Accurate Power Quality Monitoring in Microgrids

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***Abstract*— Traditional power grid is not resistant to severe weather conditions, especially in remote areas. For some areas with few people, such as islands, it is difficult and expensive to maintain their connectivity to the traditional power grid. Therefore, a self-sustainable microgrid is desired. However, given the limited local energy storage and energy generation, it is extremely challenging for a microgrid to balance the power demand and generation in real-time. To realize the real-time power quality monitoring, the power quality information of microgrid, such as voltage, frequency and phase angle in each home, needs to be collected in real-time. Furthermore, the unreliable sensing results and data collection in a microgrid make the real-time data collection more difficult. To address these challenges, we designed an accurate real-time power quality data sensing hardware to sense the voltage, frequency and phase angle in each home. A novel data management technique is also proposed to reconstruct the missing data caused by unreliable sensing. We implemented our system over off-the-shelf smartphones with a few peripheral hardware components, and realized an accuracy of 1.7 mHz and 0.01 rad for frequency and phase angle monitoring, respectively. We also show our data management technique can reconstruct the missing data with more than 99% accuracy.**

***Index Terms*—Smart meter, power quality, microgrid**

I. Introduction

A microgrid enables local electricity generation, energy storage and load to operate independently of the traditional power grid. Compared to the traditional power grid, a microgrid normally coordinates energy demand and generation in a small community, thus the energy transmission and distribution losses in a microgrid are much lower and the investment for transmission and distribution infrastructures can be minimized. Furthermore, because the microgrid can be isolated from the traditional power grid, it provides the power supply i) to places where the traditional power grid does not exist due to the poor economy or limited number of residences (e.g., islands); ii) when the traditional power grid is temporally not functioning due to severe weather conditions (e.g., storms). Therefore, it has been gaining increasing attention lately.

To enable the functionality of microgrid, the key challenge is to balance the power demand and generation in real-time with dynamically changing power supply and demand. When a microgrid is connected to the traditional power grid, variations in equilibrium are resolved through the support of the traditional power grid. However, when the traditional power grid is down or not connected, the challenge to maintain stability is greater because there are fewer resources in a microgrid. In a typical microgrid, the power generation comes from local generators, renewable energy and energy stored in batteries, while the power demand comes from the loads from commercial and residential buildings. To maintain the stability of a microgrid, we need to schedule the operations of local generators, batteries, and controllable workloads of appliances to offset the dynamically changing and renewable energy generation and power demand of uncontrollable appliances. To achieve the stability of the microgrid, power quality through the power lines needs to be monitored in real-time (e.g., every a couple seconds). The power quality of microgrid is typical monitored with the data such as voltage, frequency and phase angle. However, devices that can monitor these data are normally very expensive. For example, the installation cost of one transmission-level Phasor Measurement Unit (PMU) is more than $80,000 at the Tennessee Valley Authority (TVA). The reason why PMU is so expensive is that specialized DSP chips are needed for synchrophasors for synchronizing the GPS signal. In the meanwhile, PMU requires GPS signal for synchronization and GPS does not work in indoor environment (such as homes and buildings). In this paper, we design a low cost accurate power quality data sensing hardware to sense the voltage, frequency and phase angle in each home and utilize the existing WiFi or cellular network for data communication.

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However, sensors may not be working reliably all the time. Based on our more than 4 years' experiences of energy monitoring in residential homes, the data collection from homes may suffer from different types of faults: i) data point missing; ii) sensing error; and iii) communication loss. To solve the problem of missing or incorrect data, we propose a novel data management technique to detect the incorrect data and reconstruct the missing data. The key idea is to utilize the correlation among power, voltage and frequency in the power lines. Specifically, we summarize our contributions as follows:

- We designed and implemented a high accurate real-time voltage, frequency and phase angle monitoring hardware platform with a small quantity of peripheral hardware. Experimental results show that our prototypes can achieve frequency accuracy of 1.7 mHz and voltage accuracy of 0.02 V.
- We investigated the correlation between power, voltage, and frequency in the microgrid. Through extensive experiments, we show that correlation based approach can reconstruct the missing data with more than 99% accuracy.

II. Background and Motivation

A microgrid is a distributed power system that can autonomously coordinate local generations and demands in a dynamic manner [7]. Microgrids can operate in either grid-connected mode or isolated mode. There have been worldwide deployments of pilot microgrids, such as the US, Japan and European.

A. Background

In this paper, we consider a modern microgrid, which consists of generation technology (e.g., renewable energy and local electricity generators) and batteries. To ensure compatibility with the traditional power grid, we adopt the microgrid architecture, which is similar to the one used in a traditional power grid. If the microgrid is built from nothing (e.g., island, where there is no electricity grid before), the microgrid can be built the same architecture as traditional grid with a distribution network across the community of homes. If the microgrid is built from a traditional grid, we only need to add local generators, batteries and control center into the microgrid. Within the microgrid, sensors are deployed in each home to collect energy related data (e.g., power, voltage, frequency and phase angle) and send to control center for power quality monitoring.

B. Motivation

Different from previous work on power monitoring devices, in this paper, we propose a hardware to sense the voltage, frequency and phase angle of the microgrid. In this section, we demonstrate why these sensing data is important and the reliability of sensing results.

Sensing Requirements. In traditional power grid, voltage, frequency and phase angle is used in different layers to monitor the stability and power quality of power grid. Specifically, i) voltage needs to be regulated to ensure the appliances in each home are working in the proper state; ii) frequency is used to monitor the power load in the transmission lines so that utility company knows whether to generate more or less energy; iii) phase angle difference between buses is measured by PMU to indicate the system stability and stress in advance. However, devices that can monitor these data are normally very expensive. Furthermore, the distributed renewable energy can put back unpredictable amount of energy into microgrid, which makes the distributed power quality monitoring is even more important and challenging. Thus, it is crucial to develop a low cost device for power quality sensing in microgrids.

Sensing Reliability. To realize the real-time control, it is very important to collect the energy related data from homes and send back the control instructions in real-time. However, based on our more than 2 years' experiences of energy monitoring in residential homes, the data collection from homes may suffer from different types of faults: i) data point missing; ii) sensing error; and iii) communication loss. The first two faults are caused by the error of sensors itself due to the long-term monitoring. The latter fault is caused by the unreliable wireless communication. We show some examples of faults in Figure 1. The first one is caused by the sensing error, which generates some peak and does not happen very frequently (we observe average 3 seconds sensing error in 24 hours for 2 month's data analysis). The second one is whether we receive readings in the server. The Y-axis value is set to be 1 if there is a data missing event. We can see the missing events are very bursty, which means once we have a missing event, there will be high probability there would be missing events in near future.

With the demand of real-time data collection and reality of multiple different faults in monitoring, it is crucial to manage the real-time collected data and reconstruct the missing data for real-time monitoring in a microgrid.

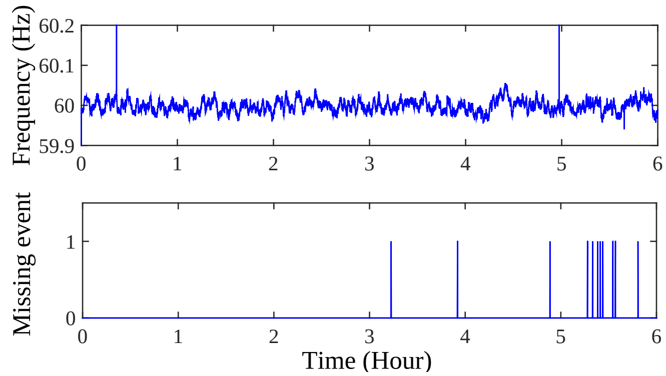


Fig. 1: Some examples of faults in energy monitoring

III. Sensing Hardware

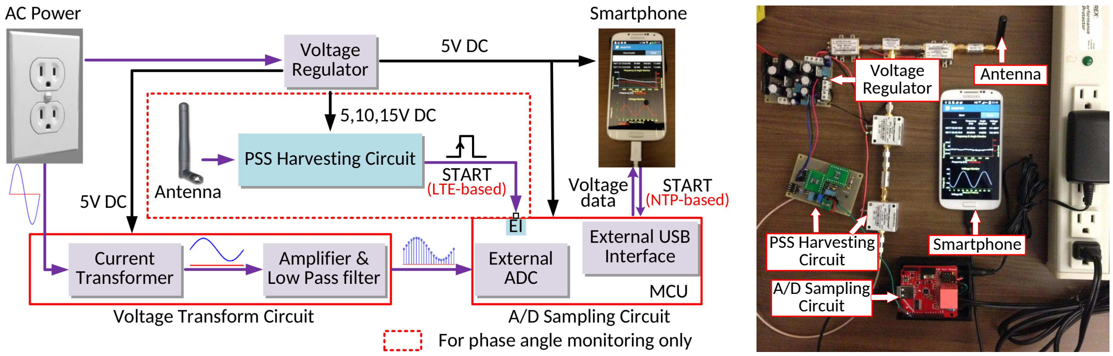
In this section, we propose the detailed design of sensing hardware in homes. The main challenge of sensing hardware is the time synchronization among sensors. Because self-sustainable microgrid requires to monitor the energy data from all the homes in real-time, the readings from different homes must be accurately synchronized. To address this challenge, we propose two time synchronization methods applied in our sensing hardware for frequency and phase angle monitoring.

A. Hardware Design and Implementation

Our sensing hardware consists of a voltage regulator module, a voltage transform circuit, a microprocessor-based analog-to-digital (AD) sampling module, a PSS harvesting circuit, and an Android-based smartphone. The system design and implementation are shown in Figure 2(a) and 2(b), respectively. The voltage regulator outputs the necessary DC power to power up the whole system, including the smartphone. A voltage transform circuit takes an analog voltage signal from 120 V wall outlet and transforms the AC power into the voltage range for analog-to-digital conversion (ADC). An 8-bit microprocessor (MCU) is used to control the voltage sampling process through external ADC at the sampling frequency of 1,440 Hz, and sends the data to smartphone every 100 ms for phasor state estimation.

The communication between the microprocessor and the smartphone is conducted by the USB host controller IC MAX3421E (USB host shield) [9]. The MAX3421E host controller contains the digital logic and analog circuitry necessary to implement a full-speed host compliant to USB specification v2.0. Under this circumstance, similar as being connected to the desktop PC, the smartphone behaves as USB slave in relation to the USB host chip, and can communicate with the MCU and be charged at the meantime. The MCU communicates with the USB host through SPI bus.

The PSS harvesting circuit, shown within the dotted line in Figure 2(a), extracts the PSS signals and transmits them to the MCU in the form of pulses. The rising edges of the pulses will be detected through External Interrupt (EI) in the MCU, and trigger new sampling cycles.



(a) Hardware design (b) Hardware implementation

Fig. 2: Power quality monitoring over smartphones

Hardware Cost. Our implementation includes following hardwares: i) a MCU (ATmega328), which costs less than \$10; ii) multiple ADCs, which costs less than \$ 10; iii) USB host controller (MAX3421E), which costs less than \$10; iii) harvesting antenna, which costs less than \$10; iv) other our designed circuits, which also costs less than \$10; and v) a smartphone to collect data and running NTP protocol, which we use Samsung S3. Note that we only use the smartphone for the prototype, we can easily design a board running NTP protocol and store the data in the board. Therefore, our total cost for hardware can be less than \$50.

B. Time Synchronization

Power grid operations should be monitored in real-time using globally synchronized timestamps, so that measurements from dispersed locations can be compared on a common time reference. Being different from current synchrophasors, our system does not rely on continuous GPS reception and hence is highly accessible and applicable to heterogeneous microgrid scenarios. Instead, we develop two techniques to provide timing signals that are necessary for precise monitoring.

Frequency monitoring: Network Time Protocol (NTP) [10] is being widely used in current computing systems, such as the Windows Time Service, in order to synchronize the local clock of digital devices with Coordinated Universal Time (UTC). Due to the uncertainty of network transmission delay, the timing accuracy of NTP is in the order of 10 milliseconds [14] and is much lower than that of the GPS signal. Nevertheless, by investigating the frequency oscillation in the power grid, we found that such time precision is sufficient for detecting a frequency disturbance event. Therefore, NTP is an appropriate alternative to GPS to provide global time synchronization to frequency measurement data.

Phase angle monitoring: Compared to frequency monitoring, phase angle monitoring requires a globally synchronized clock with higher accuracy and stability. Simply speaking, a 15-millisecond timing error, which is usually the upper bound of NTP timing error, corresponds to an unacceptable phase angle measurement error of 5.76 radians in a 60 Hz power system. Instead, we propose to harvest the precise timing signal from the 4G LTE cellular signal, which is widely available nationwide nowadays.

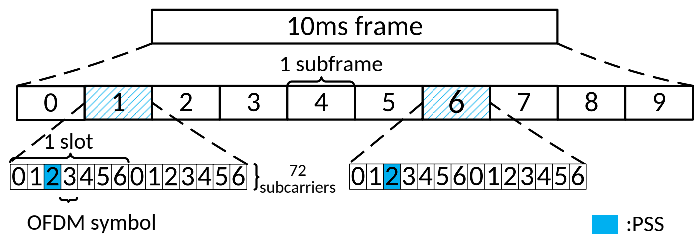


Fig. 3: Synchronization signals in LTE FDD downlink

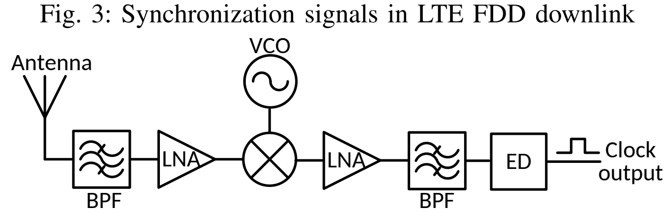


Fig. 4: System block diagram of PSS signal harvesting circuit

The enhanced base station (eNodeB) of LTE is strictly synchronized with GPS or the Precision Time Protocol (PTP) [1]. The cell ID in the LTE network is defined within two synchronization signals, namely Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS). Figure 3 illustrates the LTE frame format and the location of synchronization signals under Time-Division Duplexing (TDD) mode. The PSS repeats periodically (every 5 ms) and therefore can be regarded as a time synchronization signal. Note that though the frame structure is a little different in Frequency-Division Duplexing (FDD) mode, the PSS will also repeat every 5 ms. Thus, our design can be applied with LTE under different modes.

C. PSS Harvesting Circuit Design

Since measurement of phase angle requires more accurate timing information than the frequency monitoring does. In our system design, we aim to harvest synchronization signals from 4G LTE cellular signal for time synchronization. Similar to the GPS-based system, the harvested LTE signal can be directly used to trigger a new sampling cycle.

In LTE networks, to achieve high data transmission rate, Orthogonal Frequency Division Multiple Access (OFDMA) is utilized as the physical layer technique in the downlink data transmission. The frequency of PSS signal (200 Hz) is far

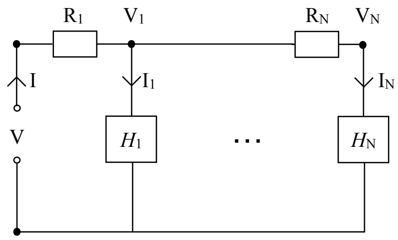


Fig. 5: The topology of homes and the transformer

lower than the bandwidth of data transmitted (in the order of 1 MHz). Since our purpose of PSS detection is not to decode the signal but only to identify the arrival of the PSS signals, the PSS signal can be detected based on the scheme shown in Fig. 4. A Voltage-Controlled Oscillator (VCO) is used to detect the frequency band with the strongest signal strength. The signal in 1900 MHz frequency band is selected and downconverted to 200 kHz intermediate frequency (IF) output. The PSS signal would be transformed as a pulse after passing the bandpass filter with a bandwidth of 120 kHz and the envelope detector. The MCU will capture the rising edge of the PSS pulses as the trigger to start a new sampling cycle.

IV. Data Management

In this section, we introduce our correlation models for reconstructing the missing data.

A. Correlation Models

In this section, we identified and built two correlation models of different sensing data: i) correlation between power and voltage; ii) correlation between frequency and voltage. The strong correlation of different sensing data can be potentially used for reconstructing the missing data.

1) Power Voltage Correlation: In this subsection, we investigate power-voltage model for N homes under the same transformer. Without loss of generality, we assume that N homes are connected under the same transformer and the transformer stays on the left side of the street and homes are connected to the transformer on the right side (shown in Figure 5). According to the Electric Power Distribution Handbook [13], a transformer can be considered as a constant kVA device for a voltage from 100% to 105%. If the power consumption of one home increases, the total current I increases and voltage V drops. We find that home H_{i-1}'s voltage value depends on i) the transformer's output voltage (V); ii) the current from the transformer to H_{i-1}; and iii) resistances of the power line from the transformer to H_{i-1}. For example, H_1's voltage value only depends on the transformer's output voltage (V), the current (I_1) through H_1, and the resistance (i.e., R_1). Based on the above analysis, the voltage values at homes H_{i-1} and H_i can be calculated by using Equation (1).

$$V_i = V - \sum_{j=1}^{i} \sum_{k=j}^{N} I_{k-1} R_{j-1} \quad i = 1, 2, ..., N \tag{1}$$

Based on Equation (1), because R_{j-1} is a fixed value, the voltage drop from transformer to each home is in linear relationship of currents going through the power line. Thus, if power consumption data is incorrect or missing, we can utilize the voltage data to detect and reconstruct the power consumption data.

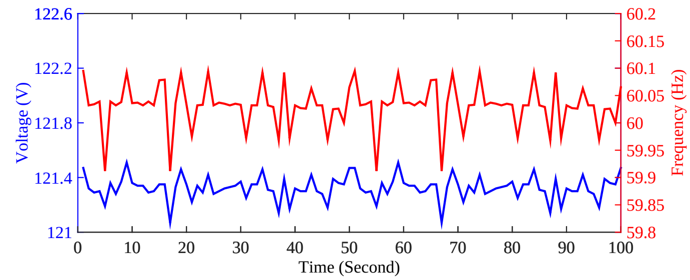


Fig. 6: Relationship between frequency and voltage

2) Frequency Voltage Correlation: In previous section, we propose the relationship between power and voltage for homes under the same transformer. However, a typical microgrid may contain multiple transformers. Therefore, it is also important to investigate the other features in a microgrid. According to the Electric Power Distribution Handbook [13], frequency is a good indicator of the relationship between power supply and demand. If the power demand surpasses the power supply, then the frequency decreases because the generator can not generate enough power. Thus, the frequency should be related to the total power consumption of the microgrid. To verify it, we conduct experiments with 3 homes. Two of them are under the same transformer while the other home is under a different transformer. The measured frequency and voltage relationship is shown in Figure 6. When the voltage value is high, which means the power demand is low, the frequency value is also quite stable but not related to the voltage value. However, when the voltage value is low, which means the power demand is high, the frequency value is synchronized with the voltage value. The reason is that the power supply in a short time duration is relatively stable. Frequency is related to power supply and demand, thus in this scenario, the frequency value has a linear relationship with the voltage value. This relationship can be modeled as follows:

$$\triangle F = \triangle V * \lambda_1 \tag{2}$$

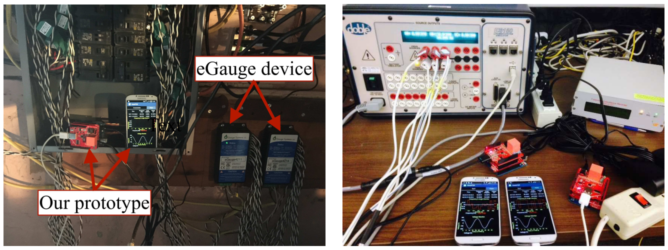
Based on Equation (2), the frequency change in each home is in linear relationship of voltage change. Thus, we can utilize the frequency voltage relationship to reconstruct some missing voltage or frequency data if the other data is available.

V. Evaluations

In this section, we evaluate the performance of our design from three perspectives: i) data measurement accuracy; ii) time synchronization between sensors; iii) data management for missing data points.

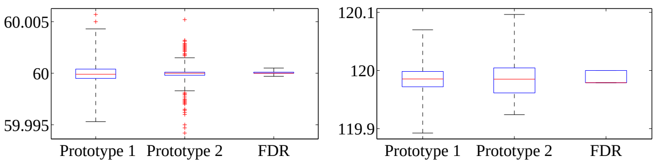
A. Frequency & Voltage & Phase Angle Measurement

We collect empirical data of voltage, frequency and phase angle from three homes. The experiment setup is shown in Figures 7(a) and 7(b). To evaluate the accuracy of our system, we test our system against the traditional Frequency Disturbance Recorder (FDR) and commercial products from



(a) eGauge and our prototype (b) Synchronization experiment

Fig. 7: Experiment setup in residential homes



(a) Frequency (Hz) (b) Voltage (V)

Fig. 8: 60 Hz, 120 V AC output

eGauge. Both standard power generator and AC wall power are used in our experiments.

First, the frequency measurement result over standard 60 Hz power generator is shown in Figure 8, and the GPS-synchronized Doble F6150 signal generator is used to generate 60 Hz, 120V AC power. The prototypes can achieve a frequency accuracy of less than 1.7 mHz and a 0.02 V voltage magnitude accuracy. Second, the measurement results over the 120V AC wall outlet are shown in Figure 9 and 10. We compare our design with both FDR and commercial eGauge energy monitoring system. We find our system has similar accuracy of voltage compared to eGauge, and much higher accuracy of frequency than eGauge over time.

For angle measurement, we conducted the experiments over wall power. The difference between our design and FDR is 0.011 rad (shown in Figure 11(a)). Compared to FDR with an accuracy of 0.0001 rad, the timing error is mainly introduced in the PSS signal harvesting process. The PSS signals are harvested in the form of pulses, and the slope of the rising edge of the PSS pulse is flatter and can be affected by the strength of the signal. To evaluate the relationship between the measurement accuracy and the quality of the LTE cellular signal reception, we emulate the environment with different signal-to-noise ratio (SNR) by using aluminum foil to cover the antenna of the PSS harvesting antenna. The performance

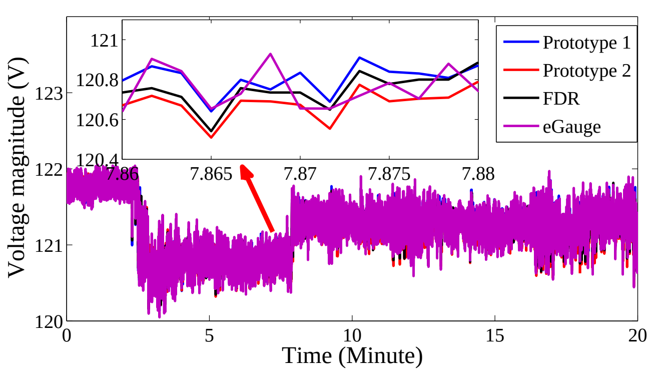


Fig. 9: Voltage measurement from wall output

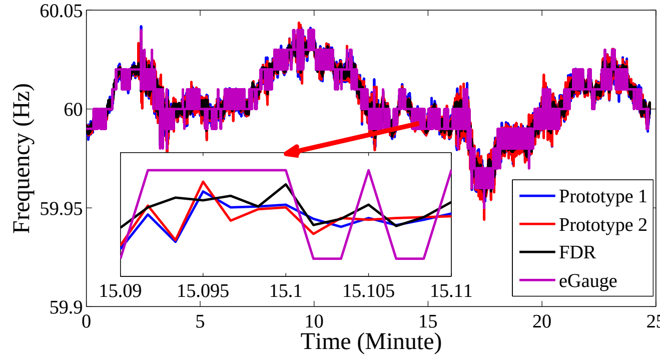
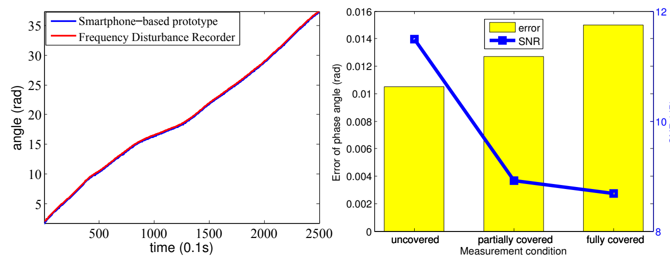


Fig. 10: Frequency measurement from wall output



(a) Wall output (b) Error

Fig. 11: Phase angle measurement

of the phase angle measurement with respect to different SNR is depicted in Fig. 11(b). PSS harvesting module can achieve the highest SNR of 11.49 dB under no cover with the error of 0.01 rad on phase angle monitoring. As the coverage area of the foil increases, the error increases to 0.0127 and 0.015 rad in partially covered and totally covered situation, respectively. However, the accuracy of phase angle sensing is still good enough for power quality monitoring.

B. Time Synchronization

The synchronization effect of NTP approach is evaluated by comparing the measurement of two prototypes, one of which disables the WiFi network to disable NTP synchronization. The local clock of both two prototypes are calibrated before the experiment starts. The voltage measurement result is shown in Figure 12. It is expected that, without synchronization, the smartphone will assign timestamps to measurement points

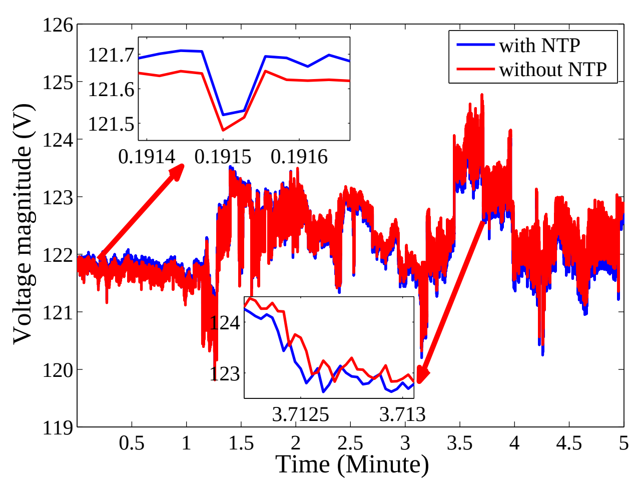


Fig. 12: Measurement with/without NTP synchronization

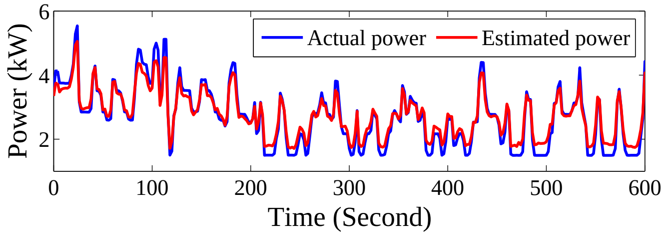


Fig. 13: Power consumption reconstruction with voltage data

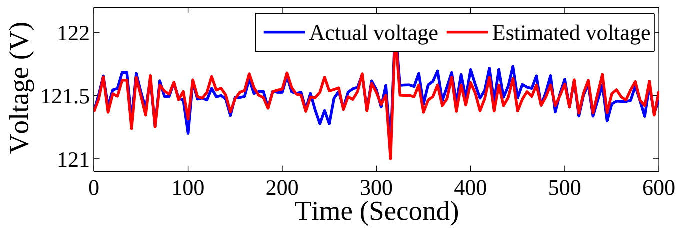


Fig. 14: Voltage reconstruction with frequency data

through local clock. The local clock which is vulnerable to the environmental factors, such as temperature, will continuously drift without calibration. 10 minutes after startup, the spikes of voltage measurement are aligned with each other. However, after 3 hours, there is a two-sample-interval (0.2 s) delay in the NTP-disabled device, which means its local time is drifted by 0.2 seconds and the measurement will be assigned a timestamp that is earlier than the real time. It's expected that this delay will accumulate as time goes.

C. Data Reconstruction

To verify the accuracy of power voltage relationship model, we conducted experiments by collecting power consumption, voltage and frequency at one home. Based on Equation (1) and (2), we estimate the power consumption and voltage data with collected voltage and frequency data, respectively. The results are shown in Figure 13 and 14. We can find that the reconstructed power consumption and voltage is very accurate compared to the ground truth. The average error of power consumption is 0.01 kW (average accuracy 99.5 %). The average error of voltage is 0.05 V (average accuracy 99.9 %).Therefore, our data management technique can reconstruct the missing data if the related data is available.

VI. Related Work

Energy Monitoring. There are many works on energy monitoring in buildings [3] [5] . A power budgeting system is proposed for virtualized infrastructures that enforces power limits on individual distributed applications to ensure actual consumption never exceeds capacity [8]. A contactless sensing method is proposed to detect 100W loads from 10cm away [12]. A lowest cost AC plug-load meter that measures real, reactive and apparent power is proposed in [4].

Different from these existing works, in this paper, we are aiming to monitor the power quality (voltage, frequency and phase angle) of power grid instead of power consumption in the power grid, which is more important for the stability of the microgrid. Our experiment results show that we can achieve similar performance compared to PMUs by reducing the cost with three magnitudes.

Sensing Deployment. Based on different application, there are massive work on how to minimize the deployment effort of sensor networks [6] . A sensor sampling methodology is proposed for better trade-offs between sampling rate and energy consumption [11]. The energy consumption of data transm ission over WiFi is investigated in [15]. An external hardware based clock tuning circuit is used to improve synchronization and reduce clock drift [2].

VII. Conclusion and Acknowledgement

To achieve the stability of the microgrid, power quality through the power lines needs to be monitored for balancing demand and generation. However, the unreliable data collection makes the control very hard and existing approaches (PMU) are very expensive. To address these issues, we design an accurate real-time energy data sensing hardware to sense the voltage, frequency and phase angle in each home. We propose a novel data management technique to reconstruct the missing data caused by sensing error. Through extensive experiments and simulations, we show that our design realized an accuracy of 1.7 mHz and 0.01 rad for frequency and phase angle monitoring, respectively. Our data management can reconstruct the missing data with more than 99% accuracy.

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References

[1] IEEE standard for a precision clock synchronization protocol for networked measurement and control systems. *IEEE Std 1588-2008 (Revision of IEEE Std 1588-2002)*, 2008.

[2] M. Buevich, N. Rajagopal, and A. Rowe. Hardware assisted clock synchronization for real-time sensor networks. In *RTSS*, 2013.

[3] M. Buevich, D. Schnitzer, T. Escalada, A. Jacquiau-Chamski, and A. Rowe. Fine-grained remote monitoring, control and pre-paid electrical service in rural microgrids. In *IPSN*, 2014.

[4] S. DeBruin, B. Ghena, Y.-S. Kuo, and P. Dutta. Powerblade: A low-profile, true-power, plug-through energy meter. In *Sensys*, 2015.

[5] X. Jiang, M. Van Ly, J. Taneja, P. Dutta, and g. Culler. Experiences with a high-fidelity wireless building energy auditing network. In *SenSys*, 2009.

[6] T.-T. Lai, W.-J. Chen, K.-H. Li, P. Huang, and H.-H. Chu. Triopusnet: Automating wireless sensor network deployment and replacement in pipeline monitoring. In *IPSN*, 2012.

[7] R. H. Lasseter and P. Paigi. Microgrid: a conceptual solution. In *IEEE Power Electronics Specialists Conference*, 2004.

[8] H. Lim, A. Kansal, and J. Liu. Power budgeting for virtualized data centers. In *USENIX ATC*, 2011.

[9] MAXIM Integrated. MAX3421E, USB peripheral/host controller with SPI interface. 2007. Copyright Maxim Integrated Products.

[10] D. L. Mills. Internet time synchronization: the network time protocol. *IEEE Transactions on Communications*, 39(10):1482–1493, 1991.

[11] K. K. Rachuri, M. Musolesi, and C. Mascolo. Energy accuracy trade-offs in querying sensor data for continuous sensing mobile systems. In *UbiComp*, 2010.

[12] A. Rowe, M. Berges, and R. Rajkumar. Contactless sensing of appliance state transitions through variations in electromagnetic fields. In *BuildSys*, 2010.

[13] T. Short. *Electric Power Distribution Handbook*. Taylor & Francis, 2003.

[14] L. Wang, J. Fernandez, J. Burgett, R. W. Conners, and Y. Liu. An evaluation of network time protocol for clock synchronization in wide area measurements. In *IEEE PES General Meeting*, 2008.

[15] Y. Xiao, Y. Cui, P. Savolainen, M. Siekkinen, A. Wang, L. Yang, A. Ylä-Jääski, and S. Tarkoma. Modeling energy consumption of data transmission over Wi-Fi. *IEEE TMC*, 13(8):1760–1773, 2014.