Automatic Detection and Positioning of Power Quallity Disturbances using a Discrete Wavelet Transform

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Abstract: Voltage sag is one of the crucial problems of power quality that affects high power devices. It may cause sensitive devices to malfunction and may increase the failure in power systems. An appropriate algorithm for identifying and positioning the voltage sag disorder is suggested in this study. This procedure identifies the voltage sag online and automatically and can identify the exact time and position of this damaging circumstance. This method operates based on the analysis of wavelets and search blocks, and its procedure uses the discrete wavelet transform (DWT) to identify the changes in voltage signals with respect to the non-fault state. Simulation results on a nine-bus IEEE network confirm the validity and accuracy of the proposed method.
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1. Introduction

Voltage sag is an unexpected reduction of voltage in a region of an electric system that, after a short time (from a half-cycle to a few seconds), returns to its original value. Generally speaking, during these situations, the voltages at the power frequency reduce to 0.1 - 0.9 (per unit) with a duration from 0.5 cycles to 1 minute [1].

Voltage sag is one of the most crucial problems because most devices in industrial plants are very sensitive to voltage reduction. Faults in transmission or distribution systems (like single phase to ground fault or two phase short circuits) are major causes of voltage dips in electrical systems. High frequency voltage sag might lead to damage to high power devices.

Voltage drop is one of the most important and most frequent power quality disorders in electrical systems. Apparatuses like chillers control units, laboratory and measuring devices, and DC or AC drives used in modern industrial factories are very sensitive to this phenomenon. Therefore, when a voltage dip occurs, they will not function properly. Voltage sags with 85% to 90% amplitude with respect to the nominal voltage amplitude with duration of 16 milliseconds can immediately interrupt important industrial processes [2].

Numerous researchers have worked on voltage sag and examined its general features and principles [3-5]. Some of them surveyed various retrievals (compensators), including SVCs and STATCOMs [6-8]. They also presented some methods for positioning faults and estimating the amplitude or frequency of voltage sags [9-13]. Of course, due to the importance of large loads, many of these studies concentrated on high power consumers to solve their problems.

The first step in recovering the power quality disorders in a power system and improving the form of voltage waves is using an appropriate and effective method to identify these disorders. Various methods can be used to recognise the distorted signals, and each method is based on a specific algorithm. These methods may include Fourier transforms (FT), Wavelet transforms (WT), abc-dq0 transforms, and neural network approaches. For instance, one of the traditional methods for identifying the voltage dip disorder is measuring the effective value (rms) of the voltage waveform and comparing it with thresholds. For example, when the effective value of the voltage is between 0.1 and 0.9 (per unit), the voltage sag disorder is acknowledged. However, this system is simple and inexpensive and has some inadequacies that may limit its uses. As an example, selecting voltage thresholds for such systems that work properly in all conditions is very sensitive because obtaining non-suitable amounts can cause the system to identify no faults in the fault condition or to categorise a non-fault signal as a fault [1].

Thus, the search to find methods that are more efficient has continued. Recognising the wavelet transform and its unique features in the analysis of non-stationary signals (most fault signals in the power systems are non-stationary) with different time and frequency resolutions is a new approach in power quality research.

With advancements in power quality observing devices, power quality raw data has increased. Therefore, the analysis of faults can be done only by an automatic procedure. The authors of this paper tried to propose a novel method. This method identifies the exact time and position of the voltage sag disorder, and, in addition, it works online and automatically. The suggested method operates based on the analysis of wavelets and compares blocks for classifying faults. The advantage of this method over the others is using a search block for identifying faults instead of a complicated system like a neural network.

2. Main Causes of Voltage SAG Disturbance

Generally, voltage sag disturbances occur due to short circuit faults in distribution and transmission systems. Starting large motors, connecting large loads and switching capacitor banks can also be causes of voltage sag. Lightening is the major cause of most faults in aerial power lines. It can cause faults by direct collision with the phase or earth lines (or the tower body). Most of the equipment in a power system are located outdoors, and they can be easily threatened by lightening, especially in rainy seasons or regions where lightening frequently occurs. Because these faults are often temporary, fortunately, they will be removed automatically after a few seconds. In addition, the operation of protecting devices may affect the specifications of voltage sag trouble [14].

Faults in transmission systems can have more influence on various devices than faults in the distribution system. When a fault occurs in a transmission system, the voltage sag may affect all the consumers, even a hundred kilometres away from the position of the fault. The effects of faults on transmission systems are mentioned in detail in [15].

Generally, voltage sag is identified by magnitude (amplitude of voltage during the disorder), duration (interval in which the effective value is less than a threshold value, typically 0.9 pu or less), and frequency. Among these three specifications of voltage sag, the rate (or frequency) of voltage dip occurrence can cause greater damage to many devices.

3. Discrete Wavelet Transform

The fast Fourier transform (FFT) is the perfect tool for determining the frequency components in a waveform. A drawback of the FFT is that frequency components can only be extracted from the complete period of a waveform. The frequency components (harmonics) are obtained from an average over the whole period of the signal. Thus, it is not an appropriate tool for a non-stationary signal such as fault signals in power systems. These types of problems associated with FFT can be resolved by using wavelet analysis. Consequently, wavelet analysis has recently been considered for analysis of non-stationary signals. It provides a powerful tool to characterise the local (time dependent) features of a signal.

Unlike the Fourier transform, where the function used as the basis of decomposition is always a sinusoidal waveform, other basis functions can be selected as the wavelet according to the features of the original signal.

The wavelet transform is defined as transforming signals to a short wave or set of short waves. Thus, the decomposed signals (wavelets) have short duration with limited energy, and their integral over their time interval equals zero [16]. Fig. 1 compares a wavelet with a sinusoidal waveform [17, 18]. As this figure shows, the energy of the sinusoidal waveform is unrestricted and can be between minus and plus infinity.

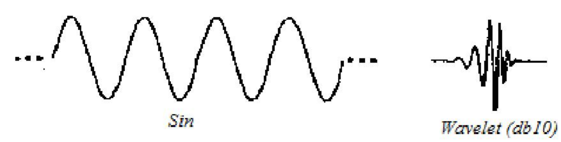

Figure 1. Comparison of wavelet and pure sinusoidal waveforms [17]

The signal in DWT is passed through a series of high-pass filters to analyse the high frequencies and through a series of low-pass filters to analyse the low frequencies. In DWT, the signals can be characterised by approximations and details. The detail at level m is defined as:

$$D_m = \sum_{m \in Z} a_{m,n} \psi_{m,n}(t) \qquad (1)$$

Where Z is the set of positive integers and ψ is the basis (mother) wavelet. The approximation at level m is defined as:

$$A_M = \sum_{m > M} D_m \qquad (2)$$

Finally, the original signal f (t) can be represented as:

$$f(t) = A_M + \sum_{m \le M} D_m \qquad (3)$$

As can be seen from these equations, by using the digital filter banks, the analysed signal can be disintegrated in several frequency levels [19, 20].

There are various wavelet families like Daubechies (dbN), Haar, and biorthogonal wavelets. In this study, a main db4 wavelet (which is from the Daubechies family) is used [21, 22]. DWT disintegrates the original signal into high-frequency and low-frequency components (Fig. 2). In the DWT, these components are called detail coefficients and approximate coefficients. High-scale approximate coefficients are low-frequency components of the original signal, whereas low-scale detail coefficients are high frequency components of it. Lower-detail levels show more jumps in the original signal because they include high-frequency parts.

In this usage, the first level of the details is used for immediate identification of any disorder and occurrence time of the phenomenon. This output can be used as a trigger signal that identifies the existence of disorder in the system.

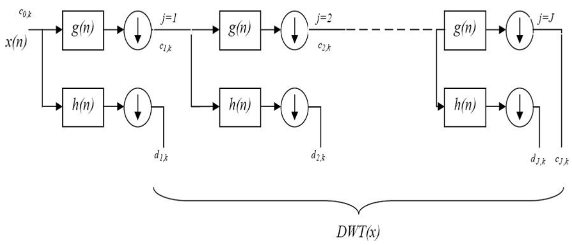

Figure 2. Obtaining the discrete time wavelet [22]

On the other hand, Equation (4) presents the relation between the energy of the original signal (f (t)) and the power of each component and the coefficients of wavelet transform.

$$E = \int | f(t)|^2 dt = \sum_{k=-\infty}^{+\infty} | c(k)|^2 + \sum_{j=0}^{+\infty} \sum_{k=\infty}^{+\infty} | d_j(k)|^2 \qquad (4)$$

Equation (4) demonstrates that the energy of the disordered signal is shared between different levels of its decomposed components. The amount of energy of each level depends on the types of power quality disorder occurring in the system.

In statistics applications, the standard deviation (Std) of a collection is calculated as:

$$Std = \sqrt{\sum_{i=1}^{k} (a_i - a_m)^2} \qquad (5)$$

In which am is the average value of ai , (i = 1,2,3,...,k) and Std indicates the standard deviation of samples (ai) from the average value (am).

By comparing Equations (4) and (5), the square of the coefficients should be added to calculate the energy in each sub band. Therefore, if an average value of a level is zero (in most cases it is zero or near zero), the Std of that level almost shows the energy of it. Thus, Std in different levels can be used for the classification of different power quality disorders.

4. Algorithim of Detection and Positioning of Voltage SAG Disturbance

The purpose of this study is to develop an automatic system that receives the fault signal as an input and automatically identifies the voltage sag and its position in the power system. In the proposed method, first, the input signal is sampled by a specific sampling frequency. To analyse any voltage sag phenomenon, some disorders are simulated and used. Five types of faults and events are investigated in this research: single phase to ground, three phases to ground, two phases to ground, two phase short circuit, and starting a large induction motor. A nine-bus IEEE standard network is used for analysis and simulation. The simplified single line diagram of the simulated system is shown in Fig. 3. This system is simulated by a combination of block sets of MATLAB/Simulink software. The Signal Processing block set is used for modelling of the suggested algorithm, and the Sim Power Systems block set is used for modelling of the nine-bus IEEE system. At first, features of the DWT are extracted, and, then, the system of detection and positioning of the voltage sag disturbance should be started.

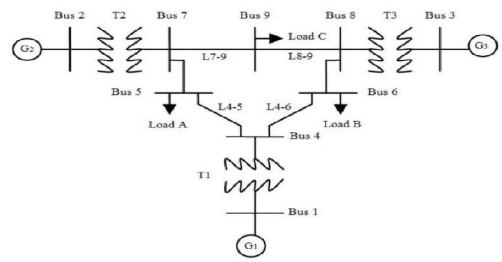

Figure 3. Standard nine-bus IEEE system

4.1 DWT Features Extraction

Simulation of the above mentioned faults and events identifies different and specific patterns for each of the voltage sag disorders. Therefore, recognition of these patterns in every disorder situation is a principal and essential step. A special technique is used to distinguish patterns. Firstly, in this procedure, one fault signal and one non-fault signal are analysed in ten levels using the discrete wavelet transform. Then, the Std of the energy in all decomposed levels and the Std of the differences between the details of fault signal and details of non-fault signal are calculated. The energy Std of the difference is not equal for any kind of disorder. Considering this specific property, an appropriate feature can be achieved for each disorder and can be used for pattern recognition.

Figures 4.a and 4.b show the Std curves of the normal (non-fault) signal energy and the disordered signal energy. By comparing these two curves, the energy of the disordered signal in the eighth level (which includes the main component of the signal) is lower than the energy of the normal signal. Figures 4.c to 4.i show energy Std difference curves for seven kinds of simulated faults and events. As can be seen from these figures, each fault or event has its specific feature and can be used for that pattern recognition.

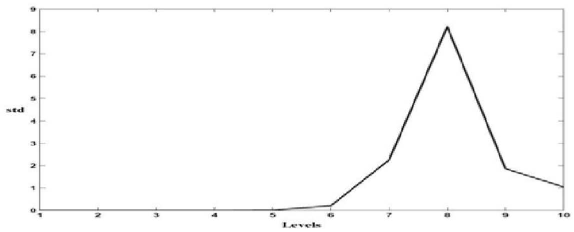

Figure 4.a. Standard deviation energy difference curve of normal signal

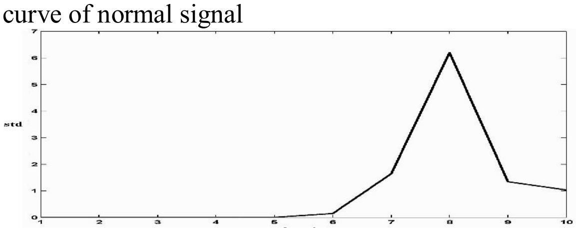

Figure 4.b. Standard deviation energy curve voltage sag disturbance

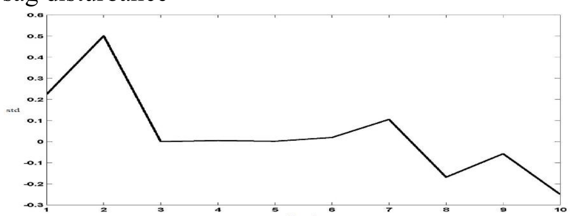

Figure 4.c. Standard deviation energy difference curve of oscillatory transient disturbance

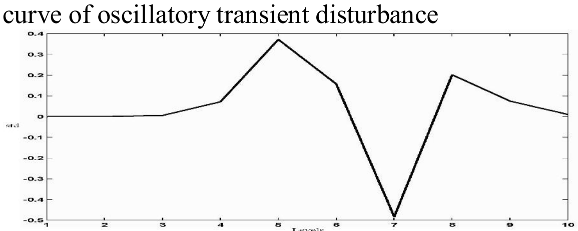

Figure 4.d. Standard deviation energy difference curve of voltage notch disturbance

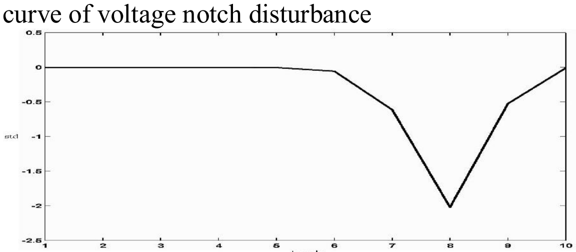

Figure 4.e. Standard deviation energy difference curve voltage sag disturbance

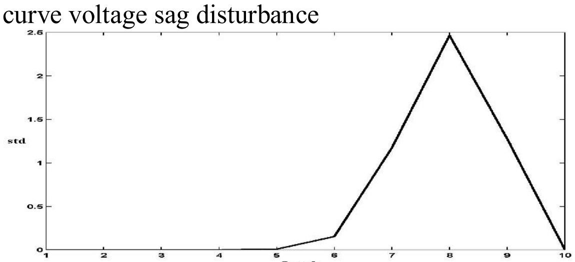

Figure 4.f. Standard deviation energy difference curve of voltage swell disturbance

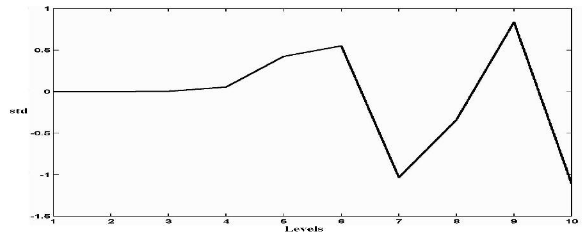

Figure 4.g. Standard deviation energy difference curve of harmonic disturbance

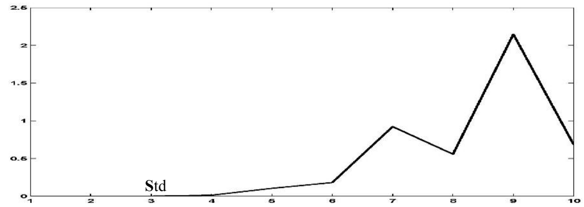

Figure 4.h. Standard deviation energy difference curve of flicker disturbance

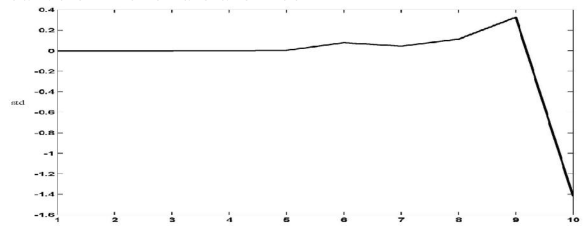

Figure 4.i. Standard deviation energy difference curve of impact transient disturbance

4.2. System of Detection and Positioning of Voltage SAG Disturbance

A novel technique is used for automatic and on-line identification and positioning of voltage sag disturbances. Fig. 5 shows the algorithm of this method that uses wavelet transforms. This algorithm gives the exact time and position of the disorder in addition to the voltage sag type.

In this algorithm, a monitoring device and a pattern synchroniser (that identifies type and time and estimates the position of the disorder) are used for each bus of the system to identify and locate the voltage sag disorder (based on the pattern of Std difference of energy levels in Figures 4.c to 4.i).

In Fig. 5, the processing system receives both normal and disordered signals online as inputs, analyses both signals into ten levels using a discrete wavelet transform, (vector D1 is for the normal signal, and vector D2 is for disordered signal) and then calculates the differences between these levels (vector A). If one of the components of vector A is not equal to zero, the system will announce the disorder and show its time.

The procedure is clear in Figures 6.a and 6.b, which show the wavelet analysis of the fault and non-fault signals in the 12 levels. It may increase the accuracy and speed of the system's response and also decrease the failures as a result of reducing extra processes. Now, the "identifying type, time, and estimating the position of disorder" block starts to process. Any device that observes the fault earlier has the priority over the others to process the fault signal. Thus, the two monitoring device, which observes the fault earlier, will locate the disorder. Then the place of fault occurrence will be estimated using the two times recorded by the two monitoring devices.

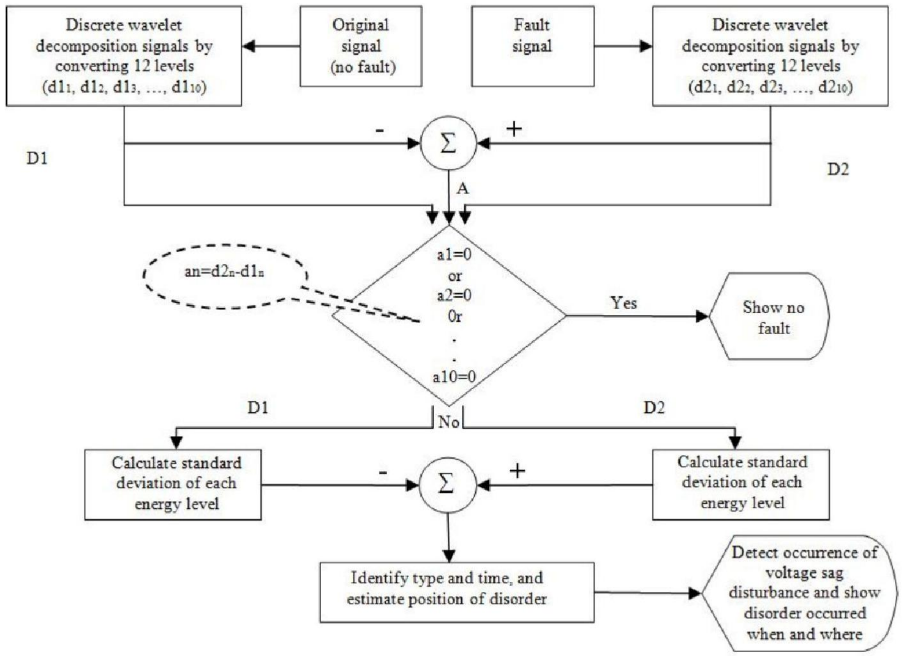

Figure 5. Automatic detection and classification algorithm of the power quality disturbance using the wavelet transform

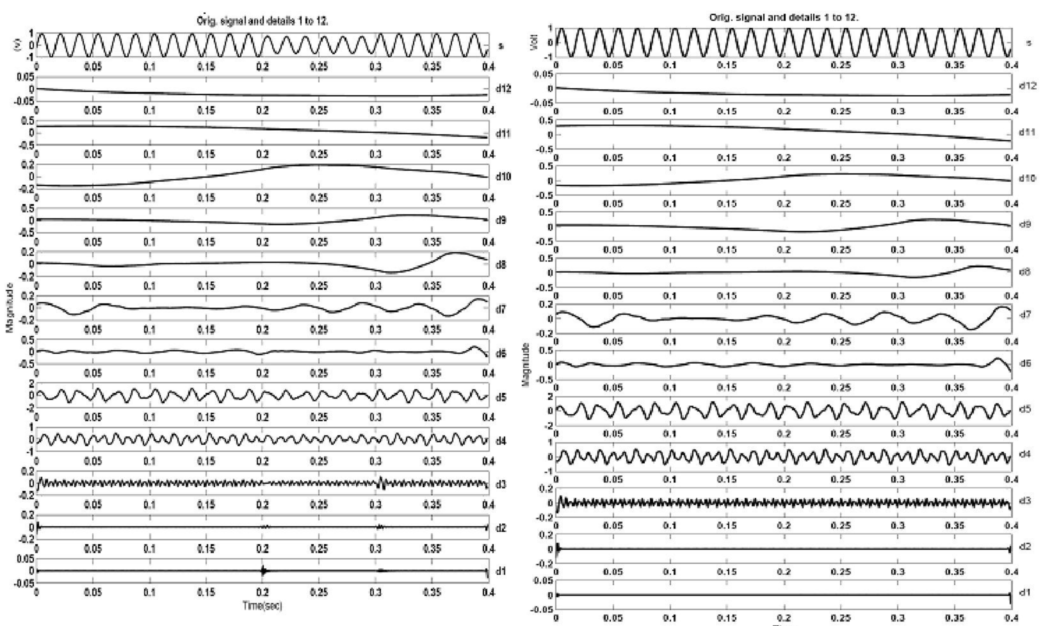

Figure 6. Discrete wavelet decomposition levels of a) a voltage signal containing voltage sag due to fault, b) the non-fault voltage signal

The synchronizer section starts to work simultaneously with other parts in this block. The pattern synchronizer section will work according to the maxima and minima (or their arrangement) of differences in energy Std of different levels. The task of this part is to declare the existence of voltage sag.

Sampling frequency in this method is very important, and, when it changes, new patterns for fault and non-fault signals must be collected. These signals must be decomposed, and the Std differences of fault signal energy levels and normal signal energy levels will be calculated again.

The proposed system can be used for positioning of voltage sag disorder compensators at suitable locations. This technique allows us to build a standard device for fast and accurate online identification and automatic positioning of voltage sag. The development of this method can reduce the power quality difficulties in power systems. It may help a system return to its primary condition (before the occurrence of the disorder) with minimum cost.

Various faults were put in different parts of the system to examine the accuracy of the algorithm and the designed system (including switching capacitors, starting large inductive motors, and several faults). The identifying system correctly declared the occurrence, type, and location of the disorders in all cases.

6. Conclusions

The technique applied in this study uses a wavelet transform to identify the type and location of voltage sag disorders. This method allows us to build a standard device for a fast, accurate online identification and automatic positioning of voltage sag. The only shortcoming of this method is its dependence on the sampling frequency. However, it is only necessary to acquire new synchronising pattern and new patterns for Std differences of the fault signal energy level and normal signal energy level based on the new sampling frequency.

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