Implementation of the Wiener Filter for Extracting Power Quality Disturbances

A. Elnady[1], A. Noureldin[2] and Yan-Fei Liu[1]
[1]Queen's University, Kingston, Ontario, Canada
[2]Royal Military College, Kingston, Ontario, Canada

***Abstract*- This paper introduces a novel modular strategy for real time extraction of the current and voltage disturbances. The main advantage of this technique is that it does not have mathematical complexity and does not require any model or state-space formulation to extract the disturbances like the other commonly used state-space techniques. In addition, it is very simple for practical and real time implementation if compared to the existing time-domain and frequency-domain methods. The proposed technique is based on the Wiener filter designed adaptively by using a sliding windowing procedure. This Wiener filter is employed to design a generalized extraction strategy for tracking and extracting the most common power quality disturbances. Digital simulation results on the most common power quality problems are demonstrated to validate the proposed strategy.**

I. INTRODUCTION

The real time disturbance extraction techniques have been addressed extensively for each one of the voltage and current quality problems [1-5]. However, there are few techniques that can be utilized in a unified or a generalized manner or approach for tracking and extracting more than one power quality problem at a time [3], [4]. Some frequency-domain techniques [6-7], such as S-transform and wavelet, have been suggested and utilized in off-line analysis for classifying and detecting power quality disturbances. Also, some artificial intelligent techniques, such as neural network and fuzzy logic, have been offered [8] in order to classify power quality problems and detect power quality events, but they suffer from mathematical burden which hinders their real time implementation. Technically speaking, these techniques work well for detecting, localizing and classifying the power quality events in the off-line analysis not for the real time extraction of the disturbances. The real time extraction is the essence of the mitigating process. Actually, there is a tremendous need for such a simple generalized extracting strategy because of the high probability of finding more than one power quality problem existent at the same bus or at the same time.

This paper introduces a generalized disturbance extraction strategy which depends on a recursive formulation of Wiener filters. Based on the authors' knowledge and survey, it is the first time ever that the Wiener filter is used for power applications in the area of power quality. The main advantages of the proposed extraction strategy are the simplicity of using the Wiener filters for the real time disturbance extraction and its modular structure which has the capability of extracting several power quality problems or disturbances at the same time.

This paper includes five sections; the second section shows the recursive formulation of the Wiener filters. In the third section, the implementation of Wiener filters for disturbance extraction is discussed; and the proposed disturbance extraction strategy is explained. The fourth section demonstrates the simulation results for the most common power quality disturbances. The last section concludes the contribution of this paper.

II. MATHEMATICAL FORMULATION OF THE PROPOSED WIENER FILTER

The FIR filter is designed as a transversal tap delay line discrete-time system as demonstrated in Fig. 1. The parameters of the filter $W_0, W_1, W_2, \ldots\ and\ W_M$ are known as the filter weights. The output $y(n)$ depends on the present and past samples of the input sequence $u(n)$. Therefore, it is possible to design a filter in order to have the output $y(n)$ mimicking a certain desired sequence $d(n)$ embedded inside the input $u(n)$ [9].

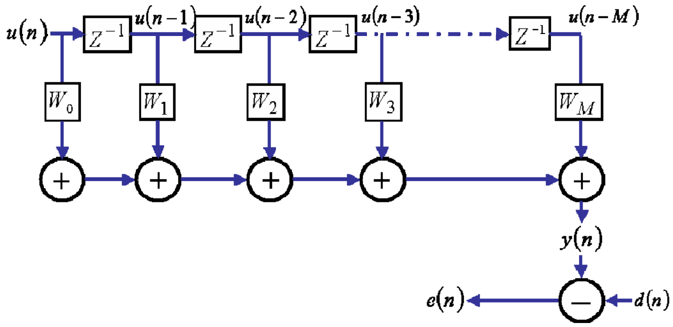

Fig. 1: Structure of finite impulse response transversal tap delay line filter

Wiener filtering theory assumes that the estimation filter, (the discrete-time filter that will provide an estimate of $d(n)$ based on the input $u(n)$), can be modeled as a tap delay line filter as shown in Fig. 1. The filter weights, $\overline{W}$, are determined adaptively. The adaptive Wiener filtering procedure is applied in two steps:

- The first step is related to choosing the optimal values of the filter parameters, (filter tap weights), and is known as

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the update procedure. The objective of the update procedure is to extract the desired signal *d(n)* from the input sequence *u(n)* by minimizing the error *e(n)* between the desired signal *d(n)* and the filter output *y(n)*. Since the error signal *e(n)* is random in nature, the filter tap weights will be determined by minimizing the mean square value of the error. This step is done in the off-line analysis on a set of available data for the power quality problems of interest.

- During the second step, the desired response *d(n)* is estimated from the output *y(n)* by filtering out all other signal components that exist at the input signal *u(n)*. This step is known as the estimation procedure. This step is done on real signals in order to instantaneously extract the disturbances for the real time implementation.

The Wiener weights or Wiener vector, $\overline{W}$, containing the optimal values of the tap weights can be obtained as follows:

$$\overline{W} = R^{-1}\overline{P} \tag{1}$$

where R and $\overline{P}$ can be obtained from the following formulas, respectively.

$$R = E\left(\overline{U}(n)\overline{U}^T(n)\right) = \begin{pmatrix} E\left(u^2(n)\right) & E\left(u(n)u(n-1)\right) & . \; . & E\left(u(n)u(n-M)\right) \\ E\left(u(n-1)u(n)\right) & E\left(u^2(n-1)\right) & . \; . & E\left(u(n-1)u(n-M)\right) \\ . & . & . \; . & . \\ . & . & . \; . & . \\ E\left(u(n-M)u(n)\right) & E\left(u(n-M)u(n-1)\right) & . \; . & E\left(u^2(n-M)\right) \end{pmatrix} \tag{2}$$

$$\overline{P} = E\left(d(n)\overline{U}(n)\right) = \begin{pmatrix} E\left(d(n) \;\; u(n)\right) \\ E\left(d(n) \;\; u(n-1)\right) \\ E\left(d(n) \;\; u(n-2)\right) \\ . \\ E\left(d(n) \;\; u(n-M)\right) \end{pmatrix} \tag{3}$$

$U(n), U(n-1), ..., U(n-M)$ are defined as the inputs at different M samples as shown in Fig. 1, and $d(n)$ is the desired output at the current sample n. Whereas, $\overline{W}$ is called a Wiener vector in this paper and defined as,

$$\overline{W} = [W_0, W_1, W_2, ..., W_M]^t \tag{4}$$

Once the Wiener vector is obtained from (1), it can be recursively utilized to extract the desired signal. This desired signal represents any power quality disturbance of interest.

III. THE PROPOSED STRATEGY FOR DISTURBANCE EXTRACTION

A. Utilization of Wiener Filters for Recursive Disturbance Extraction

The proposed formulation of the Wiener filter extracts any disturbance signal by recursively multiplying the Wiener vector, (which is obtained during the update procedure in the off-line analysis as described in the previous section), by distorted voltage and current waveforms. The real time implementation of the proposed technique is accomplished by using a sliding window of the distorted waveforms and the Wiener vector as shown in Fig. 2. By this simple process, (just multiplication between the Wiener vector and the distorted signal), the disturbances can be instantaneously and adaptively extracted. Therefore, the proposed technique is much simpler than a plenty of existing techniques.

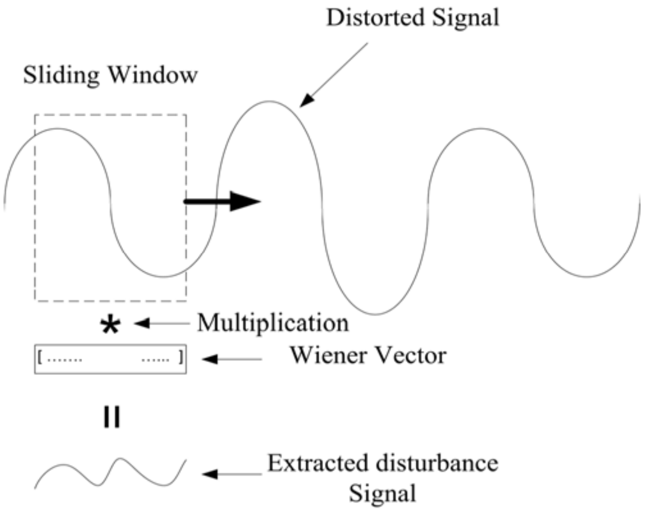

Fig. 2: Operation of the proposed Wiener filter to extract disturbance signal

Each Wiener filter can be used to extract just one power quality problem or disturbance, and the width or the order of each Wiener vector $\overline{W}$ is adjusted based on the characteristics of the power quality problem or disturbance that is required to be filtered or extracted. Consequently, the proposed extraction strategy is modular and each module can be used to extract just one power quality problem or disturbance.

The frequency response of the Wiener filter, Wiener vector, for voltage sags and swells is demonstrated in Fig. 3 in which the Wiener vector performs as a normalized band-pass filter at 60 Hz which allows the fundamental component to pass and suppresses the other components. The frequency response of the Wiener filter for harmonic extraction is illustrated in Fig. 4. This figure shows zero dB at 180 Hz, 300 Hz, 420 Hz, 540 Hz and 660 Hz.

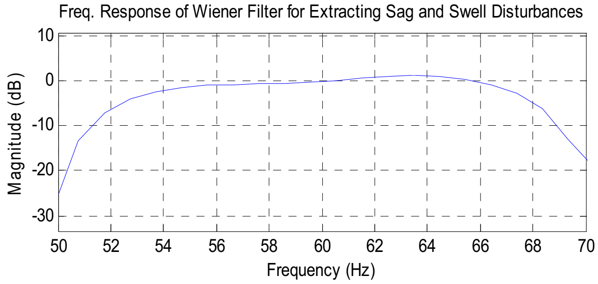

Fig. 3: Frequency response of the Sag and Swell Wiener vector

The harmonic Wiener vector can be customized to any number of existing harmonics of interest in the system under study.

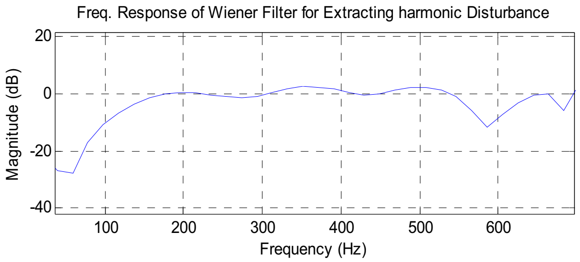

Fig. 4: Frequency response of the harmonic Wiener vector

Cyclic voltage and current fluctuations can be mathematically presented as a summation of two disturbances of frequencies $\omega_{\text{fundamental}} - \omega_{\text{mod ulating}}$ and $\omega_{\text{fundamental}} + \omega_{\text{mod ulating}}$, where $\omega_{\text{fundamental}}$ represents the frequency of the fundamental component, and $\omega_{\text{modulating}}$ represents the frequency of modulating signal for fluctuation. Fig. 5 demonstrates the frequency response of 10 Hz modulation in the fundamental signal of 60 Hz. As shown in this figure the required disturbances will be extracted with zero dB and the rest of the disturbances will be attenuated to lower than -20 dB.

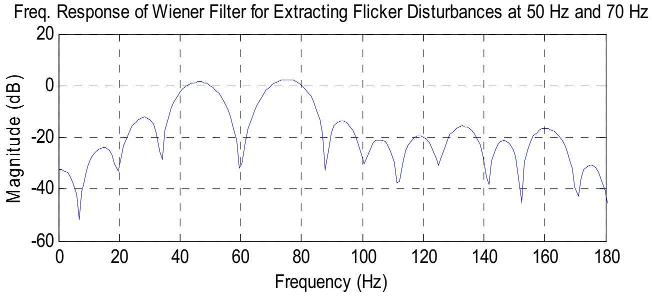

Fig. 5: Frequency response of the fluctuating Wiener vector

B. *The Structure of the Modular Disturbance Extraction Strategy*

The notion of extracting each voltage and current disturbance can be generalized and stacked to concurrently extract several disturbances such as voltage and current harmonics, voltage sags, swells and fluctuations in voltage and current. The generalized extraction strategy consists of several modules, (Wiener vectors or filters). Each module, or a Wiener filter, is responsible for extracting a specific disturbance and attenuating the rest of the disturbances. The structure of the proposed strategy is illustrated in Fig. 6

IV. SIMULATION RESULTS

This section shows the simulation results of each module of the proposed modular extraction strategy as shown in Fig. 6, and the comparison between the proposed technique and the most common technique for each power quality disturbance of interest.

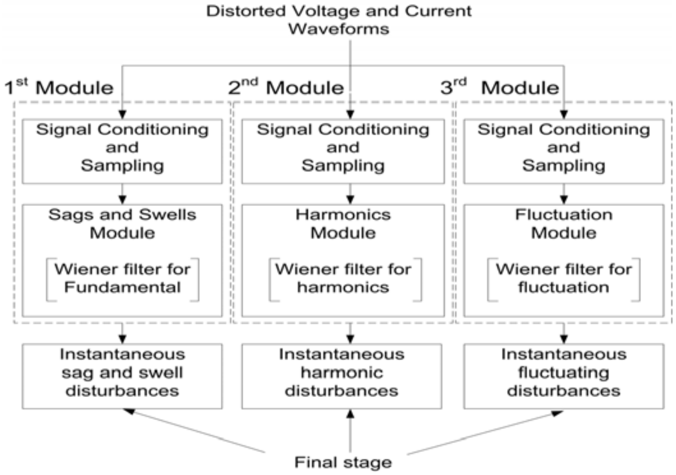

Fig. 6: The proposed modular extraction strategy

A. *Harmonic Disturbances*

The proposed filter is examined for multiple harmonics and its performance is compared with the performance of the adaptive perceptron, (Adaline) [10], technique for the same harmonics. The distorted current is expressed as,

$$
\begin{aligned}
I &= 100\sin(2\pi 60t) + 50\sin(2\pi 180t) + 30\sin(2\pi 300t) \\
&\quad + 25\sin(2\pi 420t) + 15\sin(2\pi 5400t) + 10\sin(2\pi 660t)
\end{aligned}
\tag{5}
$$

The extracted disturbances of proposed Wiener filter and the adaptive perceptron are demonstrated in Figs. 7 and 8, respectively. The comparison between these two waveforms shows great matching in the steady state performance between the adaptive perceptron technique and the proposed technique.

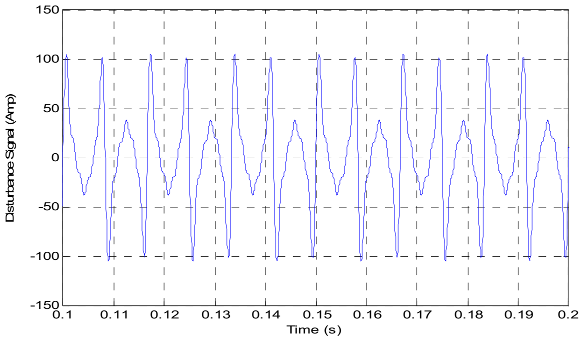

Fig. 7: Disturbance extraction by the proposed Wiener filter

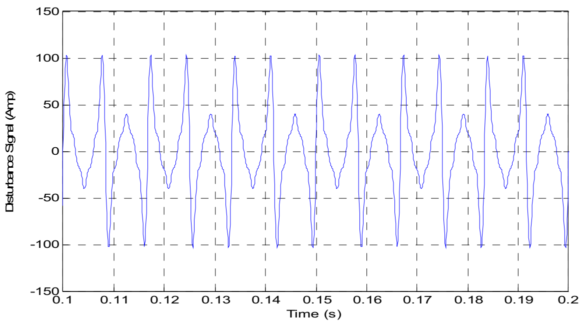

Fig. 8: Disturbance extraction by the adaptive perceptron (adaline)

B. Sag and Swell Disturbances

A voltage sag is applied to the proposed Wiener filter and the d-q reference frame technique, which is a very common technique for extracting sag disturbances [11]. This voltage sag is mathematically defined as,

$$V = \begin{cases} 10\sin(2\pi 60 t)\,(kV) & t < 0.2s \\ 7\sin(2\pi 60 t + 10^{\circ})\ \ (kV) & 0.3\,s > t > 0.2\,s \\ 10\sin(2\pi 60 t + 5^{\circ})\ \ (kV) & t > 0.3\,s \end{cases} \quad (6)$$

The results of the instantaneous tracking of the forgoing voltage sag are demonstrated in Figs 9 and 10, respectively. In these two figures, it is proved that the steady state performances of both techniques are similar to each other. Also, it is apparent from Fig. 9 that the transient duration of the proposed Wiener filer is about a half cycle in order to track a new steady state value of the sagged voltage.

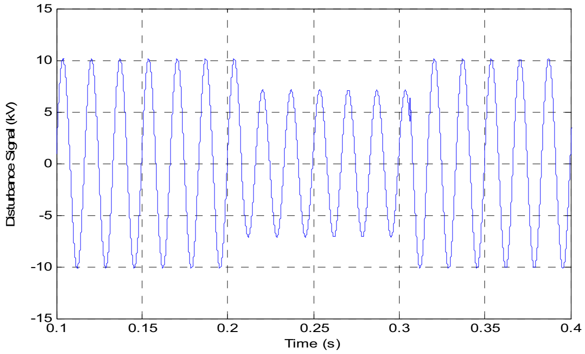

Fig. 9: Sag tracking using the proposed Wiener filter

C. Voltage and Current Fluctuating Disturbances

The current fluctuation will be presented as an example for a fluctuating disturbance. Fig. 11 depicts a current fluctuation waveform which is mathematically expressed by,

$$I_{distorted} = [1 + 0.1\sin(2 * pi * 10 * t)] * 100\sin(2 * pi * 60 * t) \quad (7)$$

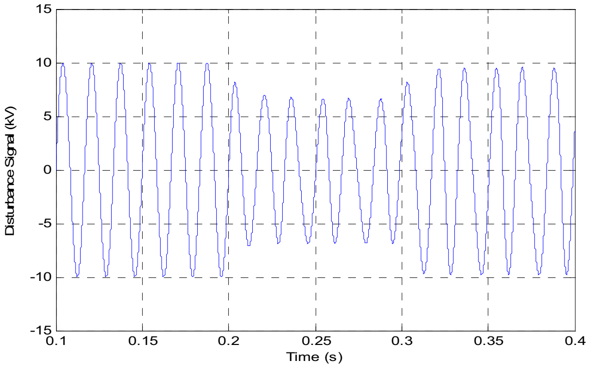

Fig. 10: Sag tracking using the d-q reference frame technique

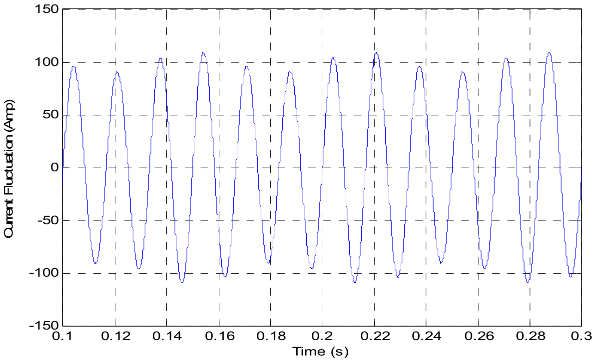

Fig. 11: Current fluctuation waveform

The Kalman filter is commonly used for these applications [3]. The extracted disturbances of the Wiener filter and the Kalman filter are illustrated in Figs. 12 and 13, respectively. The visual comparison between these waveforms indicates the accuracy of extraction and tracking of the proposed technique with respect to the Kalman filter. In addition, the proposed technique is mathematically simpler than the Kalman filter for the practical implementation.

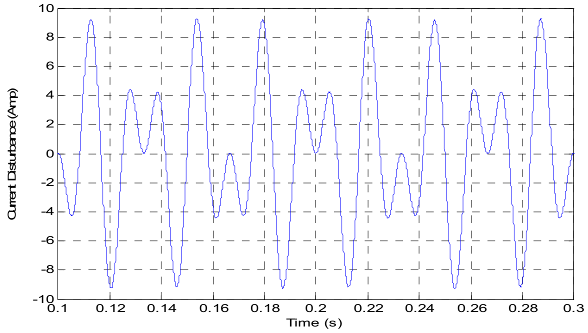

Fig. 12: Fluctuating disturbance extraction using the proposed Wiener filter

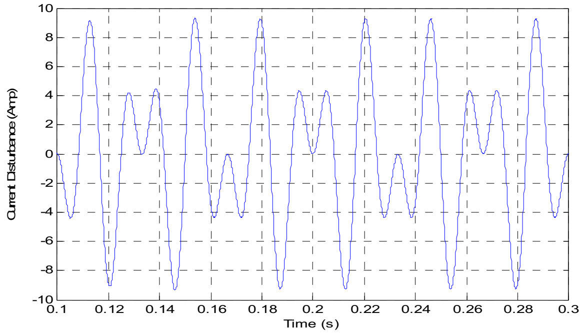

Fig. 13: Fluctuating disturbance extraction using the Kalman filter

V. CONCLUSION

The proposed extraction strategy for power quality disturbances is simple for the practical implementation and it is accurate compared to the commonly used extraction strategies and techniques. Moreover, the modular structure of the extraction strategy provides the ability to extract any number of disturbances at the same time. Finally, the simulation results for the most common power quality problems verify the viability and the practicality of the proposed concepts and ideas.

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