

# A One-Phase, Distribution-Level Phasor Measurement Unit for Post-Event Analysis

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**Abstract**—Phasor measurement units (PMUs) are devices which provide near real-time synchronized data (synchrophasor data) at widely separated points across the power grid and are mainly installed at the transmission level. The widespread installation of PMUs across the power grid is gradually becoming a reality – and promises new capabilities to significantly improve real time knowledge of the power grid’s operating state. Archived synchrophasor data provides a wealth of high-fidelity data to aid power system model sustainability analyses and to reconstruct unusual power system events. While the PMU device concept is well known in the power industry, the challenges of designing and implementing a PMU which integrates field measurements to deliver Global Positioning System (GPS) synchronized phasor data to the power industries’ networks are not as well known or understood. This paper describes the steps, challenges, and reasoning involved in building a single-phase, distribution-level PMU. Our efforts have provided a fundamental understanding of a PMU’s inner workings and direction to future efforts to improve PMU performance.

**Index Terms**—Phasor Measurement Unit, Synchrophasor

## I. INTRODUCTION

**P**HASOR Measurement Units (PMUs) are devices which sample substation voltages and currents through power and current transformers. The device then performs signal processing computations to generate voltage and current phasors referenced to the global positioning system’s broadcast timing signal. The phasors are time-stamped using information embedded in the GPS signal. The appeal of PMUs lies in the capacity to generate phasor data at locations separated by 1000s of miles, in a window of time smaller than  $1 \mu\text{s}$ , which, for anticipated power system applications, is effectively simultaneous. Additionally, each PMU in the system assigns an identical time stamp to the phasor measured in that  $1 \mu\text{s}$  window. This enables phasors derived from measurements at thousands of locations across the system to be transmitted and assembled to provide a synchronized snapshot of the system’s state at given time.

Synchrophasor data is typically generated and transmitted 10 or 30 times per second and archived. Synchrophasor data archives provide a much higher fidelity record of the power system’s state than legacy data stores. As a consequence, archived synchrophasor data is a valuable resource for investigating the power system’s state before, during, and immediately after an atypical event. The data can also be used to validate power system models – and identify models that do not accurately reflect actual system behavior. These devices can be used to analyze and understand the electrical behavior

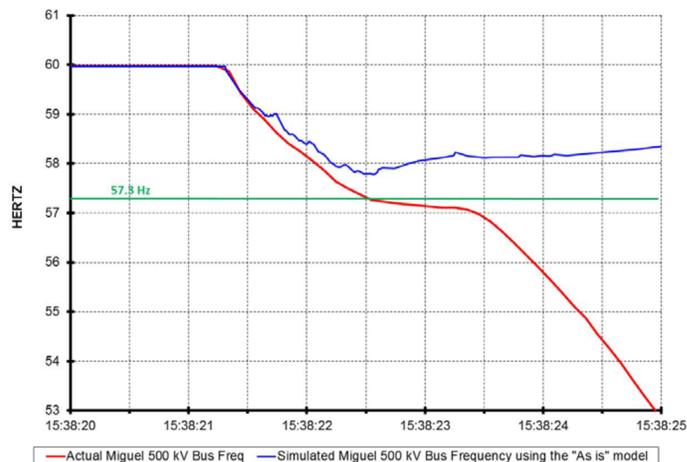


Fig. 1. Actual (red) and simulated (blue) 500 kV bus frequency in the San Diego Gas and Electric system before and after the September 8, 2011 blackout event [2]

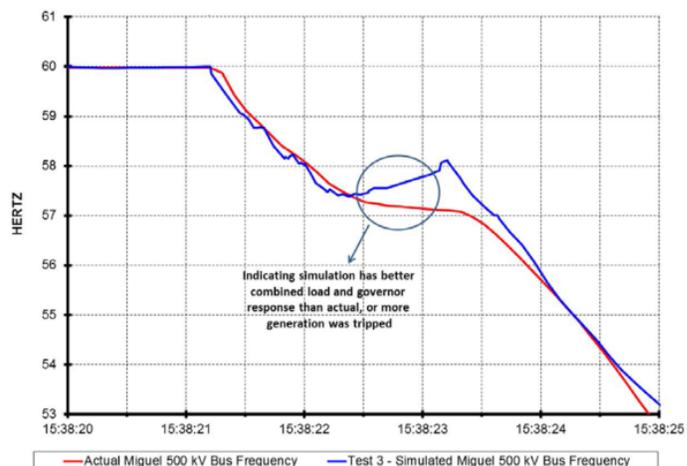


Fig. 2. Simulated (blue) 500 kV frequency after incorporating PMU data into the model [2]

of a system during a specific event. For example, the output from the model used to predict the frequency at San Diego Gas and Electric’s Miguel Substation during the Sept. 8, 2011 outage in the Southwestern U.S. did not match observed behavior. The blue curve in Fig. 1 shows the predicted frequency at a 500kV bus from the utility’s model. The actual behavior is represented by the red curve. The failure of system models to accurately represent system frequency on a major bus was an

CONFORMANCE TEST RESULT SUMMARY

| PMU     | Class | Steady State Test   |        |         |                       |        |         |                     |        |         | Dynamic State Test    |        |         |                |        |         |             |        |        |   |   |   |
|---------|-------|---------------------|--------|---------|-----------------------|--------|---------|---------------------|--------|---------|-----------------------|--------|---------|----------------|--------|---------|-------------|--------|--------|---|---|---|
|         |       | Magnitude Variation |        |         | Phase Angle Variation |        |         | Frequency Variation |        |         | Measurement Bandwidth |        |         | Frequency Ramp |        |         | Step Change |        |        |   |   |   |
|         |       | TV<br>E             | F<br>E | RF<br>E | TV<br>E               | F<br>E | RF<br>E | TV<br>E             | F<br>E | RF<br>E | TV<br>E               | F<br>E | RF<br>E | TV<br>E        | F<br>E | RF<br>E | R<br>T      | D<br>T | M<br>O |   |   |   |
| PMU A   | P     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | F | F | F |
|         | M     | S                   | S      | S       | S                     | S      | S       | S                   | F      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | S | F | F |
| PMU A-1 | P     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | F | S | F |
|         | M     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | S | S | F |
| PMU B   | P     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | S | F | S |
|         | M     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | F       | F              | S      | F       | F           | F      | S      | F | S | S |
| PMU C   | P     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | S | S | S |
|         | M     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | S | S | S |
| PMU D   | P     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | F | F | F |
|         | M     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | F       | F              | S      | F       | F           | F      | S      | F | F | F |
| PMU E   | P     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | S | S | F |
|         | M     | S                   | S      | S       | S                     | S      | S       | F                   | S      | F       | F                     | F      | S       | S              | F      | F       | F           | F      | S      | S | S | F |
| PMU F   | P     | S                   | S      | S       | S                     | S      | S       | F                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | S | S | S |
|         | M     | S                   | S      | S       | S                     | S      | S       | F                   | S      | S       | F                     | F      | S       | F              | F      | F       | F           | F      | S      | S | S | S |
| PMU G   | P     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | S       | F              | S      | S       | F           | F      | F      | F | S | F |
|         | M     | S                   | S      | S       | S                     | S      | S       | S                   | S      | S       | S                     | S      | F       | S              | S      | F       | F           | F      | S      | S | S | F |
| PMU H   | P     | S                   | F      | S       | S                     | F      | S       | S                   | F      | S       | S                     | S      | S       | S              | S      | S       | F           | F      | S      | S | S | S |
|         | M     | S                   | F      | S       | S                     | F      | S       | S                   | F      | S       | S                     | S      | S       | S              | S      | F       | F           | S      | S      | S | S | S |

S: satisfied; F: failure; P: class P; M: class M; TVE: total vector error; FE: frequency error; RFE: rate of change of frequency error; RT: response time; DT: delay time; MO: maximum over/under shoot.

Fig. 3. Texas A&M University and XpertPower Associates Conformance testing in 2012 results of most PMUs being marketed in the U.S. (masked to protect their manufacturers). Note that none completely met the IEEE standard from [4]

important contributor to the chain of events that precipitated the blackout. After the event occurred, a team investigating the blackout used synchrophasor data to identify the model error; the utility used the synchrophasor data to update their power system models to accurately reflect actual system behavior under these conditions. This new model is represented by the blue curve in Fig 2. Clearly synchrophasor data can play an important role in the validation and improvement of power system models.

A further motivation of our effort is to improve PMU state of the art performance. Our survey of PMU performance showed that no PMU currently fully conforms to the IEEE Standard C37.118.1-2011, for Synchrophasor Measurements for Power Systems. Fig. 3 shows conformance test results of most commercially available PMUs (identities are intentionally masked) conducted by Texas A&M University and XpertPower Associates. No tested PMU met all the IEEE Std requirements in steady state and dynamic conditions tests. The significant performance differences are due, in part, to the many different ways to implement a device generating phasor measurements. We understand that several legacy algorithms are commonly used to process the data; however, they need to be improved. Our efforts to build a device from a blank page provided a deeper understanding of the technical challenges in meeting the standards.

In summer 2012, we began our project to design and implement an open box PMU as part of the Synchrophasor Data Quality research activity, Trustworthy Cyber Infrastructure Protection for the Grid (TCIPG) Project at the University of Illinois at Urbana-Champaign. By implementing a one-phase device, the important functionality of the PMU is retained, while opening the door to developing lower cost devices. This project offers several research and educational applications – and ubiquitous deployment at the distribution level to monitor local system performance. We included a design objective to integrate an uninterruptible power supply (UPS) which would

enable our PMU to continuously collect synchrophasor data during blackouts or other grid instabilities. The functionality of the device is to be tested using the University of Illinois Information Trust Institute testbed, as well as by comparing it to other commercially available PMUs. Section II provides an explanation of steps and challenges involved in building an open box PMU.

II. PMU STRUCTURE

Fig. 4 shows the major components (or functions) necessary to sample power system state values and compute phasors referenced to a GPS timing signal. In Fig. 6, we show our adaptation of the general structure to implement our single phase PMU using National Instruments hardware and software. We examined several different approaches in creating a new system. With particular thought to different complications to producing reliable data and meeting the IEEE PMU standard.

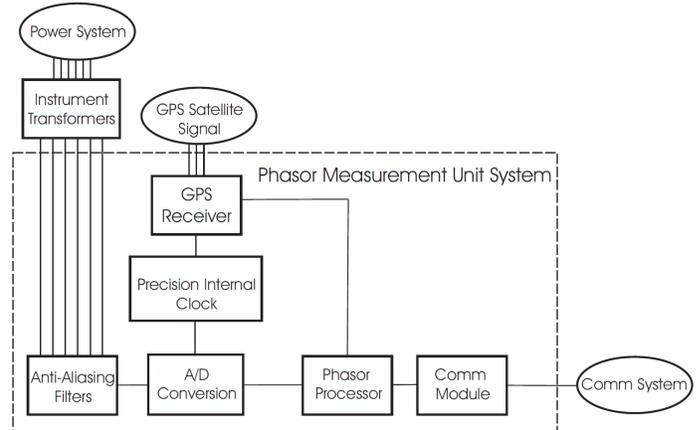


Fig. 4. Diagram of the general PMU structure

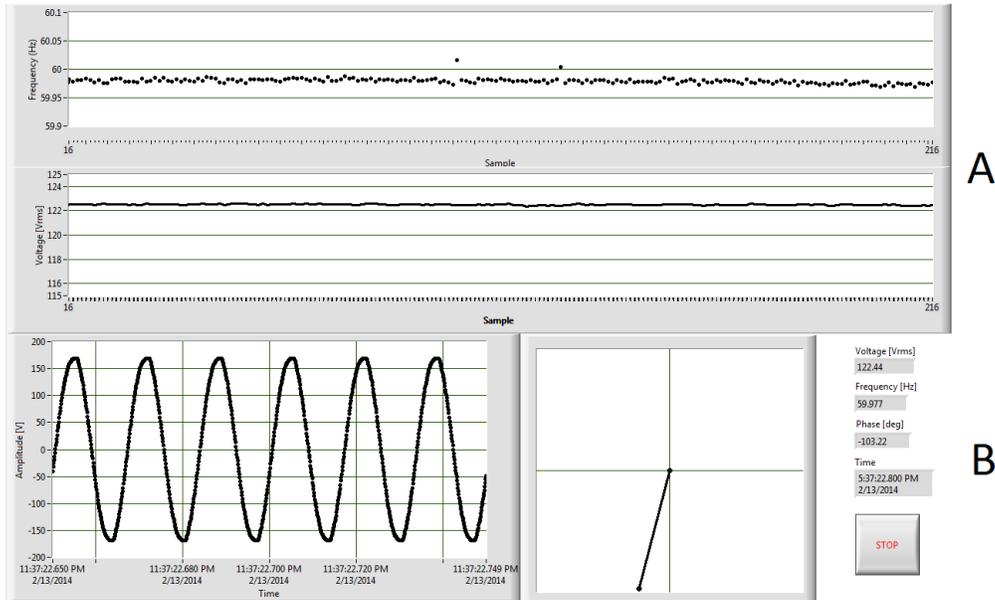


Fig. 5. Screenshot of LabVIEW front panel, showing visualization of phasor data in real time. In section A, frequency and voltage amplitude data are shown for the previous 20 seconds. In section B, phase angle and the original waveform are shown for the current data block.

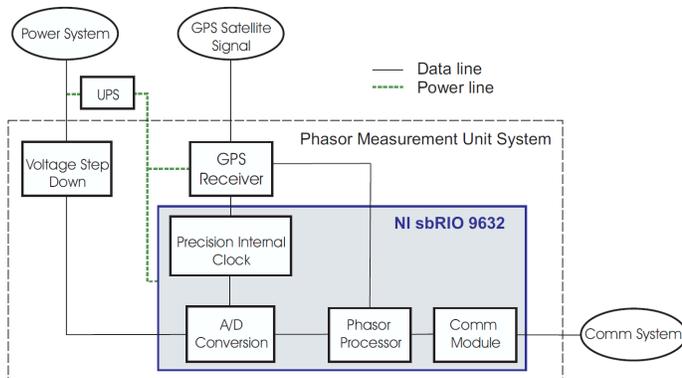


Fig. 6. Diagram of the our implementation of the single phase PMU structure

### A. Software

We chose to implement our PMU using National Instruments (NI) hardware and LabVIEW software for several reasons. The National Instruments Reconfigurable Input Output systems provide compact field programmable gate array (FPGA) based platform with flexible input and output module options. LabVIEW provides the capability to integrate existing software objects to implement an end-to-end measurement and phasor generation system. This enables comparatively simple, rapid prototyping – providing the capability to easily modify and test different system configurations and algorithms.

The LabVIEW Development System is a graphical programming environment to develop measurement, test, and control systems. It can be used directly with a wide variety of virtual instruments developed to interface with thousands of commercially available devices. However, direct LabVIEW implementation requires a man-in-the-loop, which is not useful for PMUs that must generate 10s of synchrophasor data sets per second, 24 x 7.

The LabVIEW Real-Time Module (the next level of control) uses programs developed in the LabVIEW development system and implemented in real-time on cRIO FPGAs. We attempted implementation with the Real-Time module with NI field engineer assistance, but were unable to implement the precise measurement timing controls demanded by the rapid fire computational operations involved in generating synchrophasor data. In particular, we had difficulty controlling sampling frequencies and integrating precisely timed measurements to correctly compute synchrophasor data.

We ultimately implemented our system using the LabVIEW FPGA module. This final level of control is the most complex and required completing a week-long, web-based NI training course to gain a functional understanding of its complexities. The FPGA Module compiles the graphical PMU logic developed in the LabVIEW Development System and implements that on the target FPGA hardware.

Using LabVIEW, the PMU is currently configured to use an FPGA and a real time processor to produce a synchrophasor. The code for our latest PMU implementation is shown in Fig. 13 at the end of this paper. The visualization of the software output, used in the development of the PMU, can be seen in Fig. 5. The FPGA is programmed to sample the distribution level voltage at a rate of 10 kHz and store the data in a Direct Memory Access First In, First Out (DMA FIFO) data structure. The real time processor is programmed to read data from the FIFO at a rate of 10 Hz to perform an Fast Fourier Transform (FFT) to acquire frequency. Using included NI LabVIEW functions, root-mean-square (RMS) voltage and phase are easily computed. The synchrophasor data is then labeled with the GPS synchronized time corresponding to the time at the center of the sample window used to compute the FFT. The hardware's internal clock keeps time between top of the second signal marks broadcasted by the GPS system.

There is a 0.1 s latency between the final sample measurements in a data window and a synchrophasor data frame (set of synchrophasor measurements corresponding to a time stamp) being fully formed for transmission. To date, we have not sought to send a steady stream of synchrophasor data to a phasor data concentrator, although the modifications to our system to do this are straight forward.

### B. Hardware

We initially selected four NI components to implement our PMU: cRIO 9025 Real-time Controller; LX30 cRIO Chasis; NI 9225 3-Channel,  $\pm 300$  Vrms Analog Input Module; and NI 9215 4-Channel, 10V Analog Input Module; shown in Fig. 7. Our cRIO input module's  $\pm 300$  V input range allowed us to directly sample 120 V wall voltage. Furthermore, the cRIO 9025's powerful 800 MHz processor and FPGA package easily met computational speed requirements. While programming a FPGA is more complex and time intensive than operating in the LabVIEW Real-Time Module, its speed and timing were more compatible with our performance requirements. While the unit's \$6,000 cost was high, it proved to be an excellent platform to kick start our design and implementation efforts. We realized from the outset, however, that costs would need to be reduced significantly to make widespread deployment economically viable on the distribution system.

For our second design iteration, we selected the National Instruments' sbRIO-9632, with Spartan 3 processor and 2 million gate Xilinx FPGA. The sbRIO's \$960 cost and its nearly identical functionality enabled this iteration to be implemented at one sixth the price. The sbRIO-9632's one significant capability difference was its  $\pm 10$  V analog input (vs. the cRIO's  $\pm 300$  V input), which required additional external components to step down the voltage without otherwise altering the signal.

Our third, and most recent design iteration seeks to use NI's myRIO-1900, which became available in January 2014 and costs \$250. Not only is the myRIO-1900 more compact than the cRIO and sbRIO, but it also adds wi-fi capability that we intend to leverage to reduce hard cabling requirements during installation.



Fig. 7. National Instruments cRIO (left), sbRIO (right), and myRIO (bottom)

### C. Data Collection

The sbRIO and myRIO analog inputs, which are used in sampling distribution level voltage, have a  $\pm 10$  V<sub>RMS</sub> range. To step the voltage down, we chose to use a resistive voltage divider placed across measured voltage. We chose the voltage divider over a transformer due to cost, size, and performance considerations. If the resistors are held at the same temperature by careful positioning, any resistivity changes due to thermal effects would be proportional – and not affect the step down voltage ratio. The step down ratio will be constant and can be found through testing. Using 8.43 M $\Omega$  and 395.3 k $\Omega$  resistors, we expect to dissipate 1.6 mW, which is insignificant compared to the board's power consumption.

Very precise timing measurements are crucial to meeting IEEE standards. The system must accurately combine data and timestamp. A time signal is acquired through a Garmin 18xLVC GPS receiver, which contains two information components. One is a 5 V pulse with the rising edge at the beginning of each second, seen in Fig. 8. The other GPS output is a string which gives time and location 500 ms after the top of the second, seen in Fig. 9. PMU time is maintained by the hardware's internal clock, which is corrected by the 5 V GPS pulse at the beginning of each second. Each data point is then stamped with the correct GPS time before being saved and later uploaded to a web server.

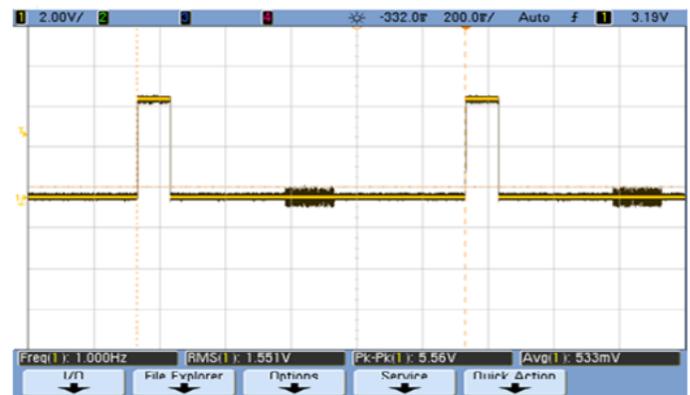


Fig. 8. Oscilloscope trace of the signal produced by the Garmin GPS receiver. The leading edge of the square pulse signals the top of each second to an accuracy better than 1  $\mu$ s. Location and timing data are contained in signal imposed of the square wave 500 ms after the leading edge

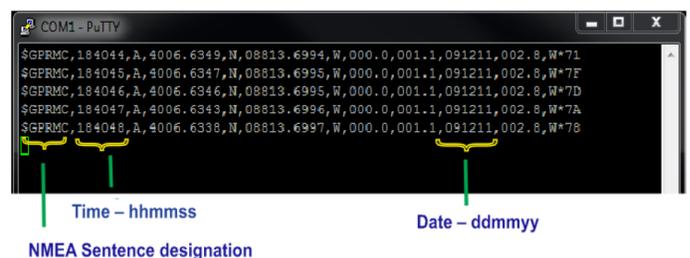


Fig. 9. GPS location and time information produced once per second; The Garmin GPS receiver provides date, time, and location data per the National Maritime Electronics Association (NMEA) Standard 0183

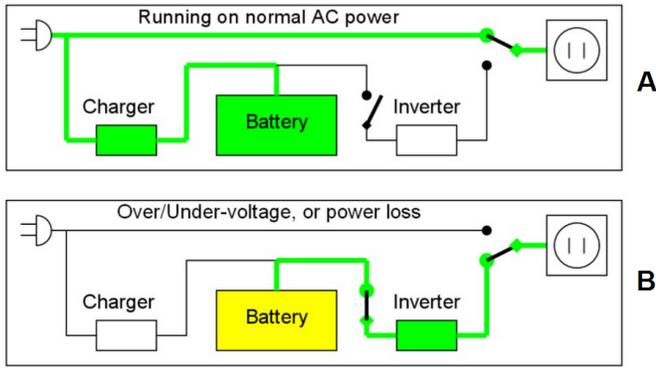


Fig. 10. Standby UPS operation diagram while powered (A), and during blackout (B) from [6]

#### D. Power Supply and UPS

The voltage requirements are 5 V for the GPS receiver and 12 V for the NI hardware with a 15W total power requirement. Under normal operating conditions, the sbRIO is powered via wall outlet and the GPS receiver is powered by the sbRIO's 5 V pin output. During power loss, the 12 V and 5 V supplies are supplied by the uninterruptible power supply (UPS). Grid instabilities are not expected to last more than an hour, therefore UPS was selected to meet this minimum requirement.

We considered two UPS topologies: standby and online. We chose the standby topology, illustrated in Fig 10. During normal operation, there is a direct connection from the power grid to the device being powered. During periods of grid instabilities, The UPS switches to draw power from its battery. We tested the continuity of power to our PMU during a power failure and found that switching did not adversely affect measurements or phasor computations during the change in system state.

#### E. Data Upload

To allow near real-time inspection of the collected synchrophasor data, a separate computer was used as a web server. To establish a connection with and transfer the collected data to the web server, we selected the ubiquitous file transfer protocol (FTP). To archive distribution voltage behavior during blackouts, the PMU saves synchrophasor data internally for an hour and uploads the data to the web server at the start of each hour. If the connection can not be made at the start of each hour, the PMU continues collecting, generating, and saving the data internally. When network reconnection is detected, the saved files are upload to the web server.

The PMU provides 10 synchrophasor data sets per second, generating 69 MB of synchrophasor data per day. If the network connection is lost for more than 89.04 hours (3.7 days) for sbRIO (and myRIO) or 178.08 hours (7.42 days) for cRIO, the accumulated data would exceed respective on-board storage capacities and synchrophasor data would be lost.

Another important design consideration is very reliable PMU to network data connections – which may pose challenging configuration and accessibility issues if the connection path

| Date      | Time          | Phase  | Vrms   | Frequency |
|-----------|---------------|--------|--------|-----------|
| 1/20/2014 | 15:0:0:000000 | 125.05 | 122.63 | 60.0523   |
| 1/20/2014 | 15:0:0:100000 | 126.63 | 122.65 | 60.0256   |
| 1/20/2014 | 15:0:0:200000 | 127.53 | 122.59 | 60.0234   |
| 1/20/2014 | 15:0:0:300000 | 128.34 | 122.61 | 60.0256   |
| 1/20/2014 | 15:0:0:400000 | 129.26 | 122.62 | 60.0289   |
| 1/20/2014 | 15:0:0:500000 | 130.24 | 122.57 | 60.0243   |
| 1/20/2014 | 15:0:0:600000 | 131.12 | 122.59 | 60.0266   |
| 1/20/2014 | 15:0:0:700000 | 131.97 | 122.56 | 60.0263   |
| 1/20/2014 | 15:0:0:800000 | 132.86 | 122.54 | 60.0280   |
| 1/20/2014 | 15:0:0:900000 | 133.77 | 122.51 | 60.0269   |
| 1/20/2014 | 15:0:1:000000 | 134.65 | 122.57 | 60.0225   |
| 1/20/2014 | 15:0:1:100000 | 135.58 | 122.57 | 60.0223   |
| 1/20/2014 | 15:0:1:200000 | 134.25 | 122.48 | 60.0224   |
| 1/20/2014 | 15:0:1:300000 | 135.04 | 122.49 | 60.0232   |
| 1/20/2014 | 15:0:1:400000 | 135.92 | 122.52 | 60.0268   |
| 1/20/2014 | 15:0:1:500000 | 136.85 | 122.44 | 60.0218   |
| 1/20/2014 | 15:0:1:600000 | 137.63 | 122.46 | 60.0267   |
| 1/20/2014 | 15:0:1:700000 | 138.47 | 122.57 | 60.0269   |
| 1/20/2014 | 15:0:1:800000 | 139.41 | 122.53 | 60.0259   |
| 1/20/2014 | 15:0:1:900000 | 140.32 | 122.52 | 60.0274   |

Fig. 11. Synchrophasor data as seen from the web server

passes through multiple firewalls. Our current web server can only be reached from the UIUC network, thus if the device is installed in places outside the campus, the web server would be unreachable. We intend to overcome this issue by establishing a server outside the university network.

Fig. 11 shows sample synchrophasor data generated by our PMU and accessed via our web server. We opted to generate and report synchrophasor data at 10 Hz. Note that in this data sample, the phase angle is increasing due to frequency being very slightly higher than 60 Hz.

Though frequency is calculated using built-in NI LabVIEW functions, we observed a periodic error in the PMU's frequency recurring every few seconds of about 0.03 Hz is an issue, as seen in Fig. 12. We also observed this error when we used a clean 60 Hz signal from a signal generator. We suspect the unexpected, spurious computed frequencies is from unanticipated algorithm behavior. We intend to identify the source and modify our design accordingly.

### III. FUTURE EFFORTS

While we have made significant progress to achieving our objectives, there is still much work to be done. We intend to investigate design and algorithm modifications to implement our PMU so that it meets IEEE Standard C37.118.1-2011 performance specifications.

Then, we intend to test our modified PMU's performance against the IEEE PMU standards to ensure proper functionality. We are seeking an established test facility to assist us with this effort.

To date, our efforts have been to compute and upload a synchrophasor data file with an hour's data to a webserver. We

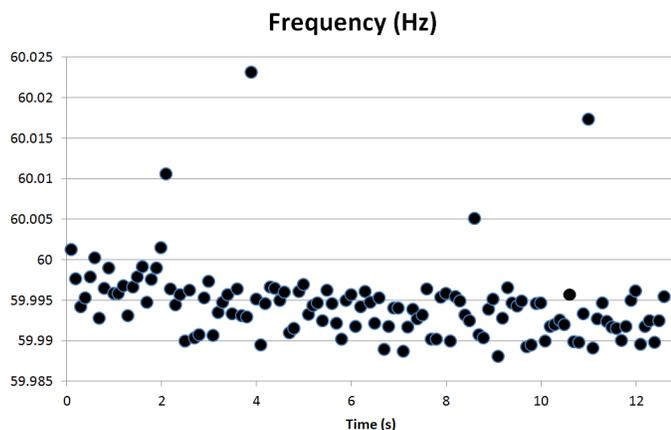


Fig. 12. Sample synchrophasor data. Note the periodic frequency anomalies that appeared in sampling both the wall voltage and a clean 60 Hz sine wave produced by a signal generator.

intend to add the capability to continuously send synchrophasor data frames to a Phasor Data Concentrator (PDC) to be established in the TCIPG Testbed. Then, we intend to deploy multiple PMUs on the local distribution system and stream their synchrophasor data through the TCIPG Testbed PDC.

In light of widely publicized concerns about the cyber security of the Smart Grid, we intend to investigate methods of encrypting synchrophasor data without unduly slowing its flow.

These research efforts are expected to be front and center in at least three master's degree theses to be completed in the next 18 months.

#### IV. CONCLUSION

This project is driven by our curiosity about the inner workings of the modern PMU particularly as commercially available PMUs are largely black boxes. Using National Instruments products, we have successfully created a PMU that measures during normal and abnormal grid operations. We see an opportunity to develop innovative approaches and algorithms that fully conform to the . The prospect of a very inexpensive PMU which functions during power grid state transitions provides added incentive to fill a unique niche not being served.

Throughout this project it became apparent that producing a synchrophasor is very difficult, even without completely adhering to the IEEE standard. It is a complex task to have the very precise hardware timing work in unison with the software. In the future, our PMU will continue to mature as more work is being conducted to improve its algorithms and better hardware is implemented. The knowledge which was gained by those working on this project is indispensable as they move forward with the PMU and foster new synchrophasor research ideas.

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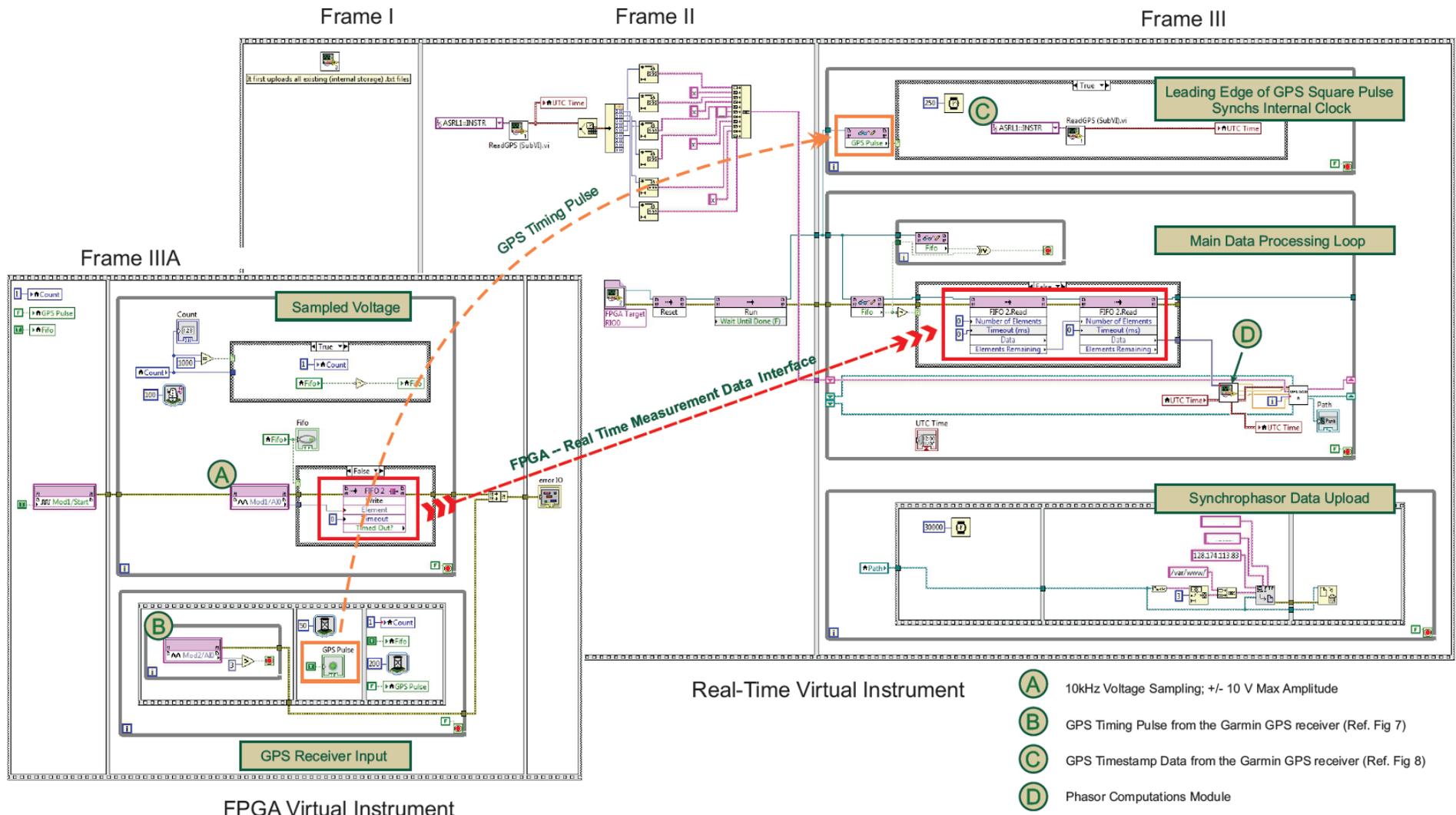


Fig. 13. Diagram of main programming of PMU. Frame I uploads and clears hardware buffers. Frame II initiates the FPGA Virtual instrument (VI) and creates a file for the data. In frame IIIA, the VI executed on the FPGA collects data in 0.1 s blocks and then sends it to the Main Data Processing Loop in frame III. Frames III and IIIA execute simultaneously in the Real-Time VI and the FPGA VI, respectively. In frame III, the real-time program processes these data blocks and assigns a timestamp to each. In the Synchrophasor Data Process the data is then uploaded to the remote server.