Power-Quality Improvement Using Wiener Filters Based On a Modular Compensating Strategy

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***Abstract*—This paper introduces a new modeless modular compensating strategy to extract and mitigate power-quality (PQ) disturbances. The main advantage of this strategy is that it does not require any model or state-space formulation to extract the disturbances, such as the other commonly used state-space techniques. In addition, it is very simple for practical implementation compared to the time-domain and frequency-domain methods. The proposed strategy depends on recursive implementation of the Wiener filtering theory. The suggested strategy is validated by digital simulation results on the most common stationary and transient PQ problems.**

***Index Terms*—Modular compensating strategy, power-quality (PQ) problems and recursive Wiener filter.**

I. INTRODUCTION

THE deregulation era has stipulated a specific quality of power that is delivered to loads. Power-quality (PQ) problems have become the focus of interest of the operators in utilities due to the negative impact of their disturbances on industrial and domestic equipment. PQ problems can be classified into voltage-quality problems and current-quality problems [1]. Voltage and current harmonics are the most common stationary PQ problems in any distribution system; they always cause malfunction in sensitive equipment. Voltage and current fluctuations, (flicker), become common in industrial systems. If the flicker level is increased above a certain threshold, the other customers in the same system become irritated. Voltage sags and swells are the most severe PQ problems because they cause interruption of production lines in industrial plants. The previous drawbacks shed light on the importance of the mitigating processes for PQ problems.

The efficiency of any mitigating process depends first on the techniques that have been employed to extract the disturbances; and second, on the topology of the mitigating devices. A lot of research has been done on the techniques that have been adopted to extract different PQ disturbances [2]–[4]. Meanwhile, the topologies of the custom power conditioners do not get as much attention as the disturbance extracting techniques [5]–[8].

The mitigation of harmonics and reactive currents has been addressed extensively in time and frequency domains [2], [3], [9]. The time-domain techniques suffer from inaccuracy and complexity. Nevertheless, frequency-domain techniques are more accurate than time-domain techniques—they are more complicated than time-domain techniques from the practical prospective. Recently, the state-space and state-estimation techniques have been propounded to replace the old techniques for extracting the harmonic disturbances. The Kalman filter and the recursive least-square technique have been proposed to extract harmonics in power systems [10], [11]. Recently, Adaptive perceptron (Adaline) has been suggested to extract current harmonic disturbances [12].

Much work has been done on the mitigation of the voltage-quality problems, (voltage sags, swells, and fluctuations), by using different time-domain and frequency-domain techniques for their disturbance extraction [13]–[15]. Although voltage sags and swells have the most severe impact on loads, their disturbances have rarely been addressed using state-space or state-estimation techniques [16].

Voltage or current fluctuation becomes common in any industrial system. The p–q theory has been adopted to extract the flicker disturbances [15]; however, it is too complicated for practical implementation. The Kalman filter has been suggested to extract the instantaneous flicker level [17]. Also, the least absolute value has been addressed to extract the voltage flicker disturbances [18]. Recently, adaptive perceptron has been adopted to extract the modulating signal of the voltage flicker [19]. Unfortunately, most of the state-space techniques require a state-space model to extract the disturbances; this model increases the mathematical complexity and hinders the practical implementation.

This paper introduces an efficient modular compensating strategy for tracking, extracting, and mitigating PQ disturbances. The proposed compensating strategy depends on novel recursive implementation for modeless formulation of the Wiener filter that is used for the first time to track and extract PQ disturbances. These disturbances are mathematically processed to generate control and drive signals to custom power conditioners. This paper contains five sections. The discrete formulation of the Wiener filter is described in Section II. In Section III, the recursive application of the Wiener filters for extracting PQ disturbances is discussed. Moreover, the generic modular strategy for compensating PQ disturbances is demonstrated in the same section. The simulation results for mitigating and compensating the most common PQ problems are presented in Section IV. Also in this section, some comparative studies and results are demonstrated to show the efficiency of the proposed Wiener filters for disturbance extraction. The last section concludes the achievements of this paper.

Manuscript received July 12, 2006; revised June 2, 2007. This work was supported by the Natural Science and Engineering Research Council of Canada. Paper no. TPWRD-00371-2006.

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Digital Object Identifier 10.1109/TPWRD.2007.915948

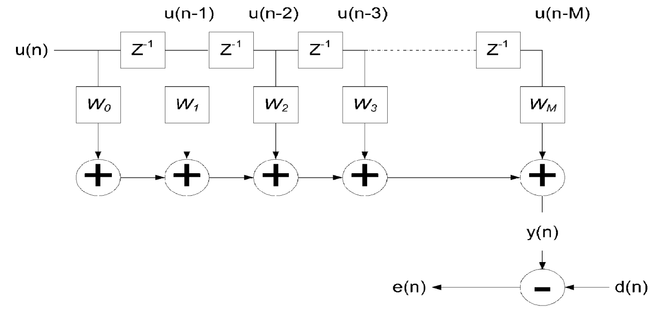


Fig. 1. Finite-impulse-response filter structure.

II. MATHEMATICAL FORMULATION OF THE PROPOSED RECURSIVE WIENER FILTER

In many applications, an estimate of a certain signal $d(n)$ (known as a desired signal) is usually required, which is embedded in another sequence $u(n)$. This problem is solved by processing the sequence $u(n)$ using a discrete-time system, (a discrete filter), to cancel all of the components of $u(n)$ except $d(n)$. Due to its guaranteed stability, a finite impulse response (FIR) discrete time system is employed in this study [20].

The Wiener filter theory assumes that the estimation filter [the discrete-time system that will provide an estimate of $d(n)$ based on the input $u(n)$] can be modeled as a tap delay line (transversal) filter [21] whose structure in discrete time is demonstrated in Fig. 1. The parameters of the filter $W_0, W_1, W_2, \ldots\ldots$ and W_M are known as the filter weights or filter tap 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 $u(n)$.

This research offers implementing the adaptive filtering procedures [21], which require two steps for the real implementation. In the first step, called the update procedure, the filter tape weights ($W_0, W_1, W_2, \ldots\ldots$ and W_M) are determined by minimizing the mean square error $e(n)$. This step is done offline on the available data of the PQ problems of interest. In the second step, called the estimation procedure, the desired response $d(n)$ is estimated from the output $y(n)$ in real time by filtering out all other signal components that exist in the input signal $u(n)$.

In the update procedure, the cost function $J(n)$ is defined by the mean square error which is the mathematical expectation of the square of the error as expressed by

$$J(n) = E\left(e^2(n)\right) = E\left(\left(d(n) - y(n)\right)^2\right). \qquad (1)$$

The output $y(n)$ is obtained through the vector multiplication of the input by the filter tap weights. The previous equation can be rewritten as

$$J(n) = E\left(e^2(n)\right) = E\left(\left(d(n) - \overline{W}^T\overline{U}(n)\right)\left(d(n) - \overline{U}^T(n)\overline{W}\right)\right) \qquad (2)$$

where $W^T = (W_0 \quad W_1 \quad \cdot \quad \cdot \quad \cdot \quad W_M)$ is the filter tap weight vector and is called Wiener vector in this study. The input vector $U^T(n) = (u(n) \quad u(n-1) \quad \cdot \quad \cdot \quad \cdot \quad u(n-M))$ contains all of the present and past samples of the input sequence. Equation (2) can be rewritten, after arranging the aforementioned terms, as follows:

$$J(n) = \sigma_d^2 - 2\overline{W}^T\overline{P} + \overline{W}^T R\overline{W} \qquad (3)$$

where $\sigma_d^2 = E\left(d^2(n)\right)$ is the variance of the desired output, and R is the autocorrelation (auto covariance) matrix of the input sequence and is given as follows, as shown in (4) at the bottom of the page. The cross correlation vector between the input sequence and the desired output is denoted as $\overline{P}$ in (3) and defined as

$$\overline{P} = E\left(d(n)\overline{U}(n)\right) = \begin{pmatrix} E\left(d(n)u(n)\right) \\ E\left(d(n)u(n-1)\right) \\ E\left(d(n)u(n-2)\right) \\ \cdot \\ E\left(d(n)u(n-M)\right) \end{pmatrix}. \qquad (5)$$

Equation (3) represents a quadratic surface, (or performance surface), for the relationship between the cost function $J(n)$ and the filter weights $\overline{W}$. The optimal values of the filter weights, or Wiener vector, can be obtained by minimizing $J(n)$ with respect to $\overline{W}$. Consequently, the Wiener vector $\overline{W}$ containing the optimal values of the tap weights can be obtained as follows:

$$\overline{W} = R^{-1}\overline{P}. \qquad (6)$$

Equation (6) is adopted in this research and applied in this update procedure to obtain the Wiener vector $\overline{W}$. This Wiener vector is employed in the estimation procedure for the real-time extraction of the PQ disturbances using a sliding window technique.

The update procedure starts with a window of data (both the input data $u(n)$ and the desired output data $d(n)$) and the window size is equal to the filter order. The elements of R and $\overline{P}$ are computed. Afterwards, the data window slides by only one sample and collects one more sample of the input signal and desired output. The update procedure continues with sliding the

$$R = E\left(\overline{U}(n)\overline{U}^T(n)\right) = \begin{pmatrix} E\left(u^2(n)\right) & E\left(u(n)u(n-1)\right) & \cdot\ \cdot & E\left(u(n)u(n-M)\right) \\ E\left(u(n-1)u(n)\right) & E\left(u^2(n-1)\right) & \cdot\ \cdot & E\left(u(n-1)u(n-M)\right) \\ \cdot & \cdot & \cdot\ \cdot & \cdot \\ \cdot & \cdot & \cdot\ \cdot & \cdot \\ E\left(u(n-M)u(n)\right) & E\left(u(n-M)u(n-1)\right) & \cdot\ \cdot & E\left(u^2(n-M)\right) \end{pmatrix} \qquad (4)$$

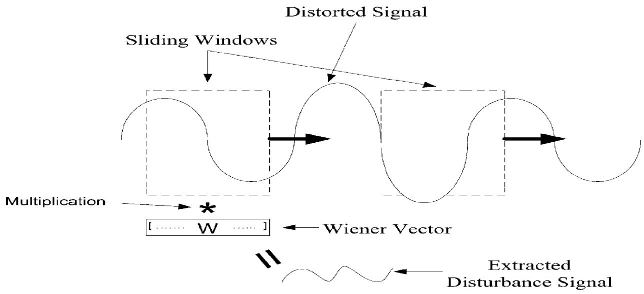


Fig. 2. Operation of the proposed Wiener filter to recursively extract a disturbance signal.

data window until the data samples end. Finally, (6) is applied to extract the Wiener vector $\overline{W}$ that corresponds to the desired signal $d(n)$.

III. Proposed Compensating Strategy

This section explains the estimation procedure and how the Wiener filter (formulated in Section II) is recursively employed to extract the PQ disturbances. Also, it presents a generic modular structure for the proposed compensating strategy that handles several PQ disturbances.

A. *Utilization of the Wiener Filter for PQ Disturbance Extraction*

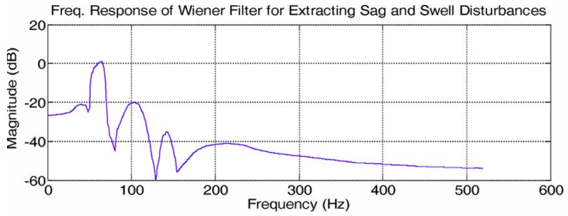
As presented in the previous section, the Wiener filter is newly employed to generate the Wiener vector $\overline{W}$. Consequently, this Wiener vector can be employed for real-time extraction of disturbances. For each type of the common PQ disturbances, (such as harmonic disturbances, sags, swells, and fluctuations), a Wiener vector is generated using (6) from the previous data of the PQ problems of interest. The width of the Wiener vector is determined by the order of the employed Wiener filter. In fact, there is a tradeoff between the width of the Weiner filter and the delay of its response. Better performance always results from a relatively large width of the Wiener vector (corresponding to a high filter order); however, a relatively wide Wiener vector causes more delay in the extracted signal, which may affect the real-time extraction of the transient disturbances. In general, the order of the Wiener filter should be carefully chosen to guarantee zero phase shift.

As mentioned before, the main advantage of the proposed Wiener filter in this paper is that it extracts the disturbance without mathematical complexity or without the need to formulate a model for disturbance extraction. The proposed technique instantaneously extracts any disturbance signal by recursively multiplying the Wiener vector, (which is obtained during the update procedure as described in Section II), by a window of the distorted voltage and current waveforms. Then, this window slides by one sample and the previous multiplication is repeated. As a result, the real-time implementation of the proposed technique is accomplished by sliding the data window, which contains the distorted signal, to obtain the instantaneous disturbance signal as shown in Fig. 2.

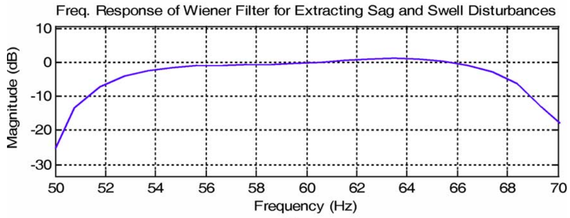
The most important characteristic for classification and extraction is the frequency of the signal since the proposed filters distinguish the signals based on their frequencies. In the update procedure, the desired signal $d(n)$ for each specific PQ problem should be well defined. For instance, if it is required to extract the harmonics, then the $d(n)$ should be all of the harmonic contents of interest in the distorted signal. The most important point for defining $d(n)$ is the frequencies of the signals, not their magnitudes. Also, for sag and swell extraction, the $d(n)$ should be the fundamental component of 60 Hz with any magnitude. Eventually, each Wiener vector should be associated with a desired signal $d(n)$ of a known frequency or with a specific PQ problem.

The frequency response of each Wiener vector should be tested before the real-time implementation; in this study, the frequency response is obtained by using MATLAB. The frequency response of the Wiener filter for voltage sags and swells is demonstrated in Fig. 3 in which the Wiener vector performs as a normalized bandpass filter at 60 Hz which allows the fundamental component to pass and suppress the other components. The response of the filter in Fig. 3(b) proves one more advantage in case of any frequency drift. As shown in Fig. 3(b), the filter has a flat response around zero decibel in the sideband around 60 Hz. That means if the supply frequency drifts, the filter is still able to extract the sagged or swelled voltages adequately.

The frequency response of the Wiener filter for harmonic extraction is illustrated in Fig. 4. This figure shows zero decibel at 180, 300, 420, 540, and 660 Hz. The harmonic Wiener vector can be customized to any number of existing harmonics in the system under study. The magnitude of harmonics does not affect



(a)



(b)

Fig. 3. Frequency response of the sag and swell Wiener vector. (a) Entire response. (b) Zoom-in for graph (a) around 60 Hz .

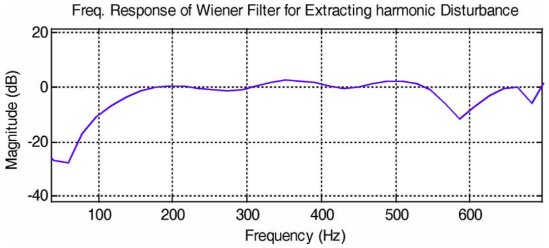
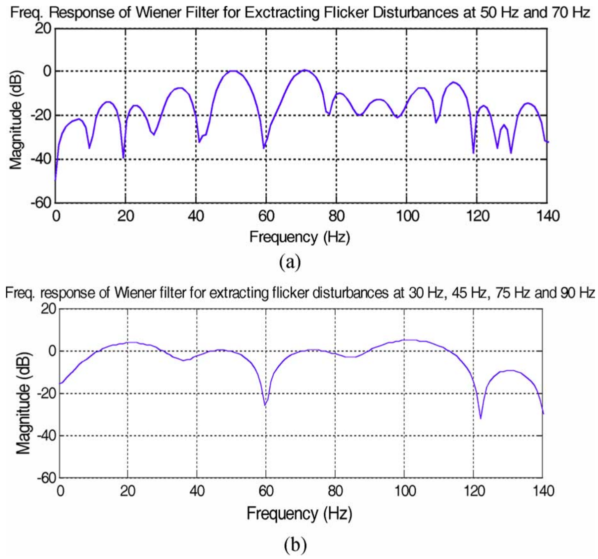


Fig. 4. Frequency response of the harmonic Wiener vector.



(a)

(b)

Fig. 5. Frequency response of the flicker Wiener vector. (a) Frequency response of the flicker Wiener vector with a single-frequency modulating signal at 10 Hz. (b) Frequency response of the flicker Wiener vector with a two-frequency modulating signal at 15 Hz and 30 Hz.

the operation or accuracy of extraction because the basic operation of this filter depends only on the frequency of harmonics.

Cyclic voltage and current fluctuations can be mathematically presented as a sum of disturbance signals of frequencies $\sum_{n=1}^{m} \omega_{\text{fundamental}} - \omega_{\text{modulating}-n}$ and $\sum_{n=1}^{m} \omega_{\text{fundamental}} + \omega_{\text{modulating}-n}$, where $\omega_{\text{fundamental}}$ represents the frequency of a fundamental component, $\omega_{\text{modulating}}$ represents a modulating signal with a specific frequency, and m is the number of frequencies inside the modulating signal [18]. Fig. 5(a) demonstrates the frequency response of the flicker Wiener filter for just 10-Hz modulation in the fundamental signal. Also, Fig. 5(b) illustrates the frequency response for a modulating signal with two frequencies of 15 Hz and 30 Hz. It is evident that Fig. 5 depicts the disturbances of almost 0 dB at frequencies $\omega_{\text{fundamental}} - \omega_{\text{modulating}}$ and $\omega_{\text{fundamental}} + \omega_{\text{modulating}}$ for each frequency $\omega_{\text{modulating}}$ inside the modulating signal, and shows the suppression of the 60-Hz fundamental component in order to just extract the fluctuation disturbances. IEEE standards 141-1993, 519-1992, and IEC 61000-3-3 do not require 100% compensation for voltage flicker disturbances; they require the flicker disturbances to be reduced lower than the irritation level. The performance of the flicker Wiener vector, as indicated in Fig. 5, shows the capability of the proposed filter for extracting flicker disturbances of multiple frequencies at 0 dB which match with IEC 61000-4-15 that stipulates the flicker modulating frequencies from 0.5 Hz to 33 Hz.

B. Generic Modular Compensating Strategy

The notion of extracting each PQ disturbance can be stacked together in order to simultaneously extract several disturbances, such as voltage or current fundamental, harmonics, and fluctuations. The generic strategy consists of several modules (Wiener vectors or filters). The suggested generic compensating strategy is demonstrated in Fig. 6 in which the distorted signal is sampled and applied to three modules. Each module has one Wiener filter or Wiener vector which is responsible for extracting a specific disturbance (a PQ problem). It is also possible for any module to include more than one Wiener filter based on the characteristics of the extracted disturbances such as multifrequency flicker.

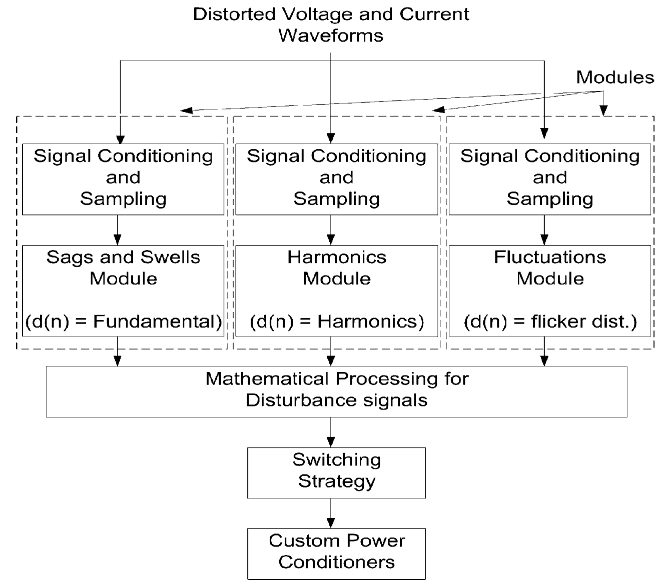


Fig. 6. Generic modular compensating strategy.

The output of each module is determined by the signal $d(n)$ (shown in Fig. 6), as defined and explained in Sections II and III.

Each module works as a classifier and filter at the same time because the Wiener vector of each filter is designed to extract a specific disturbance, with a definite frequency, and attenuate the other disturbances or components. The operation of all modules, shown in Fig. 6, is demonstrated in Fig. 7. In this figure, a general distorted waveform is presented Fig. 7(a). The extracted fundamental, harmonics, and flicker disturbances are illustrated in Fig. 7(b)–(d), respectively.

Consequently, the extracted disturbance signal is mathematically processed to generate switching strategies and driving signals in order to operate the parallel or series power conditioners. The parallel power conditioner is devoted to current-quality problems, and is configured with regular three single-phase current-controlled voltage-source converters. The series power conditioner is devoted to voltage-quality problems, and it consists of three single-phase PWM voltage-source converters. The topologies of the power conditioners in this research are similar to the ones utilized in [16]. Another advantage of this proposed strategy is that it is modular. Each module is responsible for a specific problem. Also, the proposed strategy is expandable; it is possible to add any number of modules because each module is totally independent of the others.

IV. SIMULATION RESULTS

This section presents the mitigating performance of the proposed compensating strategy for PQ improvement. An example for harmonic mitigation will be addressed in the first subsection, the Wiener filter that is used inside the harmonic module has the order of 85. In the second subsection, the compensation of a single-frequency fluctuation disturbance will be illustrated;

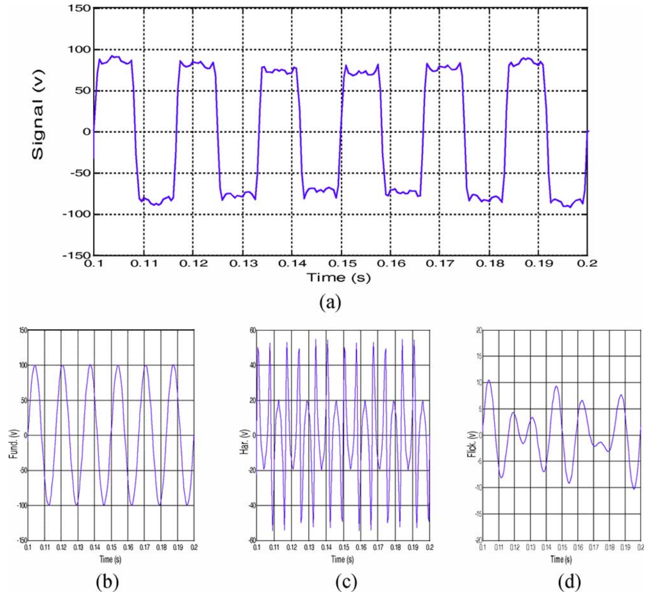


Fig. 7. Performance of the generic modular compensating strategy for extracting and classifying several disturbances. (a) General distorted signal. (b) Extracted output of the first module (example of a stationary PQ problem). (c) Extracted output of the second module (example of a transient PQ problem). (d) Extracted output of the third module (example of a complex PQ problem).

in that case, the utilized Wiener filter has the order of 255. In the last subsection, the mitigation of sags and swells will be explained by using the Wiener filter with the order of 40. As mentioned in Section III, the order of the Wiener vector or filter is determined based on the characteristics of the PQ problems.

A. Harmonic Disturbance Mitigation

In this part, current harmonics will be considered as an example for harmonic disturbances. The proposed harmonic module, (shown in Fig. 6), is examined for multiple harmonics, and its performance is compared with the adaptive perceptron, (Adaline), technique [12]. The adaptive percetron technique is considered to be the most simple and accurate technique for harmonic extraction. The distorted current can be expressed by

$$\begin{aligned} I =\ & 130\sin(2\pi 60t + 10^\circ) + 50\sin(2\pi 180t + 20^\circ) \\ & + 30\sin(2\pi 300t + 30^\circ) + 21\sin(2\pi 420t + 40^\circ) \\ & + 17\sin(2\pi 5400t + 50^\circ) + 14\sin(2\pi 660t + 60^\circ). \end{aligned} \tag{7}$$

This distorted current waveform is depicted in Fig. 8. The output of the proposed Wiener filter (based on the frequency response of Fig. 4) and the adaptive perceptron technique is demonstrated in Figs. 9 and 10, respectively. The comparison between these figures proves the similarity of both techniques for instantaneous extraction of harmonics. Moreover, the proposed technique is as simple as the adaptive perceptron since both techniques do not required any sophistication or mathematical burden to extract the harmonic disturbances.

The quantification of the simplicity for the employed Wiener filter compared with the adaptive perceptron is given in Table I. The comparative study of Table I is done to obtain just one point of disturbances in Figs. 9 and 10.

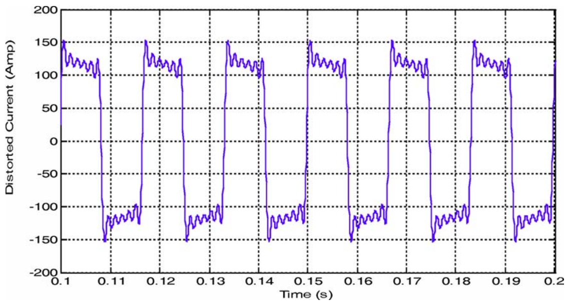


Fig. 8. Distorted current waveform.

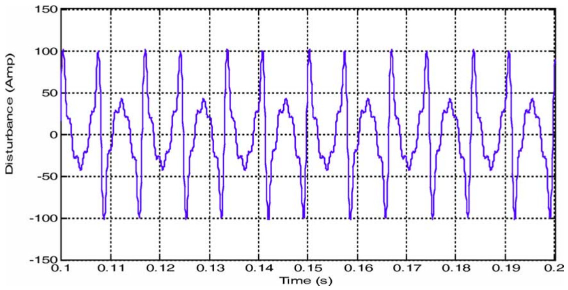


Fig. 9. Disturbance extraction by the proposed Wiener filter.

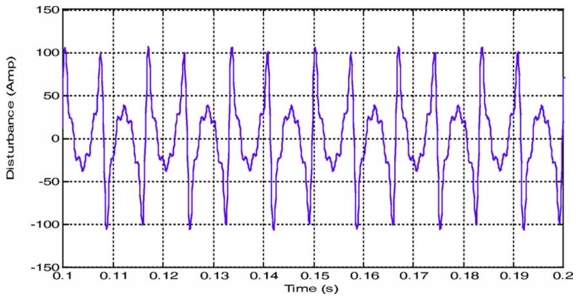


Fig. 10. Disturbance extraction by the adaptive perceptron.

TABLE I
Quantification for Simplicity of the Wiener Filter Compared to Adaptive Perceptron Based on the Employed Wiener Filter of Order 85

Required mathematical operations	Proposed Wiener filter	Adaptive perceptron
Multiplication and division operations	85	44
Addition and subtraction operations	84	72

The disturbance signal (depicted in Fig. 9) is used to operate a parallel power conditioner. The power conditioner is operated using a hysteresis current controller. The mitigated current waveform is displayed in Fig. 11.

The effectiveness of this mitigating process is confirmed by harmonic spectrums before and after the mitigating process; these spectrums are illustrated in Figs. 12 and 13. Also, the current total harmonic distortion (THD) is reduced from 50% to 4.2%.

If the supply frequency drifts due to any transient disturbance in the system, the proposed filters work adequately because the frequency response of the filter, at low-order harmonics, is flat around 0 dB as illustrated in Fig. 4. Consequently, there will

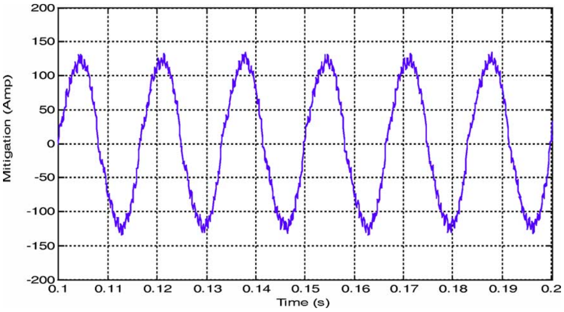


Fig. 11. Mitigated current waveform.

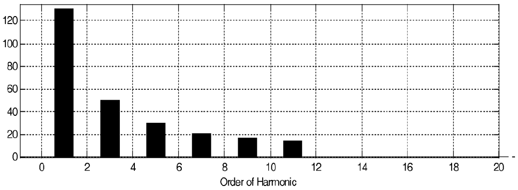


Fig. 12. Harmonic spectrum before compensation.

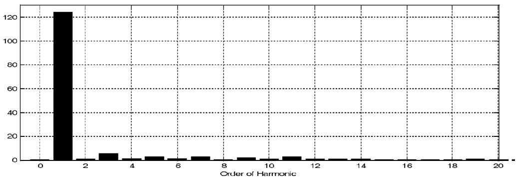


Fig. 13. Harmonic spectrum after compensation.

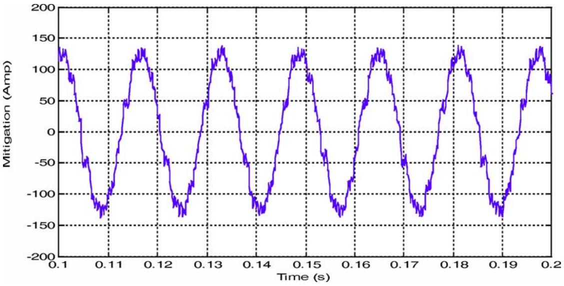


Fig. 14. Mitigated current waveform with a frequency drift of 2 Hz in the fundamental component.

be slight attenuation or amplification if the supply frequency drifts. Although the frequency curve is not flat at high-order harmonics, their values are usually less influential on the distortion level of any waveform. If fundamental frequency drifts by 2 Hz; then, the frequency drifts by 2$*$ harmonic order for any other harmonic signal. The distorted current of (7) is considered with a fundamental frequency drift of 2 Hz. The mitigated current waveform using the same harmonic Wiener filter is demonstrated in Fig. 14.

Also, the harmonic spectrum of the previous mitigated current waveform is illustrated in Fig. 15 where the low-order harmonics are adequately minimized. The THD for this case is 8.9%; however, no worry about the THD value for that case because the frequency drift is a transient PQ problem.

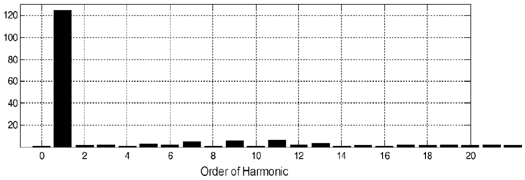


Fig. 15. Harmonic spectrum after compensation with a frequency drift of 2 Hz in the fundamental component.

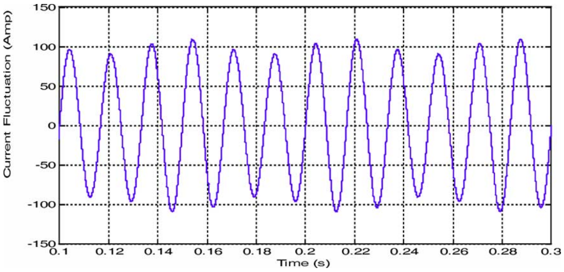


Fig. 16. Current fluctuation waveform.

Fig. 17. Interharmonic spectrum of current fluctuation.

B. Fluctuating Disturbance Compensation

The single-frequency modulation for cyclic current fluctuation is a common current problem in industrial distribution systems, and it will be considered in this section. It is difficult to extract its disturbance because it is defined as the multiplication of two signals with known frequencies—the fundamental and modulating signals [18]. Fig. 16 gives an example for the current fluctuation waveform which is based on a modulating frequency of 15 Hz. The disturbances embedded in the fluctuation waveform are demonstrated in the interharmonic spectrum of Fig. 17 in which the base frequency is equal to the modulating signal frequency. This spectrum indicates the disturbances at third and fifth orders with a value of 5 A. These disturbances lead to the fluctuation in the envelope of the current as shown in Fig. 16.

The extraction of the disturbance signal is performed by the proposed Wiener filter and the Kalman filter. It is known that the Kalman filter can be used for such applications [10]. The tracking results of the Wiener filter and the Kalman filter are illustrated in Figs. 18 and 19, respectively.

It is obvious from the previous two curves that the proposed recursive Wiener filter is as accurate as the Kalman filter with very slight differences. These differences emanate from the frequency response of the Wiener vector for the fluctuating current as explained in Fig. 5.

The extraction of the fluctuation disturbance is accomplished by multiplying the Wiener vector by the distorted current waveform as described in Sections II and III. Meanwhile, the extraction of flicker disturbance by using the Kalman filter requires

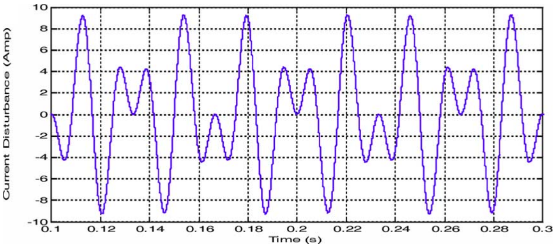


Fig. 18. Fluctuating disturbance extraction using the proposed Wiener filter.

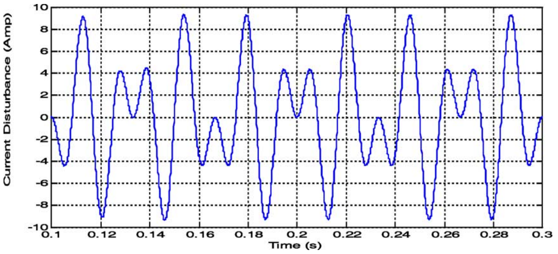


Fig. 19. Fluctuating disturbance extraction using the Kalman filter.

TABLE II
INDICATION FOR SIMPLICITY OF THE WIENER FILTER COMPARED TO THE KALMAN FILTER BASED ON THE EMPLOYED WIENER FILTER OF ORDER 255

Required mathematical operations	Proposed Wiener filter	Kalman filter
Multiplication and division operations	255	1080
Addition and Subtraction operations	254	1296

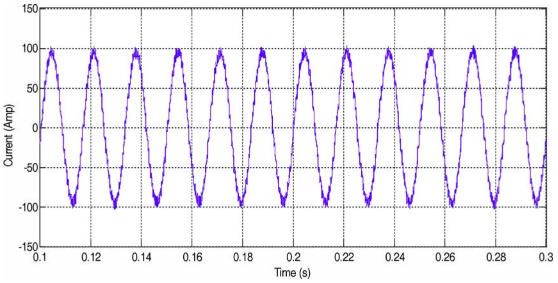


Fig. 20. Compensation of the current fluctuation.

a complicated model to form a predictor–corrector algorithm required by the Kalman filter [10]. The indication of the mathematical simplicity for the proposed Wiener filter compared to the Kalman filter is given in Table II. The comparative study of Table II is done to obtain just one point of disturbances in Figs. 18 and 19.

The compensation of the current fluctuation is depicted in Fig. 20. The effectiveness of compensation is visualized in the envelope of the compensated current which becomes constant at 100 A. Moreover, the efficiency of compensation can also be confirmed by showing the interharmonic spectrum for the compensated waveform. This spectrum is illustrated in Fig. 21. The base frequency of Fig. 21 is equal to the same modulating-signal frequency, which is 15 Hz in this case.

Fig. 21 represents the harmonic spectrum for the compensated waveform to the order of 20. It is apparent that the comparison between Figs. 17 and 21 indicates the effectiveness for suppressing the fluctuation disturbances. The high-frequency noise depicted in Fig. 20 is not shown in the harmonic spectrum of Fig. 21 because it has very high order in the range of 150, and its magnitude is small.

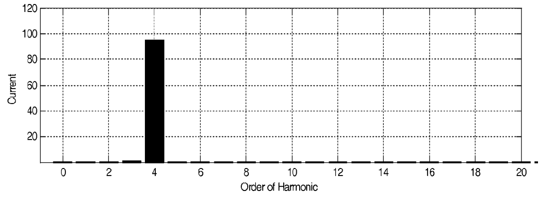


Fig. 21. Interharmonic spectrum to the 20th order.

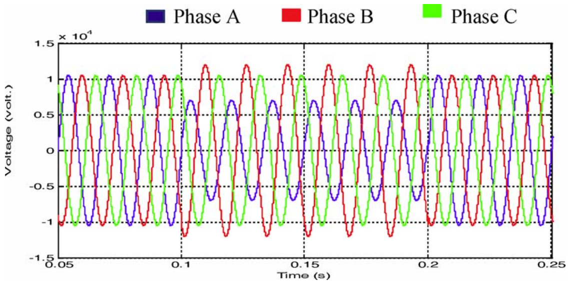


Fig. 22. Sag and swell waveforms.

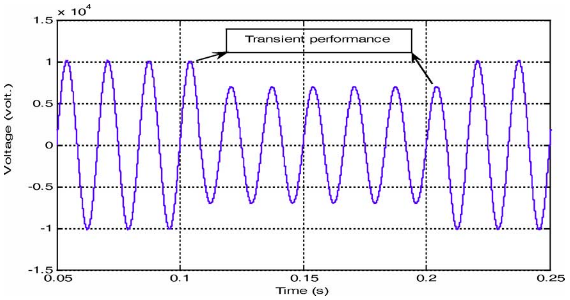


Fig. 23. Instantaneous tracking for phase A sag by the Wiener filter.

C. Sag and Swell Disturbance Mitigation

Voltage sags and swells have several types—each type of sag or swell depends on the source which causes these sags or swells, the single-line ground faults have 75% of all faults that cause sags or swells in distribution systems [22]. If the system is not perfectly grounded at different neutral points, then a single-line-to-ground fault may cause a sag in one phase and a swell in the second phase and the third phase may have a minor change. Fig. 22 exemplifies this type of disturbance. The instantaneous tracking of the sagged waveform of phase A by the proposed Wiener filter is shown in Fig. 23.

Also, the performance of the *d*–*q* orthogonal technique for tracking the same sagged waveform is indicated in Fig. 24. It is known that the *d*–*q* orthogonal coordinate is considered one of the best techniques that can be used for sag and swell tracking and mitigation [14].

As seen in Figs. 23 and 24, both techniques have the same accuracy for the steady-state performance; also, they have similar transient time which is almost half a cycle. The transient per-

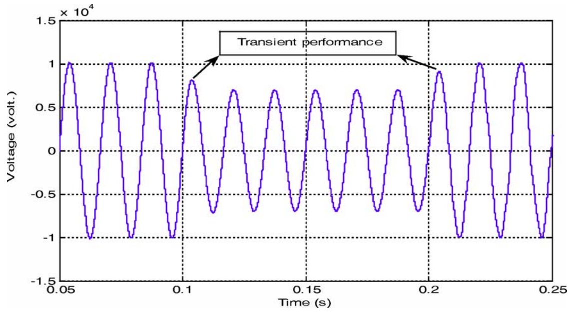


Fig. 24. Instantaneous tracking for phase A sag by the d–q technique.

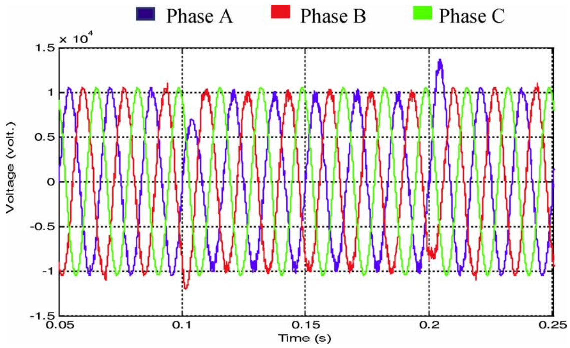


Fig. 25. Mitigation of voltage sag and swell.

formance for the Wiener filter comes from the delay associated with the FIR filter structure as explained in Section II.

The mitigation of the sagged and swelled voltages is illustrated in Fig. 25. The overshoot, roughly 35%, and undershoot, roughly 33%, result from the transient performance of the Wiener filter as shown in Fig. 23. It is noteworthy to mention that the overshoot and undershoot of Fig. 25 are not harmful to industrial loads because their duration is very small, (almost half a cycle). Based on the CBEMA curve or ITIC curve, (IEEE Standard 1195-1995), half a cycle transient time will not negatively affect most of the industrial equipment at low-voltage levels since these curves allow severe voltage dips up to 0.5 cycle for the safe operation of the equipment.

V. CONCLUSION

This paper introduces a new modular compensating strategy for the most common stationary and transient PQ problems. The proposed extracting technique, which depends on a novel formulation for Wiener filters, is fast and accurate compared to the other commonly used techniques. Moreover, the contribution of the proposed strategy is implicated in its mathematical simplicity, accuracy, and speed compared to other state-space techniques which are utilized for the same applications. The harmonic disturbances are extracted and mitigated accurately. Current fluctuation disturbances can be extracted and compensated with more mathematical simplicity and less computational burden than the commonly used techniques for fluctuation extraction. The proposed strategy can be utilized not only for the stationary PQ problem, but also for transient ones, such as voltage sags and swells. Evidently, the proposed compensating strategy is modular and expandable based on the requirement of PQ in the system.

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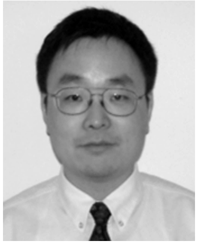

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