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Load balancing and monitoring current level in power grid frequency over mobile platforms

K.K.Resma
PG Scholar,EEE department
Nandha Engineering College
Erode,Tamilnadu, India
resmamrin@gmail..com

S.Menakambal
Assistant Professor, EEE department
Nandha Engineering College
Erode,Tamilnadu, India
menakasanthose@yahoo.com

Abstract—Information about the frequency deviation is critical to reliable and stable operation of the power grid. Current wide-area power grid monitoring systems consist of Phasor Measure-ment Units (PMUs) at both high-voltage transmission level and low-voltage distribution level, but are generally unsatisfactory for large-scale deployment over highly distributed microgrids in individual households and local communities due to their high cost and low accessibility. In this paper, we present a practical system design which significantly improves the accessibility and reduces the cost of frequency monitoring by unleashing the capabilities of modern mobile platforms in computation, commu-nication, and storage. In our system, the Network Time Protocol (NTP) is exploited for time synchronization, replacing inflexible GPS receivers that are widely used in current PMUs. A small quantity of peripheral hardware components are used to build up an embedded sensing component for efficient and accurate frequency measurement. The experiment results compared to the traditional Frequency Disturbance Recorders (FDRs) show the effectiveness of the proposed frequency monitoring system.

I. INTRODUCTION

Power grid is a critical infrastructure of the modern society, but is susceptible to various types of disturbances. When a significant disturbance occurs, the frequency of the power grid varies in both time and space, and, in many ways, exhibit the characteristics of electromechanical wave propagation phenomenon [1]. Therefore, information about the frequency deviation is particularly important to and highly desired for reliable and stable power grid operations.

How to obtain the frequency information more accurately and efficiently has been an active research topic for decades. Current power grid monitoring systems allow direct mea-surement of frequency and voltage phase angle by installing Phasor Measurement Units (PMUs) at either high-voltage transmission level [2] or low-voltage distribution level [3]. In particular, as a member of the PMU family, the Frequency Disturbance Recorders (FDRs), were developed in 2003 and deployed at the low-voltage distribution level such as 120V wall outlet with significantly reduced costs. Based on these FDRs, a US-wide Frequency Monitoring Network (FNET) has been designed, implemented, and deployed [4], enabling many applications of power system monitoring, control, and management. It is expected that 2,000 FDR units will be deployed worldwide in the next few years.

These power grid monitoring systems, although having been proved to be effective in wide-area power grid infrastructure, are generally considered unsatisfactory for monitoring the operating status of the newly emerging distributed power systems, so-called microgrids [5]. Microgrids enable local integration of energy generation, distribution, and storage at the consumer level for better power system efficiency and control of demand [6]. The obstacles of efficient monitoring of microgrid operations mainly stem from the high installation cost and low accessibility of current PMUs, which prevent large-scale deployment of PMUs into individual households in high volume. For example, the installation cost of one PMU at the transmission level was more than $80,000 at the Tennessee Valley Authority (TVA). These PMUs are not intended for use at the distributed consumer level, and require professional installation which reduces end-users' incentives of having PMUs in their home energy systems.

which are not intended for such real-time data processing. Specialized DSP chips are used in present PMUs for data processing [3], but are too expensive and difficult to be integrated into mobile platforms.

Our main idea to overcome the aforementioned challenges is to reduce the systematic cost of frequency monitoring by developing efficient embedded sensing platforms and adopting GPS-free time synchronization methods, without

Our detailed contributions are as follows:

We implemented a low-cost frequency monitoring prototype on the smartphone platform with a small quantity of peripheral hardware, which can be further integrated into the smartphone charger for better flexibility and convenience. The highly-integrated system lowers both the manufacturing and installation costs of the frequency monitoring system.

We proposed a novel time synchronization approach based on the Network Time Protocol (NTP), which significantly increases the system flexibility by eliminating the requirement of GPS reception and line of sight to the satellites. The NTP timing information is used for both providing global timestamps and calibrating the local clock at smartphones.

We developed a user-friendly graphic interface for frequency monitoring, as a smartphone application. The visualization of monitoring results would facilitate the understanding of end users. The extendibility of such interface also enables further integration of more power grid monitoring functionalities, such as phase angle and power quality monitoring, into the same platform.

The rest of this paper is organized as follows. Section II discusses the background knowledge of power grid frequency monitoring. Section III discusses the motivation for using mobile platform for PMUs. Section IV provides an overview of our system design. Section V presents our time synchro-nization approach based on NTP. Section VI presents our performance evaluation results in comparison with FDRs. The related work is depicted in section , respectively. Finally, the conclusions and future work are drawn in Section VIII.

II. BACKGROUND

A. GPS-based Time Synchronization

Synchronization among different PMUs is important for wide-area power system frequency measurement. Each mea-surement must be assigned a timestamp for lateral comparison with measurements retrieved from other devices. To enable the global synchronization and timing accuracy, the Pulse-Per-Second (PPS) signal being retrieved from GPS receivers are usually used as the timing signal by PMUs [8][1]. The PPS signal is an analog output signal with a rising edge at each one second boundary of the Universal Coordinated Time (UTC). Since the precision of PPS signal is in nanoseconds with non-accumulative time drift [9], PMUs at dispersed locations can measure local system frequency synchronously using the integrated GPS clock. For example, a FDR would start a new 1-sec measurement cycle each time when it receives the PPS signal, and then transmits the frequency monitoring results back to FNET every 100ms for visualization. Such a moni-toring result is calculated based on the AC waveform samples during the past 100ms, and is assigned to the timestamp of the first sample during this time period. For example, when the sampling frequency is 1,440 Hz and the current PPS rising edge corresponds to UTC time 17:05:04, the 144 samples generated between 17:05:04.1 and 17:05:04.2 are used to measure the system operating frequency, which is assigned to the timestamp 17:05:04.1. The FDR's local clock is used for sampling between two PPS rising edges.

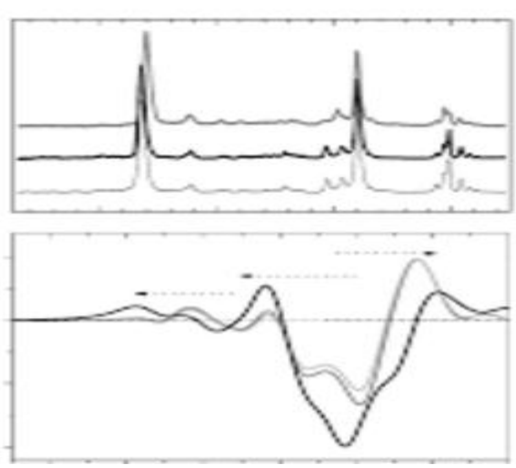
[1]In the rest of the paper, the PPS signal and GPS signal are used interchangeably.

B. Time Synchronization via NTP

For better accessibility and lower cost, less expensive yet accurate and reliable timing sources have been studied in re-cent years. With nearly no cost, Network Time Protocol (NTP) [10] becomes an alternative timing source of GPS. Due to the uncertainty of network delay, the timing precision of NTP is in the order of 10ms [11], which is much lower than the PPS signal. However, by investigating the sample events recorded by FNET, we observe that this time precision is sufficient for detecting a frequency disturbance event. Being different from the PPS signal which continuously feeds the processor, the NTP timing information is only available when the monitoring device sends a request to the remote NTP server. The uncertain round-trip delay, therefore, further complicates the design of time synchronization method.

III. MOTIVATION

Modern mobile platforms, especially smartphones, are considered as an ideal platform for PMUs. As an example of low-cost PMUs, the FDR device includes a DSP chip to implement the real-time frequency estimation algorithm, a specialized ethernet module to upload the monitoring result to the server,



OCB/LSB Harvesting technique

In this technique, if voltage is at higher in PWM can be monitored. The source voltage from the PWM can be taken to the comparisons by using the differentiator. Reference voltage, input voltage and the output voltage are given. Output voltage from the PWM and input voltage from the user, both voltage can be compared and equalize

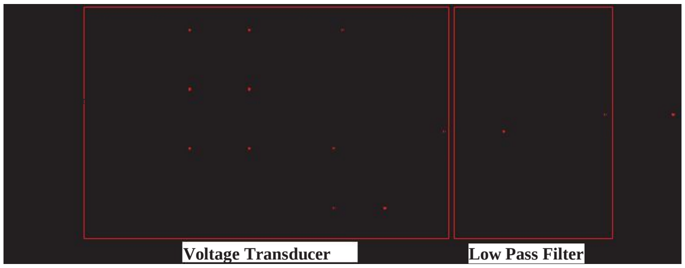


Fig. 2. Design of the voltage transform circuit

and a LCD module to display the monitoring results to end users. The aforementioned components have all been provided by modern smartphones. With the rapid development of IC and semiconductor manufacturing, the cost of a smartphone has been significantly reduced, and faster CPUs and more functionalities are integrated into the smartphone platform. For example, the Samsung Nexus S smartphone, with a price around 100 dollars, is equipped with 1 GHz ARM Cortex-A8 CPU, 512 MB RAM, 4.0-inch LCD screen, WiFi connection and cellular network access. These capabilities, together with its accessibility, make the modern smartphones an ideal choice for implementing the microgrid monitoring systems.

IV. SYSTEM DESIGN

A. Hardware design

Our developed frequency monitoring system consists of a voltage transform circuit, a microprocessor (MCU) mod-ule and an Android-based smartphone. The system design and implementation are shown in Fig. 1(a) and Fig. 1(b), respectively. The voltage regulator part outputs the 5V DC power to power up the smartphone, MCU module and the amplifiers. A voltage transform circuit, as shown in Fig. 2, takes an analog voltage signal from 120V wall outlet and transforms the AC power into the voltage range for analog-to-digital conversion (ADC) purpose. A low-pass filter with 230 Hz cut-off frequency rejects high-frequency noise. An 8-bit microprocessor ATmega328 (Arduino Uno board) with 10-bit internal ADC is then used to sample the voltage waveform at the sampling frequency of 1,440 Hz, and send the raw data to smartphone every 100 ms for processing.

The communication between the MCU and the smartphone is conducted by the USB host controller IC MAX3421E (USB host shield) [14]. 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, the smartphone behaves as USB slave in relation to the USB host chip, and can communicate with the MCU. The smartphone behaves as being connected to the desktop computer and will be charged while being connected to the USB host controller. The MCU communicates with the USB host shield through serial peripheral interface (SPI) bus.

B. Software design

At the smartphone, the frequency estimation algorithm and visualization programs are packaged into one Android application. To keep the application responsive, each computa-tionally intensive operation such as the frequency computation specified in Section II-C, are distributed to a newly generated application thread, instead of residing in the application main thread or UI thread. As shown in Fig. 3, our frequency monitoring application consists of four major components, which are explained in detail as follows:

1) USB communication component. Through the USB connection, the smartphone will send the sampling trig-ger command every 2 seconds to the MCU, and the MCU will respond with the sampled measurement data. Our application will also monitor the connection status of the USB accessory. Once the smartphone is connected to the USB host controller with a correct hardware signature, our application will run automatically and build the USB connection as “plug-and-play”.

2) Internet access component. Network access is neces-sary to obtain the NTP timing information. The UTC timestamp is retrieved by requesting the NTP server. In addition, the measurement information is uploaded via the Internet to FNET servers hosted in the University of Tennessee. Since the network delay is uncertain and may be up to several hundred milliseconds, the network connection is packaged into one standalone thread.

3) Frequency estimation component. The frequency es-timation algorithm described in Section II-C is imple-mented in this component. The MCU will store the sampled data within the last 0.1 seconds and send them to the smartphone at one time. Once these 144 samples

Fig. 3. Experiment setup

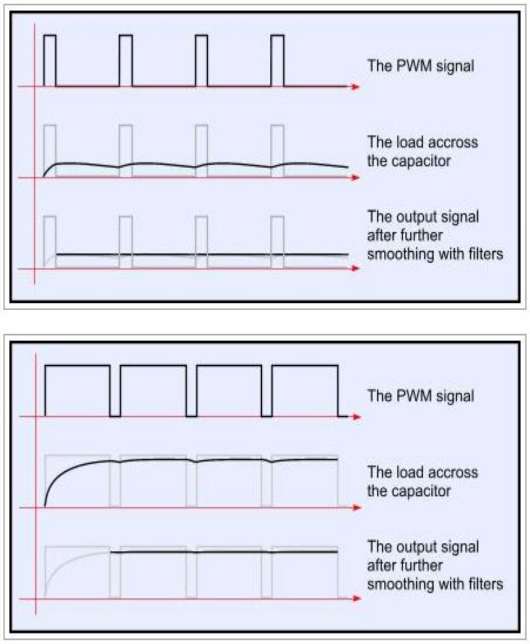


Fig4.Output signal after filtering from PWM signal

Voltage output from MSP430 is given to the PWM.PWM generate the signal into square waveform by using the clock generator.

V. CONCLUSION AND FUTURE WORK

In this paper, we present the design and implementation of our smartphone-based power grid frequency monitoring system. In this system, we proposed to use NTP instead of GPS as the source for time synchronization. The proposed time syn-chronization approach significantly reduces the system timing error, which is sufficiently low for ensuring precise frequency monitoring on the power grid. Experiments compared with FDR devices show the accuracy and effectiveness of the system on frequency monitoring. The system can be widely deployed as a complementary of the FDRs. The wide-area deployment of power grid monitoring devices will increase the accuracy of abnormal detection and location.

Our future work focuses on further improving our frequency monitoring system, measuring the phase angles of the pow-er grid, and integrating more functionalities of power grid monitoring onto mobile platforms. First, we will improve our frequency monitoring system by fabricating the MCU board and the voltage transform circuit into one PCB board, so that our monitoring system could be integrated into the smartphone charger for better accessibility. We will also improve our design of the voltage transform circuit to efficiently suppress the random noise contained in the power voltage signal. Second, we aim to further improve the accuracy of time synchronization which is necessary for precise monitoring of phase angles and cannot be achieved by NTP. Simply speaking, a 15 milliseconds timing error, which is usually the upper bound of NTP timing error, corresponds to 330 degrees of phase angle error in a 60 Hz system. An alternative high-accuracy timing source is the GSM signal, and we will extract the timing information from the GSM signal in a low-cost yet efficient manner. Third, our system will be further extended to incorporate more functionalities such as power quality measurement that monitors power grid operations in a much wider range of frequency spectrum.

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