum) analysis as it takes a discrete signal in time domain and transforms that signal into the discrete frequency domain representation. A FFT used for transformation of signal from time domain to frequency domain. Speed is main advantage of this technique and also high speed calculations.
3) In time frequency signal processing, a filter banks is special quadric time frequency distortion (TFD) that represents signal in joint time frequency domain. This technique used for estimation of specific sub-band components.
4) Another special type of filter is Kalman Filter. Their

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solutions are based on set of state space equations. These are used for real time tracking harmonics as proposed in [12], frequency estimation under distorted signal [13], estimating voltage and current parameters on power system protection and parameter of transient [14].

5) In 1994, use of wavelets was proposed which led to study of non stationary harmonic distortion in power systems. This technique decomposes signals in different frequency sub-bands and characteristics can be studied separately.
6) The STFT mainly used in power quality analysis and called as sliding window version of FFT. The advantage of STFT is its ability to give the harmonic content of signal at every time period specified by defined window.

III. Wavelet Transformation Technique

The wavelet transform is representation of signal as sum of wavelets at different location and scales. The main advantage of wavelet transform is its varying length window. The wavelet transform can be classified in three different ways. The continuous wavelet Transform possesses ability to construct a time-frequency representation of signal that offers very good time and frequency realization. The second type of transform known as wavelet series which maps function of continuous variables into sequence of coefficients. The third is Discrete wavelet in which wavelets discretely sampled and has advantage of temporal resolution as it captures both frequency and location information.

The continuous wavelet transform was developed to overcome resolution problem to short time Fourier transform. It is correlation between wavelets at different scales and signal with scale being used as measure of similarity. DWT are applied to discrete data sets and produce discrete outputs. The DWT is special case of wavelet transform that provides a compact representation of signal in time and frequency that can be computed efficiently. When compared to Fourier transform, wavelet can obtain both time and frequency information of signals while frequency information obtained by Fourier transform [3], [4]. The signal can be represented in terms of both the scaling and wavelet functions as follows:

$$f(t) = \sum_n Cj\,(n)\Phi(t-n) + \sum_n \sum_{J=0}^{J-1} dj\,(n)_2^{2j}\,\psi(2^j t - n) \quad (1)$$

where

c_j is the J level scaling coefficient,

d_j is the j level wavelet coefficient,

Φ (t) is the scaling function,

ψ (t) is wavelet function,

J is the highest level of wavelet transform,

t is time.

For practical applications and for efficiency reasons one prefers continuously differentiable function with compact support as mother wavelet. Wavelet theory can be expressed by continuous wavelet transformation as,

$$\text{CWT } x\,(a, b) = \text{W}_x\,(a, b) = \int_{-\infty}^{\infty} x(t)\psi_{a,b}(t)dt \quad (2)$$

where Ψ_a, a (scale) and b (translation) are real numbers. The discretization of this equation is necessary for practical application. For Discrete time system,

$$\text{DWT}_{\psi}\, x\,(m, n) = \int_{-\infty}^{\infty} x(t)\psi_{m,n}(t)dt \quad (3)$$

$$\psi_{m,n}(t) = a_0^{\frac{-m}{2}}\,\psi\left(\frac{t-n\,b_0 a_0^m}{a_0^m}\right) \quad (4)$$

where a = a_0^m and b = $nb_0a_0^m$

The DWT analysis can be performed using fast pyramidal algorithm related to multirate filter banks (See Fig. 1).

Various power quality disturbances for small scale signal decomposition can be detected by use of choice of analysis of mother wavelet. Daub 4 and Daub 6 wavelets are useful for fast and short transient disturbances. Daub 8 and 10 are suitable for slow and long transient disturbances. At scale 1, mother wavelet localized in time and oscillates more rapidly in short spam of time. As wavelet reaches higher scale analyzing wavelets become less localized in time and oscillations, so as a result of high scale signal decomposition, fast and short transient disturbances detected st lower scales and for high scales, slow and long transient disturbances will be detected.

Both time domain & frequency domain methods can be used to analyze vibration signals. The time domain refers to a display or analysis of the vibration data as a function of time. The frequency domain approach allows both the amplitude & phase spectrum to be an identified and are more useful for vibration analysis. The Fourier transform is a frequency domain approach which converts a continuous time signal into frequency domain. Fourier representation X (f) which is calculated by the Fourier transforms integral shown by:

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-i2\pi ft}\,dt \quad (5)$$

The disadvantage of frequency-domain analysis approach is that a significant amount of information (transients, non repetitive signal components) may be lost during the transformation process. This information is non retrievable unless a permanent record of the raw vibration signal has been made. The problem of Fourier transform is overcome up to some extent using Short Term Fourier Transform. STFT is simply the result of multiplying the time series by a short time window and performing a discrete Fourier transform. Mathematically for a signal, it is written as

$$\text{STFT}\{x(t)\} \equiv X(\tau,\omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-j\omega t}\,dt \quad (6)$$

For discrete signals, this transform is known as Short Term Discrete Fourier Transform (STDFT) expressed mathematically with signal $x[n]$& window $\omega[n]$ as

$$\text{STFT}\{x[n]\} \equiv X(m,\omega) = \sum_{n=-\infty}^{\infty} x[n]\omega[n-m]\,e^{-j\omega n} \quad (7)$$

Application of STFT have been used to for analyzing different vibration signals for different application but having problem that time resolution is same for all spectral components.

This problem is overcome by using the wavelet transform. It is a technique which allows the time-frequency place to be divided in a more flexible way such that a smaller time is user for higher frequencies & larger time is used for lower frequencies. It is calculated by convolving the wavelet with the original signal, multiply the shifted wavelet with the original signal, then sum the result to produce a single value. The continuous wavelet transform is defined as the convolution between the original signal *s* (*t*) and a wavelet $\Psi_{a,b}(t)$.

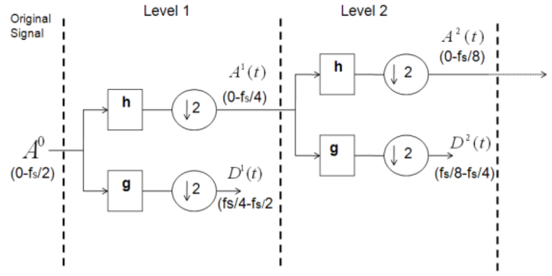

Fig. 1. Multi-resolution wavelet decomposition

$$W_{\Psi}(a,b) \;=\; \int_{-\infty}^{+\infty} S(t)\,\overline{\Psi}_{ab}\,(t)dt \tag{8}$$

where *s*(*t*) is the input signal; ‘*a*’ is the scaling factor; ‘*b*’ is the translation parameter; and Ψ(*t*) is called mother wavelet. The wavelet function is given by

$$\Psi_{a,b} \;=\; \frac{1}{\sqrt{a}}\,\Psi\left(\frac{t-b}{a}\right) \tag{9}$$

The Discrete Wavelet Transform (DWT) coefficients are usually sampled from the CWT on a dyadic grid parameters of translation $b = n\times2^m$ and scale $a = 2^m$ and is defined as,

$$\Psi_{m,n\,(t)} = \frac{1}{\sqrt{2^m}}\,\Psi\left(\frac{t-n2^m}{2^m}\right) \tag{10}$$

It is not strictly a time-frequency representation but rather a time-scale representation of the signal. WT can give a time-frequency analysis if the centre frequency of the wavelet is estimated for each scale.

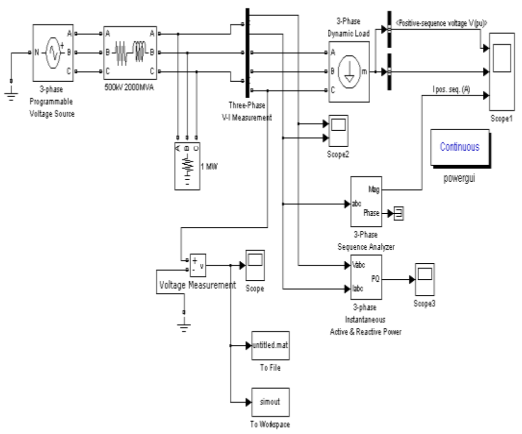

Fig. 2. Proposed simulations for voltage sag generation

IV. Proposed Simulation

A dynamic load is connected on a 500 kV, 60 Hz power network. The network is simulated (Fig. 2) by its Thevenin equivalent (voltage source behind a R-L impedance corresponding to a 3-phase short circuit level of 2000 MVA). The source internal voltage is modulated in order to simulate voltage variation during a power swing. As the dynamic load is a nonlinear model simulated by current sources, it cannot be connected to an inductive network (R-L in series). Therefore, a small resistive load (1 MW) has been added in parallel with the dynamic load. The dynamic load power is a function of its terminal positive-sequence voltage V open the dynamic load menu and notice that both exponents np and nq are set to 1 and that the specified minimum voltage Vmin is 0.7 Pu. It means that the load active power P and reactive power Q are defined by the following equations:

If $V > Vmin$

$$P = Po\times(V/Vo); \quad Q = Qo\times(V/Vo)$$

If $V < Vmin$

$$P = Po\times(V/Vo)\ \hat{}2; \quad Q = Qo\times(V/Vo)\ \hat{}2$$

In other words, as long as voltage is higher than 0.7 Pu, the load current is constant. When voltage falls below 0.7 Pu the load behaves as constant impedance. In order to demonstrate the variation of *P* and *Q* as function of voltage, the source internal voltage is controlled by the 3-Phase Programmable Voltage Source block. Open the source menu and notice that the specified type of amplitude variation is a sinusoidal modulation (Amplitude of the modulation = 0.5 Pu, Frequency of the modulation = 1 Hz). Therefore, the source positive-sequence voltage varies between 0.5 Pu and 1.5 Pu. The initial source voltage is 1 Pu. Modulation starts at = 0.2 s and stops after 1 cycle at t = 1.2s. A 3-Phase Sequence Analyzer block (from the Extras/Measurement library), is used to monitor the positive-sequence component of load current. Another block from the Extras/Measurement library is used to compute the load active and reactive powers.

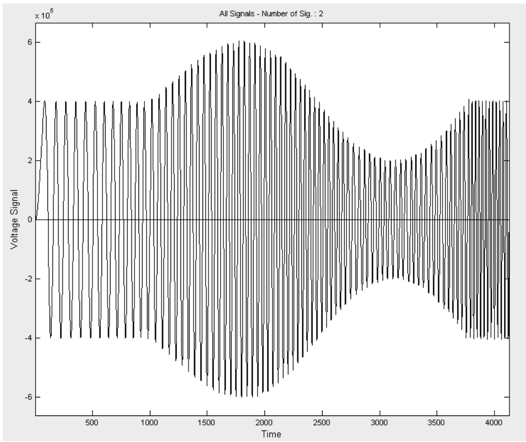

Fig. 3. Generated voltage signal

V. Multi Signal Decomposition and Results

One phase from this simulated system has been taken, Fig. 3 for further decompositition through Daubechies Db4.

Daubechies wavelet *N* = 4

For K equal to 0,1,2,3

$$S_j(0) = h(0)S_{j+1}(0) + h(1)S_{j+1}(1) + h(2)S_{j+1}(2) + h(3)S_{j+1}(3).$$
$$S_j(1) = h(0)S_{j+1}(2) + h(1)S_{j+1}(3) + h(2)S_{j+1}(4) + h(3)S_{j+1}(5).$$
$$S_j(2) = h(0)S_{j+1}(4) + h(1)S_{j+1}(5) + h(2)S_{j+1}(6) + h(3)S_{j+1}(7).$$
$$S_j(3) = h(0)S_{j+1}(6) + h(1)S_{j+1}(7) + h(2)S_{j+1}(8) + h(3)S_{j+1}(9).$$

and

$$d_j(0) = g(0)S_{j+1}(0) + g(1)S_{j+1}(1) + g(2)S_{j+1}(2) + g(3)S_{j+1}(3).$$

$$d_j(1) = g(0)S_{j+1}(2) + g(1)S_{j+1}(3) + g(2)S_{j+1}(4) + g(3)S_{j+1}(5).$$
$$d_j(2) = g(0)S_{j+1}(4) + g(1)S_{j+1}(5) + g(2)S_{j+1}(6) + g(3)S_{j+1}(7).$$
$$d_j(3) = g(0)S_{j+1}(6) + g(1)S_{j+1}(7) + g(2)S_{j+1}(8) + g(3)S_{j+1}(9).$$

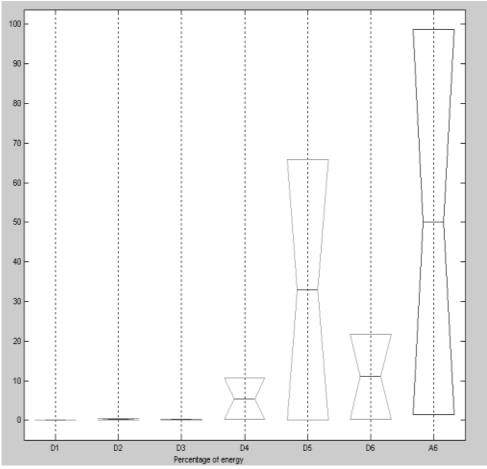

Fig. 4. Energy level of decomposed signal

Voltage signal has been decomposed up to level 6th and 5th decomposition coefficient gives the highest level of energy Fig. 4 and Fig. 5.

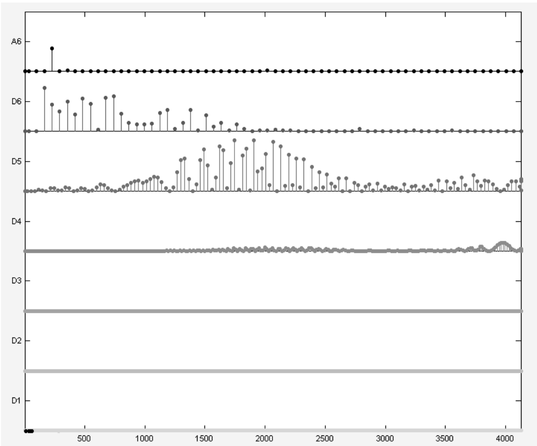

Fig. 5. Daubechies coefficient for signal decomposition

VI. Conclusion

In this paper a new method based on wavelet decomposed energy has been proposed for the detection of voltage sag in power system. The location of nonlinear load and disturbance in signal and harmonic pollutions can be detected through coefficient. The presence of voltage sag in the system can be detected from the magnitude of detail power at the higher level of decomposition. Simulation results show that the proposed method can be give useful indications about the location of dominated voltage sag, upstream or downstream point of wavelet coefficients.

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