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Smart-Metering for Monitoring Building Power Distribution Network using Instantaneous Phasor Computations of Electrical Signals

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Abstract—This paper presents a smart-metering framework based on computations of instantaneous phasors of voltage and current signals measured at a given node. The idea and requirement of electrical transparency inside a building is presented initially. Then the implementation of phasor estimation algorithm is discussed for the purpose of smart-metering. The capability of the smart-meter to do detailed power quality analysis is also presented. The ongoing work of hardware implementation and real-time testing of such smart-metering is also mentioned in the paper.

Keywords— *harmonic analysis, instantaneous phasors, power quality, smart-meter*

I. INTRODUCTION

The implementation of smart-metering is one of the significant steps towards the realization of smart-grids [1-2]. Considering the profuse penetration of nonlinear devices into the grid, energy management and maintaining the quality of power has become more challenging than ever. The scenario of a network inside a building is considered here. The smart grid envisions that the future grid would be an intelligent grid of intelligent devices; each device being a programmable/programed entity [3-4]. Individual smartness of devices along with a supervisory envelope of smartness could give the optimal performance and energy efficiency, along with other desired qualities such as reliability, context-awareness etc. Each device that consumes power could have its own personality or a behavior profile owing to its built-in smartness. This introduces nonlinearity and difficulty in predicting the electrical states of a network with numerous such devices. Hence, for a supervisory control node to be functional, real-time metering and data processing are expected in such a framework.

The smart-meter network is expected to monitor in real-time the status of the electrical network and communicate the required information to a control node capable of taking decisions [5]. The usefulness of smartness of the system would be more visible through adequate customer participation. The metering system, after statistical analysis of data, should be able to give easily executable suggestions to the customer regarding the power quality at a node or the quality of the total supply to the building.

There are numerous studies on the efficient management of smart meter data collection and post-processing. There are

various standards/policies set on smart meters [6-7] and the Advanced Metering Infrastructure (AMI) based on ZigBee is not entirely new [8-10]. In recent research literature, more focus has been given to protocols related to smart-meter communication [11-12], the transfer of meter data within the grid [13], anonymization of information transferred [14] etc. Studies on reliability enhancement using smart meters have also been of research interest [15].

This study focuses on a feasible measurement methodology implementable for smart-meters for a building. Each measurement node is considered as a Wireless Sensor Node (WSN) in this paper. The capability of the algorithm to perform power computations and also computations of power quality indicators are also discussed. Section II describes the requirement of electrical transparency for a supervisory control node of a building so as to make smart decisions. The potential of smart-meters to significantly contribute to this need through signal estimations is highlighted. The mathematical formulation of the algorithm for signal decomposition based on instantaneous phasors is also detailed and the corresponding power/power-quality computations are shown. Simulations results are presented in Section III and a suitable hardware setup, which is part of the ongoing research, is mentioned. Section IV provides the conclusion.

II. ELECTRICAL TRANSPARENCY THROUGH ESTIMATION OF INSTANTANEOUS HARMONIC PHASORS

A. Electrical signal transparency

Any electrical network, from a computational perspective, is a conglomeration of properties like sources, resistances, capacitances, inductances which are switched, mutually coupled, energized etc. As the complexity of the interconnections increases, the predictability of the network as a whole decreases even if the individual devices become smarter in regulating their own behavior. Conventionally, connecting a power-consuming entity to an electrical network requires mainly a point of sufficient potential and an appropriate mode of supply (AC/DC). With future smart devices, there could be a communication protocol that the device should follow to draw power from a node [16]. As part of the protocol, the device can self-introduce itself to the network, informing its electrical characteristics or even its dynamic mathematical model, if any. Each of the devices must be self-aware for this purpose. Hence the network becomes electrically transparent to the supervisory control. This

promotes plug-and-play feature for any device even when AC and DC grids are present in parallel within a building. The supervisory control node of the network, being a computationally capable node, can manage such numerous devices simultaneously. The electrical network in the building, along with the computational capabilities, can transform into a high-confidence building-operating-system. The major disadvantages of this would be the very high computational expense and heavy dependency of the supervisory control on the information given by many heterogeneous devices.

There are only a few types of devices which are smart by themselves in the world today which can be directly used to achieve the goal of electrical transparency. Also, a faulty device can confuse the supervisory control. Another scheme, to make the supervisory control functional, would be to place homogeneous measurement units at the significant nodes so as to provide electrical signal transparency of the network. They are homogeneous in the sense that the measurement units are functionally identical, also having the similar individual components which make up the measurement setup. Homogeneity is a desired property when manufacturing such meters. Significance of the node depends on the loads connected to that node and the expected variations at that node. The minimal set of significant nodes to be chosen is a study by itself, but the total number of desired nodes can be customized by the end user. The smart-metering system and the supervisory control would use the measurements from those nodes. The power computations and the power quality analysis can be done using the measurements of voltage and current signals, even if the nature of the terminal devices are not known. Since the devices for measurement are homogeneous, it would be easier to implement communication protocols based on them. This scheme need not interfere with the electrical transparency achievable through communication of individual devices. This makes both the schemes independent. As an added advantage, it is easier to maintain privacy of the end user if electrical signal transparency is given more weightage rather than the electrical transparency achieved through information about individual devices.

The achievement of electrical signal transparency would not only be about measuring the voltage and current signals, but also about converting them into easily usable and computable forms. Many computations on electrical signals are based on the assumption that the signals involved are pure sinusoids. This assumption is violated in the scenario of where multiple harmonics are present due to various types of devices. For performing quantitative computations, each signal must be resolved into simpler forms. Such decompositions of signals are often done in time domain and frequency domain by Fourier-like algorithms [17]. The next section discusses an implementation of a phasor measurement block based on recursive Fourier analysis of a signal [17].

B. Implementation of a Phasor Measurement Block

Instantaneous phasor measurement in this context intends to break down the harmonic-filled signal into its respective time-domain fixed-frequency signals and represent each sample of each decomposed signals as amplitude-angle pairs. The phase angle measured here is with respect to a pure

sinusoid with similar amplitude but with a zero phase angle. The signal model below with f_i as the fundamental frequency is considered.

$$X(t) = \sum_{h=1}^{\infty} x_h(t) = \sum_{h=1}^{\infty} A_h(t) \times \cos(\omega_h \times t + \phi_h(t)) \quad (1)$$

where $A_h(t)$ is the time-varying amplitude, the $\phi_h(t)$ is the time-varying relative phase angle and the harmonic angular frequency is given as

$$\omega_h = 2\pi \times h \times f_1 \quad (2)$$

Considering that such a signal is sampled at a rate f_s , the number of samples per fundamental cycle (N_s) would be

$$N_s = \left(\frac{2\pi \times f_s}{\omega_1} \right) \quad (3)$$

The instantaneous phasor estimation can be done using the following equations. The change in signal with respect to its past time-domain amplitude is used in the update equation.

$$\Delta = X(t) - X\left(t - \frac{2\pi}{\omega_1}\right) \quad (4)$$

$$A_h^{real}(t) = A_h^{real}\left(t - \frac{1}{f_s}\right) + \left(\frac{2}{N_s}\right) \times \Delta \times \cos(\omega_h \times t) \quad (5)$$

$$A_h^{imaginary}(t) = A_h^{imaginary}\left(t - \frac{1}{f_s}\right) + \left(\frac{2}{N_s}\right) \times \Delta \times \sin(\omega_h \times t) \quad (6)$$

$$A_h^{estimated}(t) = \sqrt{(A_h^{real}(t))^2 + (A_h^{imaginary}(t))^2} \quad (7)$$

$$\phi_h^{estimated}(t) = \tan^{-1}\left(\frac{A_h^{imaginary}(t)}{A_h^{real}(t)}\right) \quad (8)$$

The estimated instantaneous harmonic phasor, which is a complex number, is given as

$$Y_h^{estimated}(t) = A_h^{estimated}(t) \times e^{(j \times \phi_h^{estimated}(t))} \quad (9)$$

C. Computations of harmonic power and power quality

The voltage and current signals (the instantaneous amplitudes) at a node needs to be simultaneously measured using sensors which can be wirelessly transmitted to a central computing node. After performing the signal decomposition, the computations of real and reactive power can be performed using the estimated time-dependent amplitude and phase-angle of voltage and current [18].

Considering the voltage and current signals of the form below, the instantaneous h^{th} harmonic phasors at time t can be used to compute the corresponding powers. The maximum value of h would be 35 as per the IEEE Std. 519 on harmonics.

$$V^{signal}(t) = \sum_{h=1}^{\infty} A_h^V(t) \times \cos(\omega_h \times t + \phi_h^V(t)) \quad (10)$$

$$I^{signal}(t) = \sum_{h=1}^{\infty} A_h^I(t) \times \cos(\omega_h \times t + \phi_h^I(t)) \quad (11)$$

$$S_h(t) = P_h(t) + i \times Q_h(t) = \frac{V_h(t) \times I_h^*(t)}{2} \quad (12)$$

where computations of the apparent power is shown using the peak instantaneous harmonic phasors rather than the RMS (Root Mean Square) phasors, which explains the division by two.

$$V_h(t) = A_h^V(t) \times e^{(i \times \phi_h^V(t))} \quad (13)$$

$$I_h^*(t) = A_h^I(t) \times e^{(i \times -\phi_h^I(t))} \quad (14)$$

The values thus computed are further useful in finding the extent of distortion in the quality of the power. The instantaneous Total Harmonic Distortion (THD) can be found using the following equations.

$$THD_V(t) = \frac{\sqrt{\sum_{h=2}^{\infty} |V_h(t)|^2}}{|V_1(t)|} \quad (15)$$

$$THD_I(t) = \frac{\sqrt{\sum_{h=2}^{\infty} |I_h(t)|^2}}{|I_1(t)|} \quad (16)$$

Similarly, the instantaneous Root Mean Square values for each of the total signals can be defined as below.

$$V_{total}^{rms}(t) = \sqrt{\frac{\sum_{h=1}^{\infty} |V_h(t)|^2}{2}} \quad (17)$$

$$I_{total}^{rms}(t) = \sqrt{\frac{\sum_{h=1}^{\infty} |I_h(t)|^2}{2}} \quad (18)$$

Many of the power quality indicators can be calculated easily because the signals have been converted to instantaneous harmonic phasors. It could be said that the electrical signal transparency which is presented here is inclusive of mathematical transparency of the signal components in the Fourier-sense. This gives flexibility in programming the smart-meters, so as to have the detailed analysis of the electrical events that take place.

Both instantaneous and statistics based information can be useful in recording events or evaluating data to perform control

action [19-21]. Since the algorithm enables the smart-meter to compute harmonic powers, intelligent energy management based on smart-meter output becomes closer to reality. Demand side management one of such operations which can be done more intelligently as the smart-meter becomes more capable of providing highly resolved accurate data about the power flow in the building.

III. SIMULATION RESULTS AND HARDWARE SETUP

The simulation of the described algorithm is performed using MATLAB software on a 2.9 GHz 8 GB Intel Core i7-3520M computer. The algorithm for instantaneous phasor measurement is tested for two test cases. In both the cases, the fundamental frequency is assumed to be 50 Hz, the sampling rate is considered to be 3.2 kHz and a 30 dB white Gaussian noise is added to the signal to accommodate the practical aspect of measurement errors. In estimation figures, the solid lines represent the actual values while the dashed lines represent the estimated values.

Case 1: In this case, the following signal is considered for checking the capability of the algorithm to measure in a noisy condition.

$$X(t) = 100 \cos(\omega_1 t + 30^\circ) + 30 \cos(\omega_3 t + 45^\circ) + 20 \cos(\omega_5 t + 80^\circ) + 10 \cos(\omega_7 t + 35^\circ) + 5 \cos(\omega_{11} t + 10^\circ) \quad (19)$$

The signal tracking is performed on this signal to find the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE) of the estimations. These two types of errors would be sufficient enough for an observer to check the effectiveness of the algorithm.

$$MAE = \frac{\sum_{i=1}^N |Actual_i - Estimated_i|}{N} \quad (20)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (Actual_i - Estimated_i)^2}{N}} \quad (21)$$

The original signal is shown in Fig. 1. The computed instantaneous THD and RMS are shown in Fig. 2. The errors obtained for this case is given in Table I.

Fig. 1. Harmonic-filled time domain signal (case-1)

The algorithm shows excellent performance indicating its suitability for smart-metering application. For the given noise-level, the estimation errors are less than 1%. Considering the

excellent sensing technologies available today, a noise level more than 30 dB is not expected in the electric network discussed here. This estimation indicates that in steady state where the harmonics are not time-varying, the accuracy which is achieved by the algorithm is very high even in presence of noise. Even when the signal component varies with respect to time, the accuracy exhibited by the metering technique would be high once the new steady state is achieved.

Fig. 2. Estimations of instantaneous RMS and THD values of the signal (case-1) (a) RMS (b) THD

TABLE I. HARMONIC AMPLITUDE AND PHASE ESTIMATION ERRORS

Harmonic	MAE		RMSE	
	Amplitude	Phase	Amplitude	Phase
1	0.0035	0.0000	0.0042	0.0001
3	0.0043	0.0002	0.0052	0.0002
5	0.0057	0.0002	0.0067	0.0002
7	0.0060	0.0003	0.0074	0.0003
11	0.0038	0.0008	0.0047	0.0011

Case 2: The same signal model is used but with time-varying nature in the harmonics. Effectively, for time duration of 4 cycles, the first and fifth harmonic signal properties are changed indicating a temporary switching of a particular device at a node.

$$X(t) = \begin{cases} 105 \cos(\omega_1 t - 10^\circ) + 30 \cos(\omega_3 t + 45^\circ) \\ + 19 \cos(\omega_5 t + 130^\circ) + 10 \cos(\omega_7 t + 35^\circ) \\ + 5 \cos(\omega_{11} t + 10^\circ) & \text{if } (0.06s < t < 0.14s) \\ 100 \cos(\omega_1 t + 30^\circ) + 30 \cos(\omega_3 t + 45^\circ) \\ + 20 \cos(\omega_5 t + 80^\circ) + 10 \cos(\omega_7 t + 35^\circ) \\ + 5 \cos(\omega_{11} t + 10^\circ) & \text{otherwise} \end{cases} \quad (22)$$

The signal and estimations are shown in Figs from 3 to 5. The algorithm does converge according to the measurements that come in, but deviations are found around the points of transition in the signal states. For reducing the oscillations in estimation, there is scope for implementation of a smoothening algorithm. The algorithm shows convergence nonetheless and is independent of any window-length; unlike any frame-based signal processing techniques. Since the algorithm has only a few mathematical operations in its computational procedure, the algorithm is fast considering its time-complexity. The ease of real-time implementation,

sample-by-sample based instantaneous phasor computations etc. are attractive features of the algorithm discussed.

Fig. 3. Time domain signal with changing harmonic content (case-2). The times at which the signal properties change are marked by ellipses.

Fig. 4. Estimations of instantaneous peak amplitude and phase angle for first harmonic component (case-2) (a) amplitude (b) angle

Fig. 5. Estimations of instantaneous RMS and THD values of the signal (case-2) (a) RMS (b) THD

The experiments on the hardware setup are expected to perceive the instantaneous amplitudes of the current and voltage signals, convert them into digital values and transmit those data to a base station for further processing. Data transmission has been done via wire in conventional systems. However, the installation and maintenance of the wired communication systems might be more expensive than the cost of the sensors [22]. Furthermore, any wired mechanism for

communication would not be able to provide flexibility when the measuring units need to be displaced or replaced. Recent advance of wireless technology enables the energy monitoring system to overcome these difficulties. Wireless sensor network is a solution that targets the low-cost and low-power consumption applications. Wireless sensor network protocol is standardized as IEEE 802.15.4 or Zigbee [23]. It is an open standard operating on unlicensed band and offers a maximum data rate of 250 kbps.

In the experiment setup, each load is equipped with a WSN. A typical WSN like MEMSIC IRIS mote usually consists of sensor components, a microcontroller and a transceiver [24], thereby it is able to collect the measurements, pre-process and transmit the data to a base station. In order to measure the instantaneous values of the current and voltage in the presented work, the current and voltage transducers like LA25-NP and LV25-P can be used. The outputs of these sensors are fed into a simultaneous sampling ADC device to capture both the signals at the same time and convert them into digital values that can be read by the microcontroller. The WSN then sends the data to the base station located at a distance. The base station includes a gateway and a computer to receive and process the data. This framework is currently being implemented for real-time testing as part of the progression of the study done.

IV. CONCLUSION

This study presents the idea of electrical transparency of a network inside a building and the electrical signal transparency possible through smart-metering. The algorithmic framework for real-time estimation of instantaneous phasors is presented, the outcome of which is further used to compute power and its quality-indicators. Simulations studies have been performed to validate the study and a suitable wireless transmission framework is mentioned. The future study intends to optimize the wireless configuration for real-time testing and to improvise the estimation quality of the algorithm.

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