NEW DETECTION TECHNIQUES

FOR POWER SYSTEM DISTURBANCE MONITORING AND ANALYSIS

M. Kezunović, P. Spasojević
Texas A&M University
Department of Electrical Engineering
College Station, Texas 77843-3128

B. Peruničić
Lamar University
Department of Electrical Engineering
Beaumont, Texas 77710

Abstract– This paper introduces new disturbance detection techniques that are developed using digital signal processing algorithms. These techniques enable much closer monitoring of power system signals and conditions than what is presently available by using standard equipment. This is done by providing unconventional capabilities such as detection of subharmonics, voltage sags, transients and impulses. These new techniques may benefit distribution automation, SCADA system and individual recording and measurement device designs by improving their capability for selective monitoring and analysis of power system signals and conditions.

Keywords: Disturbance Detection, Disturbance Monitoring, Digital Signal Processing Algorithms

INTRODUCTION

Power system disturbance monitoring and analysis had been implemented in the past by using meters and recording devices. This approach had an inherent limitation since meters were designed to measure only the fundamental harmonic parameters and recorders were designed with a limited selectivity of disturbance triggers.

A need to provide more accurate assessment of various disturbances in power systems has been recognized recently when issues such as performance of power meters under nonsinusoidal conditions, impact of harmonics, and power quality assessment became the focus of research [1–3].

Recent investigations have prompted development of sophisticated digital recording systems which would allow for capturing only waveforms of interest such as faults, harmonics, and slow variation of load characteristics [4–6]. Yet another research effort was aimed at evaluating measurement errors of the existing power meters under nonlinear conditions [7,8]. Furthermore, new signal processing algorithms for detection of selected types of disturbances and for measurements of only specific parameters of a distorted waveform were also developed. As a result, it was possible to track phasors and detect their frequency deviation [9–13], and to measure power, RMS values, and line parameters under nonsinusoidal conditions [14–16].

Introduction of these new approaches have significantly improved power system disturbance monitoring and analysis by providing operators with selective means of either detecting, and hence immediately recognizing disturbance of interest, or measuring a predefined parameter that characterizes specified disturbance.

The purpose of this paper is to introduce some novel detection techniques that can be used to further enhance power system disturbance monitoring and analysis. The focus of this paper are techniques for detection of changes in the fundamental harmonic, which are quite often difficult to capture selectively with the existing equipment. These techniques are based on digital signal processing algorithms introduced by the authors for measurements of common power system quantities such as frequency, power, and line parameters [9,14,16]. The same basic algorithm theory has been applied in this paper to development of the novel techniques for disturbance detection. The paper demonstrates new techniques for detection of deviations of the fundamental harmonic parameters such as abrupt change of amplitude or large variation in frequency. Detection of presence of subharmonics, voltage sags, short transients and impulses is also implemented.

The main advantage of these algorithms is their capability to give characterization of specific disturbances which significantly enhances selectivity in disturbance monitoring and analysis. Future application of these techniques may be quite wide, ranging from sophisticated recorders and meters to custom designed systems for monitoring of load characteristics and abnormal system conditions such as voltage sags.

The first section of the paper deals with definition of detection criteria and measurement quantity to be treated with the new techniques. The following section is aimed at describing new disturbance detection techniques. Conclusions and references are given at the end.

SIGNAL AND DISTURBANCE DEFINITIONS

From the signal processing stand point, one has to define the basic properties of the signal to be processed. In order to emphasize the importance of signal analysis considerations, a block diagram of the signal processing involved in a digital detection and/or measurement is given in Figure 1.

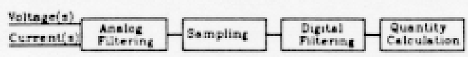

Figure 1. Signal Processing Steps

It is well known in the signal processing field that all of the processing steps indicated in Figure 1 have to be carefully designed to match given signal characteristics. It is, therefore, extremely important to understand characteristics of the signal disturbances so that appropriate signal processing algorithms may be designed. The signal associated with power system disturbances considered in this paper can be described as follows:

The main signal component is the fundamental harmonic whose amplitude may change slowly and frequency may vary slightly.

Once the signal is defined, there is a need to define what constitutes disturbances. Obviously, the defined signal represents a normal signal condition on a power system. Any abrupt changes that happen in a short time interval represent disturbances. Typical examples are fast changes in signal magnitude, transients and impulses. Occurrence of subharmonics, in this case, also represents a disturbance.

Furthermore, definitions of detection criteria has to be established for the mentioned disturbances. Disturbance detection criteria has to be related to a given type of disturbance. For the purposes of demonstrating various detection criteria, it may be assumed that a detection criterion is defined as any visible indication of a disturbance occurrence. As an example, a detection technique for the fundamental harmonic may produce small value (close to zero) if there is no disturbance and a large value in the case of a disturbance.

DISTURBANCE DETECTION TECHNIQUES

Signal processing algorithms used in this section are based on quadratic forms of signals. These forms are introduced by the authors in an earlier paper [17] and have been successfully used for definition of other measurement techniques [9,14,16].

In order to derive some basic conditions for development of detection techniques based on quadratic forms, let us consider a sinusoidal signal consisting of only one harmonic with constant amplitude and frequency:

$$X_n = X\cos(n\delta + \phi_o) \qquad (1)$$

where $\delta = \omega\Delta t$, ω-angular frequency, Δt-time between samples.

Let us now define a quadratic form of the signal X_n as follows:

$$QHX_n = \sum_{k=0}^{N-1}\sum_{m=0}^{N-1} h_{km}X_{n-k}X_{n-m} \qquad (2)$$

After some known trigonometric transforms are applied, the value of expression (2), for the signal given in (1), can be obtained as follows:

$$QHX_n = \frac{X^2}{2}|H^V(e^{-j\delta})| \cdot \cos[2n\delta + 2\phi + \angle H^V(e^{-j\delta})] + \frac{X^2}{2}ReH^C(e^{-j\delta}) \qquad (3)$$

where:

$$H^V(e^{-j\delta}) = \sum_{k=0}^{N-1}\sum_{m=0}^{N-1} h_{km} e^{-j(k+m)\delta} \qquad (4)$$

$$H^C(e^{-j\delta}) = \sum_{k=0}^{N-1}\sum_{m=0}^{N-1} h_{km} e^{-j(k-m)\delta} \qquad (5)$$

If the weight matrix **H** is selected in such a way that its elements h_{km} satisfy, for a constant frequency $\delta_o = \omega_o \Delta t$, the following condition:

$$H^V(e^{-j\delta_o}) = 0 \qquad (6)$$

then for $\delta = \delta_o$ the value of the quadratic form given by equation (3) is equal to:

$$QHX_n = \frac{X^2}{2} ReH^C(e^{-j\delta_o}) \qquad (7)$$

where:

$$ReH^C(e^{-j\delta_o}) = \sum_{k=0}^{N-1}\sum_{m=0}^{N-1} h_{km}\cos(k-m)\delta_o \quad (8)$$

It can be shown that the value of the quadratic form given by equation (7) will also be insensitive to small frequency change $\delta - \delta_o = \Delta\delta << 1$ if the following condition is satisfied:

$$\frac{dH^C(e^{-j\delta_o})}{d\delta_o^k} = 0 \qquad k = 1, 2, \dots n \qquad (9)$$

Furthermore, it can be observed that the value of the quadratic form given by equation (7) is zero if:

$$ReH^C(e^{-j\delta_o}) = 0 \qquad (10)$$

If, however:

$$ReH^C(e^{-j\delta_o}) = 1 \qquad (11)$$

then the quadratic form (7) gives a square of the RMS value.

All the properties given by equations (6), (9) and (11) can be utilized to design techniques, based on quadratic form given by expression (2), to detect normal signal conditions and disturbances.

In order to illustrate development of detection techniques, the following matrix **H** can be used:

$$\mathbf{H}_o = \begin{bmatrix} 1 & -2\cos\delta_o & 1 \\ -2\cos\delta_o & 4\cos^2\delta_o & -2\cos\delta_o \\ 1 & -2\cos\delta_o & 1 \end{bmatrix} \quad (12)$$

This matrix is selected since it is quite simple, and yet it satisfies conditions given by equations (6), (9), and (10). Further discussion is related to definition of the disturbance detection techniques derived using matrix **H** as given by expression (12), and the quadratic form given by equation (2).

Detection Technique #1 – For the fundamental harmonic signal, it may be desirable to detect that the signal is normal, i.e., there is no abrupt change in amplitude and no significant change in frequency, except for very small variations $\Delta\delta << 1$. Let us define detection criterion as follows: the quadratic form value under these conditions should be close to zero, and if these conditions are not satisfied, the value should be significantly different from zero. In particular, the technique should recognize abrupt changes in signal amplitude.

If matrix **H** given by expression (12) is used, the quadratic form defined by equation (3) is equal to:

$$QHX_n = \frac{X^2}{2}\cdot 4(\cos\delta - \cos\delta_o)^2[1+\cos(2n\delta - 2\delta)] \qquad (13)$$

From equation (13) the following can be concluded:

- for $\delta = \delta_o \quad QH_oX_n = 0 \qquad (14)$
- for $\delta - \delta_o = \Delta\delta << 1$

$$QHX_n \approx (\Delta\delta)^2 \frac{X^2}{2} 2\sin^2\delta_o[1+\cos(2n\delta_o - 2\delta_o)] \qquad (15)$$

Equation (14) is equal to zero if the fundamental harmonic signal does not experience deviation in frequency. For small deviations in frequency, the quadratic form output is small and has a value proportional to the square of the frequency change, as shown by equation (15). It can also be shown that this technique provides small value for slow changes in the signal amplitude. The application of this detection technique for the mentioned cases is shown in Figures 2(a) and 2(b).

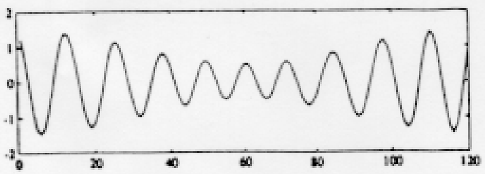

Figure 2(a). Input Signal Showing Small Change in Frequency and Slow Variation in Amplitude

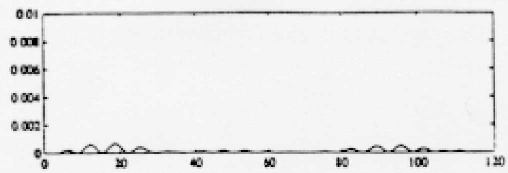

Figure 2(b). Output Signal Showing Very Small Value

If the change in amplitude is linear in the window of the samples, and is defined as:

$$X_n = X_o + \Delta X;\ X_{n-1} = X_o;\ X_{n-2} = X_o - \Delta X \quad (16)$$

then the quadratic form has the following value for $\delta = \delta_o$:

$$QHX_n = \frac{\Delta X^2}{2} \sin^2 \delta_o [1 - \cos(2n\delta - 2\delta)] \quad (17)$$

The application of the detection technique for this case is shown in Figures 3(a) and 3(b).

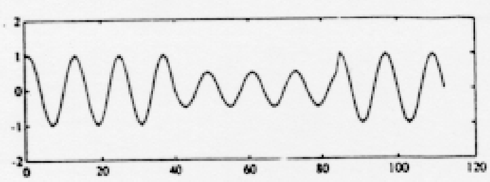

Figure 3(a). Input Signal Showing Fast Change in Signal Amplitude

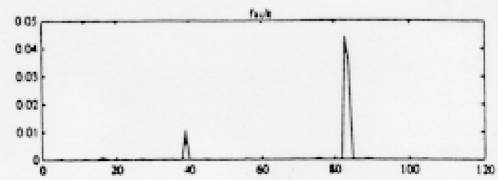

Figure 3(b). Output Signal Showing a Large Value at the Moments of the Amplitude Change

Detection Technique #2 – For the fundamental harmonic signal it may also be desirable to detect presence of a subharmonic. Let us define detection criterion as follows: the quadratic form value is zero if a subharmonic is not present and when a subharmonic is present the value is not zero but has a visible oscillating value proportional to the square of RMS value of the subharmonic amplitude.

Again, the quadratic form given by expression (2) is used together with H matrix given by expression (12). The signal containing a subharmonic may be represented as follows:

$$X_n = X_o \cos n\delta_o + X_S \cos n\delta_S \quad (18)$$

where X_o and δ_o are parameters of the fundamental harmonic while X_S and δ_S are parameters of a subharmonic.

The quadratic form value for this signal is equal to:

$$QHX_n = 2X_S^2(\cos\delta_o - \cos\delta_S)\cos^2(n-1)\delta_S \quad (19)$$

The application of this detection technique is shown in Figures 4(a) and 4(b).

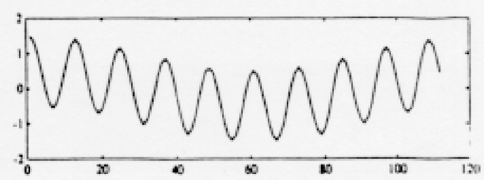

Figure 4(a). Input Signal Contains Fundamental Harmonic and a Subharmonic

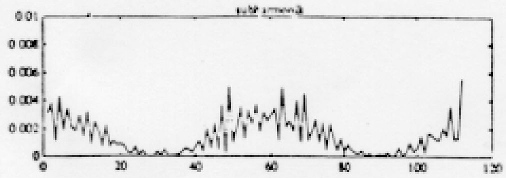

Figure 4(b). Output Signal Showing an Oscillating Value When a Subharmonic is Introduced.

Detection Technique #3 - For the fundamental harmonic signal it may be desirable to detect an occurrence of a short transient whose duration is much smaller than the signal period. Let us define detection criterion as follows: the quadratic form value is zero if there is no transient present and the value is significantly different from zero and positive when a short transient is present.

The signal containing transient may be represented as follows:

$$X_n = X_o \cos n\delta_o + Q \cdot q^{(n-m)} \cdot u(n-m) \quad (20)$$

where $u(n-m)$ is a unit function indicating occurrence of a transient in the moment $\underline{m}$. If the same matrix H_o is used, the values of the quadratic form for this signal at various time moments are equal to:

$$\begin{aligned} n < m \quad & QH_oX_n = 0 \\ n = m \quad & QH_oX_m = Q^2 \\ n = m+1 \quad & QH_oX_{m+1} = Q^2(q - 2\cos\delta_o)^2 \\ n = m+2 \quad & QH_oX_{m+2} = Q^2(q^2 - 2q\cos\delta_o + 1)^2 \end{aligned} \quad (21)$$

Equation (21) illustrates behavior of the detection technique. This technique is designed for short transient detection, but a similar technique may be derived for detection of short impulses. In this case, the impulses are recognized as transients with $q = 1$.

The application of both detection techniques is shown in Figures 5(a) and 5(b).

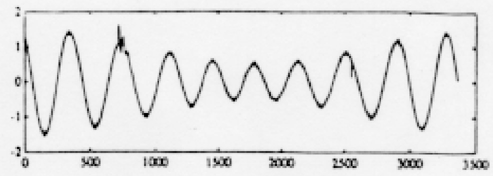

Figure 5(a). Input Signal Showing Both Short Transient and Short Impulse Disturbances

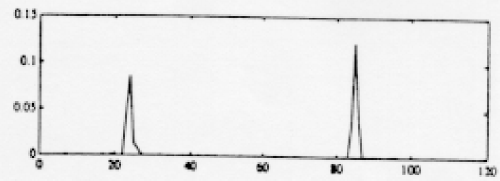

Figure 5(b). Output Signal Showing a Large Value When Either of the Disturbances is Present

CONCLUSIONS

Results presented in this paper illustrate the following:

- Digital signal processing algorithms implemented using quadratic and bilinear forms can be utilized to develop a number of new detection and measurement techniques.
- These techniques can be applied to disturbance monitoring and analysis that involve detection of the fundamental harmonic deviations, subharmonics, harmonics, voltage sags, transients and impulses.
- These unconventional detection techniques can be utilized in a variety of device and system designs such as disturbance and fault recorders as well as distribution automation and SCADA systems.

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