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An alternate approach for power quality computation using sample shifting technique towards load characterization

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ABSTRACT

This paper aims to estimate the pollution created by domestic electric appliances by evaluating harmonic components of electrical parameters like voltage, current, active and reactive powers and total harmonic distortions which in turn define the power quality issues. These parameters are used to create load signature pattern which is different for various appliances. Load respective signatures are analyzed for characterization to define basic electrical performances and are exploited to estimate healthiness during their running. Sample shifting technique (SST) is utilized to estimate harmonic components of the parameters. A comparatively easy to implement SST works only on the sample values and does not require any complex computation. A microcontroller based hardware prototype is developed to create signature patterns of appliances for characterization purposes utilizing SST in its firmware and its performance is evaluated with IEEE 1459-2010 dataset. These signature patterns are exploited for characterization of five different appliances.

1. Introduction

Power quality is a kind of electrical properties that may influence the proper function of electrical systems. Poor power quality can be described in various ways like, the consistency of power variation in magnitude and frequency, harmonic content in the waveform, transient changes, imbalance of phases, low power factor etc. Under the influence of inappropriate power quality, an electrical gadget may glitch, flop intermittently or not work by any means. Now-a-days, more and more distributed generation and sustainable power sources, e.g. wind, solar and tidal power etc., are utilized using power inverters to form a micro grid or tied with grid. A noteworthy power quality issue is the presence of harmonics in the voltage provided by the inverters. Besides, the loads with non-linearity in nature or with power electronic component based ones, generate harmonic currents when a purely sinusoidal supply is applied which, in turn, produces harmonics in the applied voltage. Harmonics are not desirable because they create overheating, increased losses, decreased power capacity, neutral line overloading, voltage and current waveform distortion, and so on. In order to have a better power quality, total harmonic distortion (THD) of voltage and current should be low value, often underneath 5% [1,2]. Various techniques for power quality measurement [3–6] as well as its improvement techniques [7] are described. To calculate THD the fundamental component and total harmonic components of voltage and current are needed to be separated from each other [7,8]. The individual harmonic components can be decomposed using sample shifting technique (SST), proposed by the authors [9,10], or with Fourier analysis etc. ways. The SST has the advantage of decomposing individual harmonic components of both active and reactive power, voltage and current parameters only from the samples of voltage and current signals.

Besides, for the efficient use of energy from grid and/or solar etc kind of RESs, the concept of SMART home is being evolved where the electrical appliances are designed to smart enough in terms of their functionalities and behavior under different supply conditions. The use of power electronic components is becoming ubiquitous in almost every such smart appliances and this results their characteristic a highly nonlinear one. Thus power quality or, in other words, power pollution issues are now becoming challenging concerns to the utilities and accordingly finding out the sources of the power pollution along with their mitigation techniques are of utmost important to the researchers. Accordingly, the performance analysis of the smart appliances is also becoming important in order to investigate about degradation in their running conditions, creating pollutions to the power system, and decrease in running efficiency with respect to time etc [11,12]. Power consumed and consumption pattern as well, harmonic generation, power factor and current signature, transient behavior etc. of every load is unique [13,14] and these unique features are used for performance

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analysis. Thus, electric signature analysis (ESA) in real time is extremely helpful to study the general behavior of the electric appliances [15–18]. Several studies have been proposed for the performance evaluation with power signatures in nonintrusive energy management (NIEM) [19–22]. Load signature pattern are utilized to characterize electrical loads [23–26] which helps the electricity consumer [27] about their usage and which can further help the utility for proper tariff design [28].

Motivated with these, the authors have tried to establish relationships among load signatures with various parameters related to power quality issues of various electric home appliances in order to characterize them for their healthy and unhealthy running.

For this, the authors have developed a hardware prototype which works on recently developed SST [10] using sample values of voltage and current signals only. The power quality parameters are evaluated using easy to implement SST instead of complex computation like FT or wavelet transform. The paper is organized such that the Section 2 deals with brief basics of ESA along with the measurement methodology of various electrical parameters. In Section 3, brief of the recently introduced generalized SST is explained and formulated to determine harmonic components of various parameters in polluted environment. In Section 4, the parameters along with their components are estimated using MATLAB based simulation. The proposed work is also tested with a prototype hardware system for five different appliances for estimating pollution created by them from their various signature patterns. In Section 5 load characterization based health monitoring of electrical equipment is explained while the achievements and critical findings are listed in conclusion section.

2. Materials and methods

2.1. Signature analysis for load characterization

The newly introduced electric signature analysis (ESA) is a diagnostic and analysis technique that is being used to characterize and analyze electrical machines, and other electric equipment. A periodic analysis of the driven loads, the power supply and perform inrush testing on motors and/or other loads helps in identifying a variety of mechanical and electrical problems. The degradation in the performance of the loads can thus be traced and hence a trend analysis of equipment performance can be made which can also be utilized as a preventative maintenance tool.

The electric signature analysis method is based on the analysis of two primary parameters viz. voltage and current of the load. It consists of voltage signature analysis (VSA), current signature analysis (CSA), and extended Park's vector approach (EPVA) and instantaneous power component analysis (IPCA). Since only smart home appliances are of interest where most of them are single phase equipment, EPVA is not considered in the paper as it requires three phase supply.

In order to adept other three techniques in an embedded controller for smart appliances, the authors have extracted the features of harmonic power estimation technique which is published in [9]. As stated in [9], a sample shifting technique is devised and adopted instead of Fourier Transform (FT) in order to evaluate the power components. As a consequence of authors' previous work [9,10] for parameter measurement using a micro-controller, the SST is extended to evaluate the VSA and CSA as well as IPCA only from the voltage and current sample values by a low cost embedded processor. The following sub-sections elaborate the mathematical background of finding out these parameters from sample values only.

2.2. Formulation of power estimation under pure sinusoidal environment

A pure sinusoidal voltage, current signals across a load are expressed as

$$v(t) = V_m \sin \omega t \text{ and } i(t) = I_m \sin(\omega t - \phi) \quad (1)$$

where, $v(t)$ and $i(t)$ are the instantaneous values of voltage and current signals with respect to time, V_m and I_m are their maximum values,ϕ is the phase difference between them and ω is the angular frequency.

The active and reactive powers of the load in terms of sample values are

$$P = P_{avg} = \frac{1}{2\pi}\int_0^{2\pi} v(t)i(t)d(\omega t) = VI\cos\phi = \frac{1}{N}\sum_{n=1}^{N} v_n i_n \quad (2)$$

$$Q = VI\sin\phi = VI\cos(90-\phi) = \frac{1}{N}\sum_{n=1}^{N} v_n i_{-90^\circ n} \quad (3)$$

where,v_n and $i_n$are the n^{th} sample values of voltage and current signals respectively, $i_{-90^\circ n}$ is the 90° shifted sample values of i_n, the shifting technique is explained in [10] and N is the total number of samples over a line cycle. V and I are the r.m.s. values of the $v(t)$ and $i(t)$ respectively. P and Q are the active and reactive powers consumed by load.

2.3. Formulation of power under polluted environment

The voltage and current signals, contain h number of harmonics, are expressed as

$$v(t) = \sum_{k=1}^{h} V_{km}\sin k\omega t \text{ and } i(t) = \sum_{l=1}^{h} I_{lm}\sin(l\omega t - \phi_l) \quad (4)$$

where, $v(t)$ and $i(t)$ are the instantaneous values of the composite voltage and current waveforms. ϕ_l is the phase angle of l^{th} harmonic current component. V_{km} and I_{lm} are the maximum values of the k^{th} and l^{th} harmonic components of voltage and current respectively.

The generalized power formulas [9] for active and reactive power estimations are obtained as given below

$$\left.\begin{aligned} P_i &= \tfrac{1}{h+1}\sum_{n=0}^{2h+1} R_n\cos n(i\theta) \\ Q_i &= \tfrac{1}{h+1}\sum_{n=0}^{2h+1} R_n\sin n(i\theta) \\ P_{dc} &= \tfrac{1}{h+1}\sum_{n=0}^{2h+1} R_n \end{aligned}\right\} \quad for \quad i = 1, 2, \ldots\ldots, h \quad (5)$$

$$R_n = \frac{1}{N}\sum_{s=1}^{N} v_s i_{s(-n\pi/(h+1))} \quad \text{for } 0 \leqslant n \leqslant (2h+1) \quad (6)$$

where, v_s is the s^{th} sample value of $v(t)$, $i_{s(-n\pi/(h+1))}$ is the sample of the current waveform $i(t)$ shifted by $n\pi/(h+1)$ P_i and Q_i are the active and reactive power of i^{th} harmonic component. P_{dc} is the dc power. The detail derivations of (5) and (6) are described in Appendix A.

2.4. Formulation of voltage estimation

True r.m.s. value of voltage is estimated from the samples of composite voltage signals as

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} v^2(t)d(\omega t)} = \sqrt{\frac{1}{N}\sum_{j=1}^{N} v_j^2} = V \quad (7)$$

where, $v(t)$ is expressed in (4), v_j is the j^{th} sample of voltage $v(t)$. For the voltage signal containing h number of harmonics, the concept of Eq. (5) is extended to estimate voltage harmonic components as,

$$\left. V_i = \sqrt{\frac{1}{h+1}\sum_{n=0}^{2h+1} R_{nv}\cos n(i\theta)} \right\} \quad i = 1, 2, \ldots\ldots, h \quad (8)$$

$R_{nv} = \frac{1}{N}\sum_{s=1}^{N} v_s v_{s(-n\pi/(h+1))}$ for $0 \leqslant n \leqslant (2h+1)\theta = \frac{\pi}{h+1}$where, $v_{s(-n\pi/(h+1))}$is the sample of the voltage waveform $v(t)$ shifted by