A Smart Power Quality Monitoring Strategy

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ABSTRACT

The objective of this paper is to discuss and introduce an efficient and reliable power quality (PQ) monitoring strategy that uses the advances in signal processing and pattern recognition to improve power quality monitoring practices. The proposed monitoring strategy is capable of detecting, tracking, and classifying any power quality violation by the use of on-line measurements. Methodologies which can be utilized for identifying the source of PQ problems based on the recognized phenomena will be discussed. Various simulation results are introduced to validate the use of the proposed monitoring strategy.

1. INTRODUCTION

The proliferation of sensitive electronic equipment, besides the deregulation of the electric power industry, is making the quality of delivered power an increasingly important issue [1], [2]. Customers with sensitive electronic equipment such as computers, variable speed drives, robots, electronic controllers, and automated industrial production lines are vulnerable to power quality (PQ) variations. According to a recent study [3], the malfunction of equipment in the industrial sector, due to voltage disturbance alone, costs the US industry more than 20 billion dollars every year. A power quality monitoring strategy must be developed to make the process of classifying PQ problems, and identifying their sources feasible in the deregulated era. In the future, the identification of the source of the disturbance will be essential to solve disputes about PQ.

The objective of this paper is to demonstrate an efficient and reliable PQ monitoring strategy that uses the advances in signal processing and pattern recognition to overcome the deficiencies that exist in power quality monitoring devices.

As depicted in Figure 1. The proposed monitoring strategy for power quality disturbances consists of four stages that are tracking, detecting, classifying power quality events and identifying the source of power quality violation.

Accurate tracking and classification of power quality events will lead to improvement of the characterization of power quality phenomena. This information will be valuable for sensitive equipment designers, power quality standards developing committees, mitigation equipment designers, and characterization of customer utility interface problems.

Moreover, accurate characterization of power quality events and localization of the source of violation will ultimately help in solving power quality problems and enhance the supply quality.

This paper is organized as follows: Section 2 discusses the preprocessing of voltage and current signals which entails signal denoising and detection of PQ events. The tracking of PQ disturbances is examined in Section 3. A general frame work for classification of PQ disturbances based on a similarity measure is introduced in Section 4. Section 5 discusses the algorithms which can be utilized to identify the source of power quality problems. Finally, conclusions are presented in Section 6.

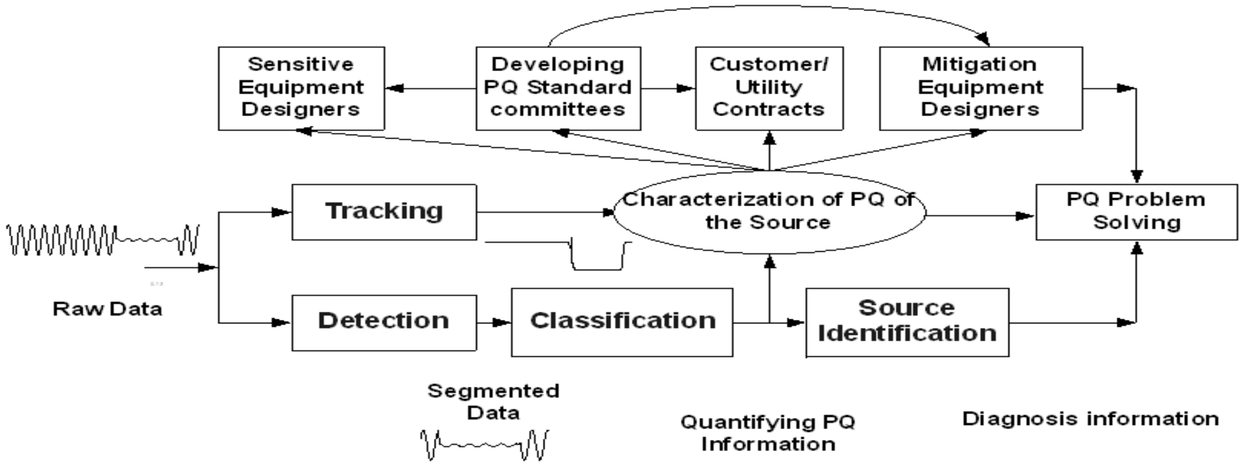

Figure 1: Proposed Power Quality Monitoring Strategy

2. PRE-PROCESSING-EVENT SEGMENTATION

Pre-processing stage is a prerequisite for any automated power quality analysis. The pre-processing stage entails signal de-noising, normalization, and detection and segmentation of power quality events. This section highlights the existing research effort toward pre-processing of electric signal and suggests Adaline as a tool for detecting any power quality violation

2.1. SIGNAL DE-NOISING AND NORMALIZATION

Accurate characterization and classification of power quality events necessitates the suppression of the high frequency noise superimposed on the signal. Wavelet Transform can be utilized effectively for de-noising the voltage signal [4-5].

2.2. DETECTION AND SEGMENTATION

Existing power quality instruments detection mechanism is based on point-by-point comparison on two adjacent power cycles [6]. The disturbance recognition is accomplished when certain threshold is reached. This method is insensitive to steady state power quality phenomena like harmonics and sub-harmonics. Moreover, this method is sensitive to the chosen threshold value. To overcome these problems, several techniques have been proposed in the literature for power quality detection. Among those techniques is the Teager energy operator based on instantaneous energy extraction and has good capability for extracting the short time energy of the signal [7]. Another approach is to utilize fractal geometry in event detecting. This approach depends on fractal number computation integrated with moving average technique [8]. Wavelet transform has been also utilized as a power quality disturbance detector as the high frequencies associated with power quality disturbance could be distinguished and localized in time using low scale levels [9-10]. In the proposed monitoring strategy, the utilization of an adaptive linear neuron (Adaline) in detection of power quality disturbances is considered. In the detection scheme, Adaline will work as an adaptive signal predictor [11]. The input to this predictor is time-delayed samples of the signal and the output of the Adaline is the predicted value of the signal. Detection of power quality events using Adaline is depicted in Figure 2

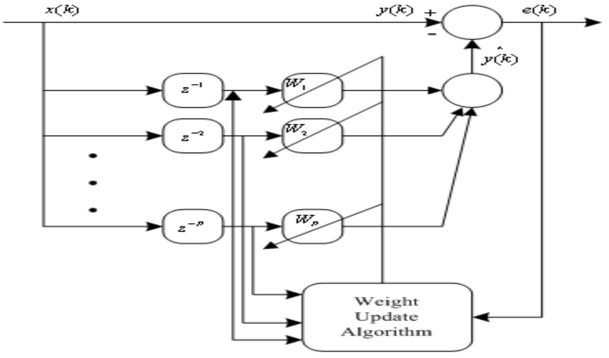

Figure 2. Detection of power quality events using Adaline

The Adaline algorithm possesses a highly tracking capability. However when a power quality disturbance occurs, the sudden change in the voltage signal gives rise to the error signal generated by the Adaline. The change in the error signal can be used in the detection of power quality events.

Figure 3 shows the utilization of Adaline in detection of voltage sag event. This event is extracted from EMTDC\PSCAD simulation of a practical distribution system [11].

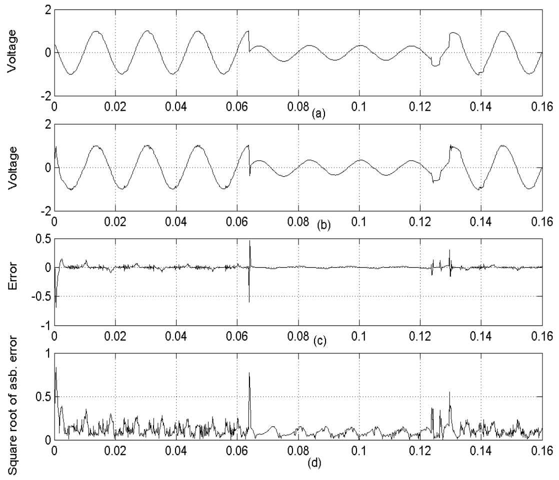

Figure 3. Detection of voltage sag events using ADALINE scheme; a) voltage signal; b) tracked signal; c) error signal generated from Adaline; d) square of the absolute of the error signal [11]

3. TRACKING OF POWER QUALITY EVENTS

Section 2 introduces the ADALINE for PQ event detection. The detection step is important in order to activate the tracking and classification algorithms. The application of the Kalman Filter (KF) for on-line tracking for power system harmonics has been thoroughly investigated by Girgis et al. [12]. Also, Dash et al. have introduced the Adaline as a tool for tracking power system harmonics [13]. Both techniques yield good results in tracking power system harmonics. Teager Energy Operator (TEO) and Hilbert Transform (HT) have been introduced as new tools that can track the disturbances which affect the fundamental frequency component, and complement the use of the KF and the ADALINE for PQ tracking purposes [14]. The mathematical simplicity of the proposed techniques, compared with the commonly used algorithms in the literature, renders them competitive candidates for the on-line tracking of fundamental voltage variations in distribution systems. Following is a brief discussion for the algorithms which can be utilized in tracking short duration voltage variations and voltage fluctuations.

3.1 Kalman Filter for Harmonic Tracking

Kalman Filter as introduced in [13],[15] will be used in tracking the fundamental component of the voltage signal as well as the harmonic components. In Kalman filter modelling for harmonic tracking each harmonic component can be represented by two state variables, which represent in phase and quadrature components as shown in Equation 1.

$$[X] = \Big[A_1(t)\cos\theta_1 \quad A_1(t)\sin\theta_1 \quad A_2(t)\cos\theta_2 \quad A_2\sin\theta_2$$

$$\ldots.\ A_n(t)\cos\theta_n \quad A_n\sin\theta_n \Big]^T \qquad (1)$$

Now Kalman filter state equation can be expressed as:

$$X_{k+1} = \phi_k X_k + w_k \qquad (2)$$

And the measurement equation as:

$$Z_k = H_k X_k + V_k \qquad (3)$$

Where ϕ_k is a unity matrix with dimension equal to $2n \times 2n$ and,

$$H_k = [\cos(\omega k\Delta t) - \sin(\omega k\Delta t) \ldots.. + \cos(n\omega k\Delta t) - \sin(n\omega k\Delta t)]$$

Z_k is the measurement vector at instance k, H_k is the vector, which gives ideal relation between states and measurement, and V_k is the noise covariance vector.

Figure 5 shows the performance of Kalman filter in tracking of the fundamental component of a voltage signal contaminated with harmonic during a sag event.

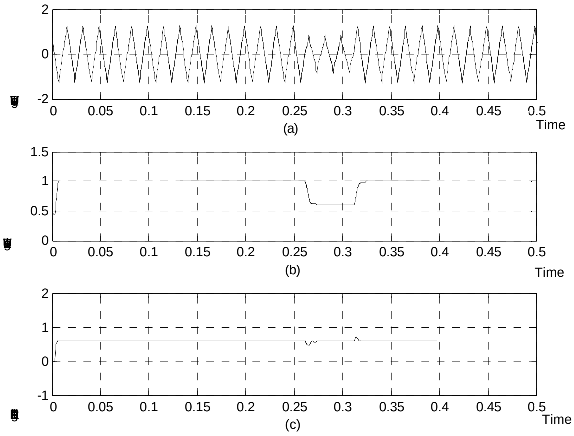

Figure 5: Kalman filter tracking of fundamental components of a voltage sag for signal contaminated with harmonics; a) voltage waveform; b) fundamental component tracking; c) phase angle tracking

3.2 Hilbert Transform

Hilbert Transform (HT) is a mathematical transform that shifts each frequency component of the instantaneous spectrum by 90 degrees without affecting the component magnitude. The HT can be employed to track the envelope of the signal as depicted in [14].

3.3 Teager Energy Operator

The TEO is a non-linear operator, which is capable of tracking the instantaneous energy content of the signal. It is proven that the value of this operator is equal to the product of the square of the multiplication of the signal amplitude by its frequency. The square of the multiplication of the signal amplitude and the frequency can be obtained by using only three consecutive samplings, one multiplication operation, and one subtraction operation. However, in order to track the signal amplitude and frequency, a separation algorithm is still needed. The separation algorithms to obtain the signal amplitude are discussed thoroughly in [14].

Figure 6 shows the tracking of short duration voltage variations using Hilbert Transform and TEO, the instantaneous nature of TEO can be noticed in this figure

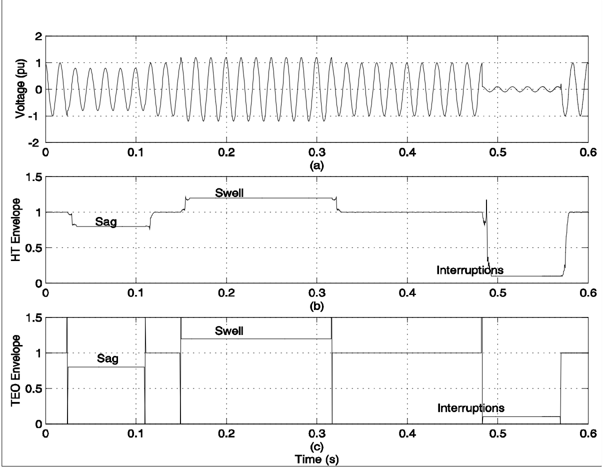

Figure 6. Short Duration Voltage Variation Tracking using Hilbert Transform and TEO

4. EVENT CLASSIFICATION

After the detection of PQ disturbances, the classification of the disturbances is mandatory to identify the disturbance type. Recently, many automated systems for the classification of PQ have been designed. Typically, they are based on the Fourier Transform [15] or Wavelet Transform [16], [17] for feature extraction. The Wavelet Transform is a relatively new and powerful tool for analyzing PQ disturbances. The Wavelet Transform has been applied for the detection and classification of PQ disturbances [18], [19], [20] because of its ability to extract information from the voltage signal simultaneously in both the time domain and frequency domains. Then, distance classifiers [20], Artificial Neural Networks (ANNs) [19], Fuzzy Logic (FL) [21] or Nuero-Fuzzy [22] are used to classify the disturbances. Distance classifiers are very simple classifiers which measure the distance between the test signal and the stored templates. However, such classifiers result in unsatisfactory classification accuracy, especially if the test signal does not exactly match the pre-stored templates. The challenge in the classification process of PQ disturbance signals, which may lead to low classification accuracy, is the non-uniform time alignment between the test signal and the pre-stored template. This fact arises from having various magnitudes, frequencies, and durations for each disturbance type. To overcome the limitations of FL and ANN classifiers and to handle the issue of alignment, a template matching automated recognition system is presented here as a powerful tool for classifying power quality events. The system is based on the strategy of measuring the similarities between the disturbances being tested, and the pre-stored signatures of different PQ disturbances. This classification strategy is depicted in Fig. 7. The power quality automated recognition system is divided into the feature extraction and the Vector Quantization (VQ) step, and the classification step. In the training stage, labeled training cases are utilized to build a database from the disturbance signatures, this database is in the form of a sequence of labels, which represent different disturbances, or it contains the parameters of trained Hidden Markov Models (HMMs). A separate HMM is constructed for each disturbance in the training stage. FT is applied to the disturbance signal by using a sliding window with a specific width and overlap. Then, the VQ is applied to the FT spectral coefficients of each window. The VQ step produces one label per window and it develops a series of labels, which characterize the disturbance sequence. The degree of similarity and matching between the test signal and the pre-stored signals represented by the sequence of VQ labels can be measured using two different approaches: HMMs, and Dynamic Time Warping (DTW) [23],[24]. In the training phase, DTW templates, and HMMs are generated and stored in a database. In the testing phase the labels generated from the VQ step is matched against all the HMMs and DTW templates in the database. This strategy has shown a promising results as discussed in [23],[24].

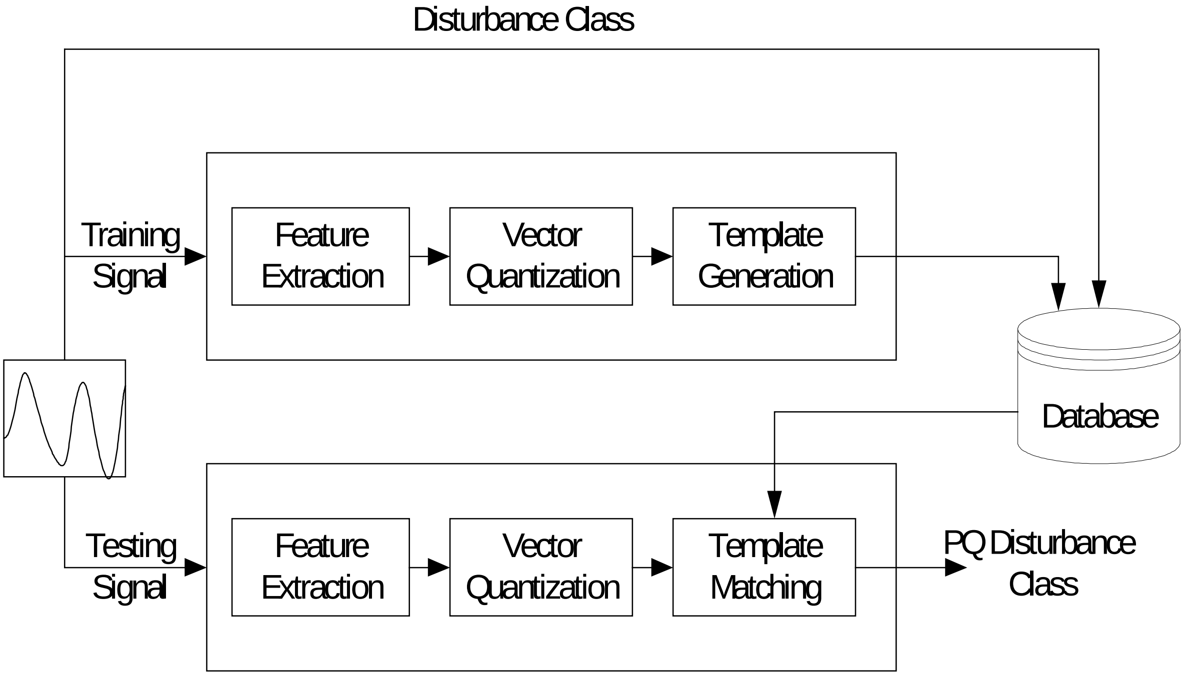

Figure 7. Classification by template matching block diagram

5. SOURCE LOCALIZATION

Power quality problems source localization is a crucial task in deregulated power system since this will solve many disputes regarding power quality problems. Moreover, it will eventually lead to minimizing the time required to enhance the quality of the supply by shorten time taken to tackle power quality problems.

After automated classification of power quality events, it is possible to run algorithms to identify the source of the classified event. Typically, the input to these algorithms would be the voltage and current signals measured at the location of power quality monitor, information regarding network topology, and voltage and current signals measured at different location of the network if a communication between power quality monitors is available.

Voltage sags, harmonics, and transients are the most annoying power quality problems in terms of financial cost they may cause. In this section a brief discussion on the existing methodologies which can be utilized in localizing source of these disturbances are discussed.

5.1 Harmonic source localization

Identification of dominant harmonic source at the point of common coupling (PCC) has recently captured the attention of many researchers. The proposed monitoring strategy can employ one of the following proposed techniques to identify the harmonic source at the PCC:

- Kalman filter method [25]
- Critical impedance method [26]

- Checking direction of harmonic current flow and checking the direction of active harmonic power flow [27]

5.2 Voltage sag source localization

In the proposed methodology a two level approach is adopted to localize the voltage sag source. Voltage sag envelope characteristics for sag originating from the supply side primarily due to faults will be different than voltage sag envelope characterization from customer side primarily due to switching operation because of the variation of active and reactive power requirements in both cases. In the first level, voltage sag envelope characterization will be developed by utilizing Hilbert Transform (HT), and then the salient features of the voltage envelope extracted by HT will be utilized to determine if the origin of the sag is the supply side or the customer side. In the second level, at the supply side, similar algorithms which utilized in protection can be used to identify the type of the fault as well as estimating the location of the fault. In the customer side, analysis of active and reactive energy consumption during sag period can be utilized to identify the source of the sag since switching operation by different customer load would generate different demand on active and reactive power which could be characterized and associated with the source of the voltage sag.

5.3 Source of transients localizations

Transients in distribution systems due to capacitor switching have been thoroughly investigated in the literature [28], [29]. Nowadays, a few studies have focused on identifying the capacitor location which causes the transient [30], [31], [32]. The method introduced in [30] is based on the FFT which is not the most appropriate tool to deal with the transient events. The method introduced in [31] is only applicable to small systems only, and is very difficult to be extended to large systems. In [32], the authors used the backward Kalman filter to deal with identifying the switched capacitor with noticeable success. However, modelling uncertainties of the capacitor status (on/off) and load levels such as process noise are not very accurate assumptions, especially if the objective is to identify the switched capacitor. a new approach for identifying the switched capacitor in distribution systems is proposed. The method relies on locating the switched capacitor bank from a transient voltage signal measured at the facility entrance by using high frequency resolution method such as ESPRIT [32]. High resolution methods can extract the transient voltage modal information which is functions in the switched capacitor location precisely. This modal information can be related to the switched capacitor location and it would outperform the methodologies which are based on FFT [33].

6. CONCLUSIONS

In this paper, a strategy based on digital signal processing and pattern recognition algorithms for improving the available PQ monitoring techniques are discussed. These algorithms facilitate precise on-line detecting, tracking, and classifying PQ events. Moreover, in a step towards linking PQ events to their causes, the existing algorithms which tackle the identification of harmonic source are discussed; a two step procedure to identify the source of voltage sag is described; a general frame work for identifying the switched capacitor from the measured transients utilizing high resolution models such as ESPRIT to extract the voltage signal modal information precisely and relate them to the location of the switched capacitor is proposed.

7. ACKNOWLEDGEMENTS

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