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"Wide Area Measurement System Utilizing Open Source Tools"

Colin Chapman, Phaelan Guan, Tyler LeRoy, Ethan Miller, Dan Park
Electrical Engineering
United States Military Academy
West Point, New York 10997 USA

Faculty Advisors: Dr. Aaron St. Leger and CPT Jeremy Spruce

Abstract

Recent advancements in measurement and wecommunication technology show promise in improving power system operation. More specifically, Phasor Measurement Unit (PMU) based Wide Area Measurement Systems (WAMS) have been identified as a key tool towards improving situational awareness, operation, and reliability of power systems. This paper presents the development of a WAMS at the United States Military Academy (USMA). The primary purpose of this system is for education and research. More specifically, specific thrusts are to develop data processing techniques, develop and validate models of WAMS, and investigate digital and physical security of WAMS. A secondary, longer term, goal is to monitor and analyze the power generation and distribution at USMA. While WAMS components are commercially available, they are costly and are proprietary in nature. Hardware and software components are closed source and difficult to analyze. As a result, commercially available solutions did not meet the unique requirements of this project. For this reason, open source tools were utilized in this effort. To be more specific, OpenPMU was employed for phasor measurement and iPDC for processing and storing data. These open source products were used as a starting point for this project. The WAMS in this work adheres to the IEEE C37.118 synchrophasor standard in most aspects and, in addition, features improvements over the available open source tools including a graphical user interface and additional data processing.

Keywords: Open Source, Power System, Wide Area Measurement, Phasor Measurement Unit, Smart Grid

1. Introduction

The purpose of this work was to create a low-cost, open-source PMU-WAMs system that measures the amplitude, phase, and frequency of 3-phase AC Power. In addition, a secondary objective was compliance with the IEEE C37.118 [1] standard. The completed system will be utilized for education and research efforts at the United States Military Academy (USMA). Commercially available PMU-WAMS are cost prohibitive and based on closed source tools which will not meet these objectives. The PMU-WAMS presented here was developed from available open source code, and commercial off the shelf (COTS) parts. PMU based measurement of power systems is much improved over traditional Supervisory Control and Data Acquisition (SCDA) systems. SCADA systems typically sample data on the order of 1Hz, and don't provide synchronized time stamped data. Conversely, PMUs can measure at rates up to 60Hz and with a Global Position System (GPS) time stamp.

A PMU-WAMS consists of numerous PMU nodes strategically located throughout the power grid, sampling the voltage and current waveforms, calculating phasors (magnitude and phase of each waveform), time stamping the data, and sending this data across a network to a Phasor Data Concentrator (PDC). Data is processed by the PDC, displayed on a graphical user interface for users and then logged into a database for future use of analysis and forensics. The initial work presented here focused on developing a single PMU, networking it with a PDC, and processing/serving data to end users from the PDC. Future work will include further testing and refinement of the PMU-WAMS and deploying the system at USMA with additional PMUs.

2. Methodology

The PMU-WAM system is comprised of multiple PMUs that communicate with one PDC in order to measure precise, synchronous data from multiple geographic positions simultaneously. These measurements include the phasor calculations for voltage and current on all three phases as well as an estimation of frequency and the rate of change in frequency. The PMUs send measurements to the PDC at rates up to 60Hz. Figure 1 illustrates the WAMS concept integrating PMUs.

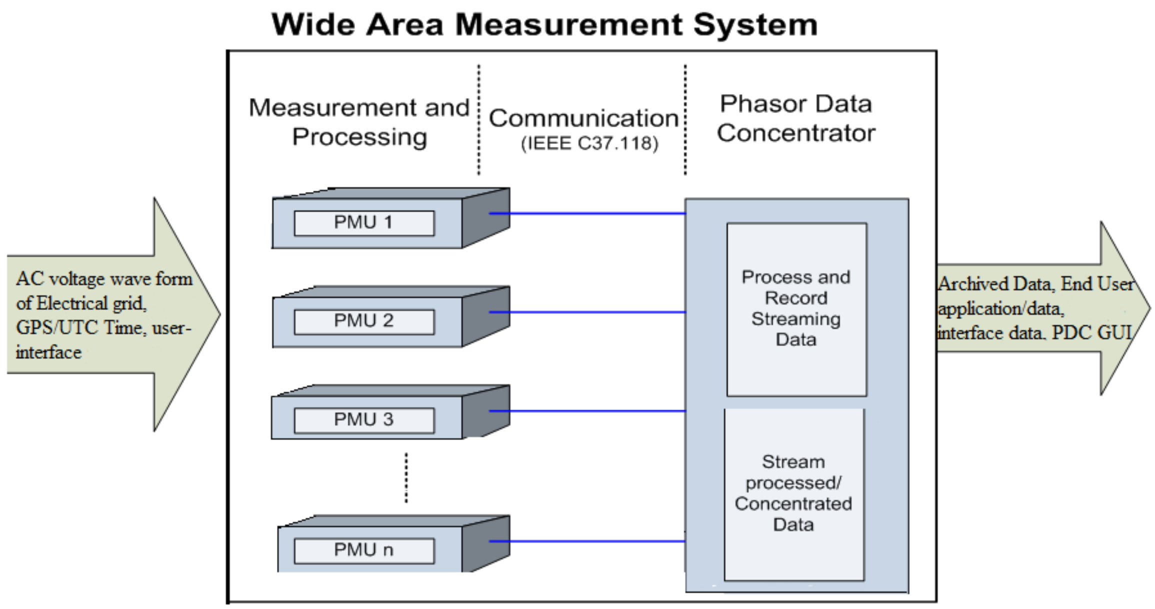


Figure 1: block diagram of PMU-WAMS

Utilizing open source tools has a few distinct advantages compared to commercially available components. Firstly, the cost is significantly reduced. Secondly, the algorithms utilized for data processing, phasor calculations, frequency estimation, etc. are available for education and research purposes. This work employed the OpenPMU [2,3] platform for developing a PMU and iPDC [4] for the data concentrator. The PMU presented here was constructed with ~$1200 in parts. The cost was minimized by making use of open source tools with off-the-shelf products. In order to make a system comparable to with commercial PMUs and PDCs, compliance with the IEEE synchrophasor standard, also known as IEEE standard C37.118 [1] was required. This standard specifies the accuracy of the PMU and the communication protocol to the PDC among other items. The accuracy standard for the PMU is established in terms of Total Vector Error (TVE), which takes into account magnitude and phase deviations between the measured phasor and the actual phasor. It is quantified by equation 1, and must be less than 1% for all of the conditions in table 1. This work focused on level 0 compliance.

$$TVE = \sqrt{\frac{\left(X_r(n) - X_r\right)^2 + \left(X_i(n) - X_i\right)^2}{X_r^2 + X_i^2}} \times 100\% \qquad (1)$$

where $X_r(n)$ and $X_i(n)$ are the real and imaginary measured values and X_r and X_i are the true values.

Table 1. total vector error compliance levels

Influence quantity	Reference condition	Range of influence quantity change with respect to reference and maximum allowable TVE in percent (%) for each compliance level			
		Level 0		Level 1	
		Range	TVE (%)	Range	TVE (%)
Signal frequency	$F_{nominal}$	± 0.5 Hz	1	± 5 Hz	1
Signal magnitude	100% rated	80% to 120% rated	1	10% to 120% rated	1
Phase angle	0 radians	± π radians	1	± π radians	1
Harmonic distortion	<0.2% (THD)	1%, any harmonic up to 50th	1	10%, any harmonic up to 50th	1
Out-of-band interfering signal, at frequency f_i where $\|f_i - f_0\| > F_s/2$, F_s = phasor reporting rate, $f_0 = F_{nominal}$	<0.2% of input signal magnitude	1.0% of input signal magnitude	1	10% of input signal magnitude	1

The PDC was implemented using an open source project called iPDC. The code from this project was implemented on a Linux-based computer and connected it to the PMU via an Ethernet connection. UDP communication was utilized with a specified handshake routine between the PMU and PDC. The PDC starts the communication with a command message to the PMU, and when the PMU responds with its configuration message, the PDC sends an additional command message to start the stream of data. The structure of each of these messages is based on the format in Figure 2 [1]. The Sync segment identifies the type of message (Command, Configuration, or Data), the Soc is a timestamp measured in seconds from January 1, 1970, and the Fracsec represents time in between each second. There is a CRC Checksum at the end of each packet to ensure security of communication. The GUI that was made for this PDC was made using MySQL, and is shown in
Figure 3.

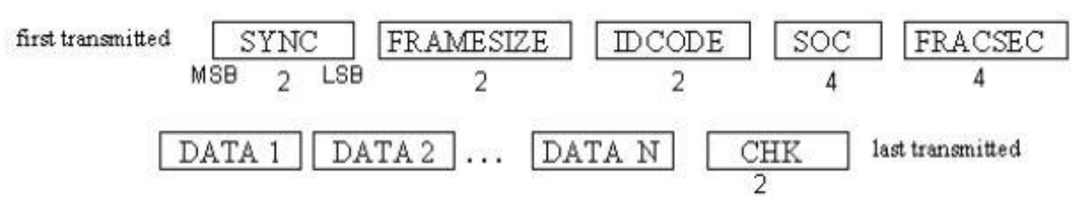


Figure 2. synchrophasor packet format

In
Figure 4 there is a simplified block diagram of the PMU showing wire parameters and power consumption for each component. The system was designed to measure 208/120V three phase AC up to 20A per phase. The unit is self powered from one 120V phase. LEM voltage [5] and current [6] transducers were chosen for the PMU. The PMU can be adapted to measure other voltage levels and current levels by swapping out these transducers. The signal processing is accomplished by converting the analog samples in digital data with a National Instruments USB-Data Acquisition Unit (DAQ) [7] and triggering acquisition from a 1Hz pulse provided by the GPS. The pulse from the GPS serves as a reference for a software based phase-locked-loop, which facilitates sampling at frequencies greater than one Hz. After the signal processor has calculated the amplitude and phases of all three phases, it puts them into phasor format and sends them over the internet (UDP protocol) to the PDC. The data sampling occurs at rates up to 6kHz, and the phasor calculations are performed and sent out at rates up to 60Hz. All signal processing is performed via modified OpenPMU software in LabVIEW [8] running on a FitPC [9].

Figure 3. graphical user interface of the phasor data concentrator

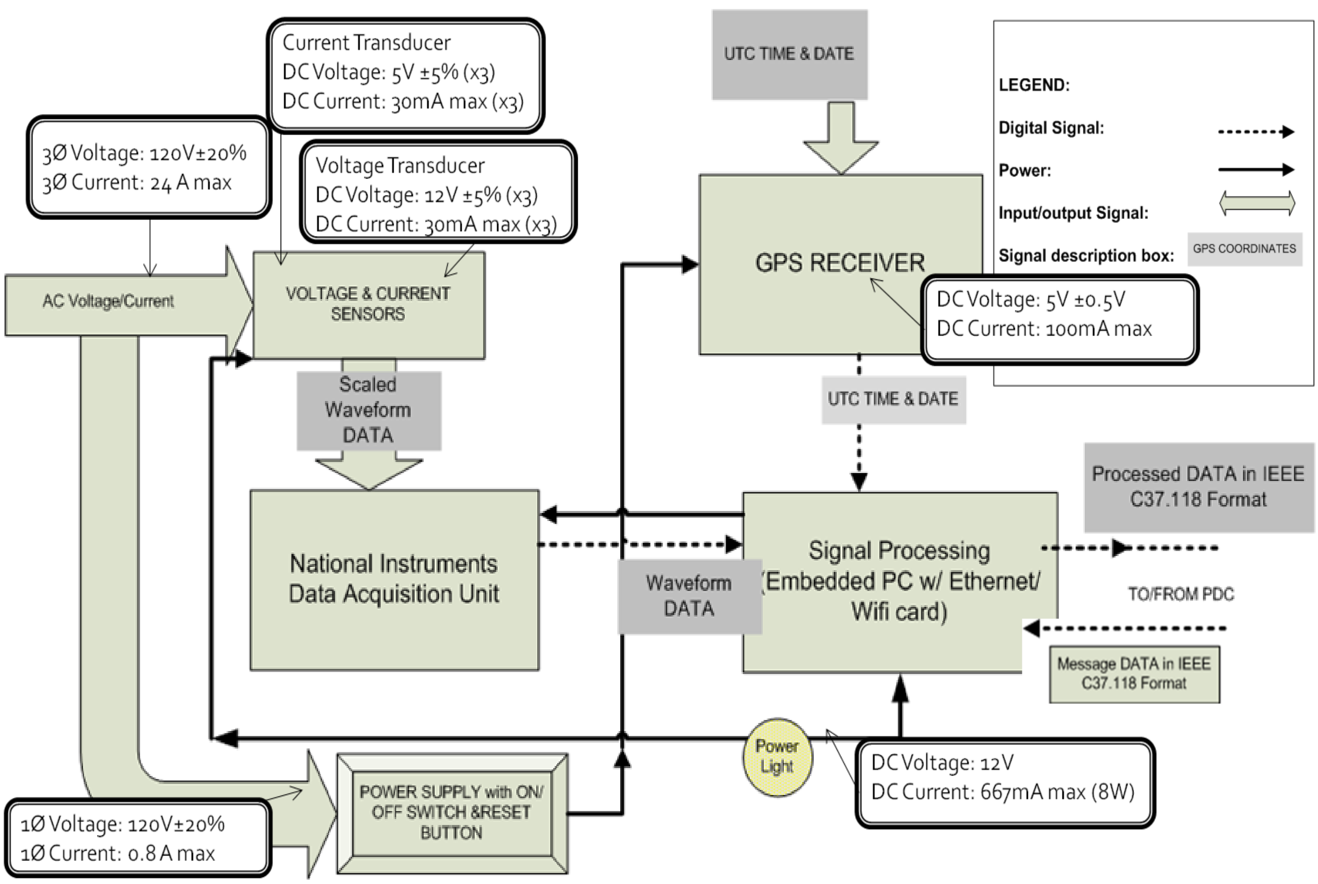


Figure 4. phasor measurement unit block diagram

4. Data and Discussion of Results

The constructed PMU-WAMS was tested for basic functionality and compliance with the IEEE C37.118 standard. The core functionality and compliance with voltage phasor measurement has been accomplished. However, some additional testing and modifications are required for full compliance. Tests were performed on the PMU, shown in Figure 5, to evaluate transducer performance across the range of voltage and current levels specified in the standard. Vector magnitude error for a voltage transducer is shown in Figure 6. The error is within ± 0.15% across the range of 95 to 140 volts rms. Similar results were seen for other voltage and current transducers. The maximum magnitude error observed across all transducers was 0.35%. Phase angle testing was conducted at 60Hz (grid frequency) to evaluate TVE.

Figure 5. completed phasor measurement unit

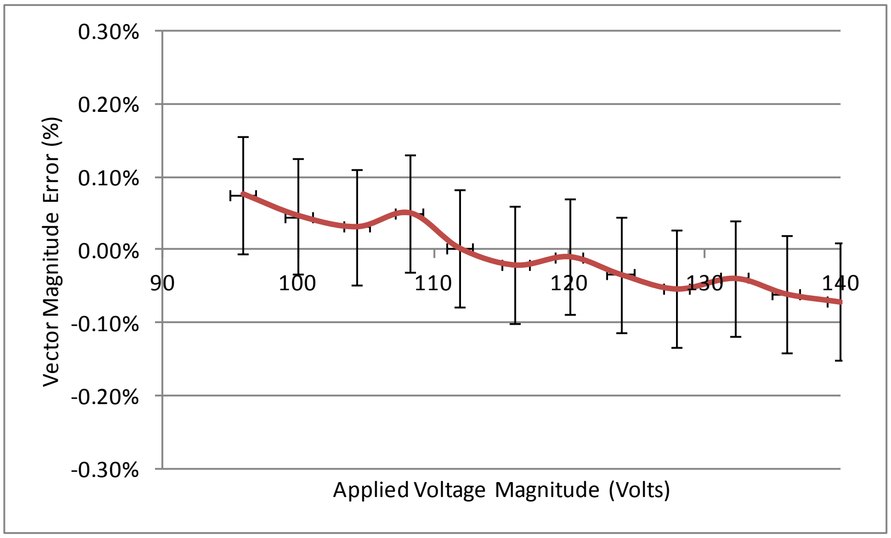


Figure 6. vector magnitude error for a voltage transducer

Phase was evaluated by measuring the voltage and current applied to the PMU and the corresponding output of the transducers on an oscilloscope. A three phase 208/120V 60Hz source from the utility was used for these tests. Phase angles were calculated based on zero crossing estimation on the oscilloscope. Approximately 750 samples were collected for input and output of each transducer. The mean and standard deviation of the input and output amplitudes and the phase shifts where calculated from this data and TVE was calculated based on two standard deviations from the mean value. Some statistical analysis was required to calculate the standard deviation of the measurement devices from this data. This was required due to observed variation in the voltage source which correlated to variation in the sensor output. This correlated variation was processed out of the results shown in Table 2.

The voltage transducers achieved the IEEE standard for almost all cases. Some extreme voltage values in the third transducer showed error slightly above 1%. The current transducers exhibited appreciable noise which resulted in large phase errors. However, much of this is due to the zero-crossing method used to calculate phase on the oscilloscope. The actual PMU uses a more sophisticated, FFT based, algorithm to calculate phase. This noise and variation was not observed in the PMU interface, seen in Figure 7. A setup for synchronized testing and evaluation of the PMU data in the GUI was not available as of this writing to verify the PMU phase calculations, but the authors are confident that the results of such testing will show much improved results.

Table 2. total vector error evaluation for phasor measurement unit

Sensor	Input RMS	Sensor Voltage RMS mean	Sensor Voltage σ	Sensor Phase σ	Maximum Magnitude Error	Maximum TVE
Voltage Transducer 1	121.62 ±0.13661V	3.9870	5.66 (mV)	0.1217°	0.22%	0.48%
VT 2	118.71 ±0.10102V	3.8721	3.18 (mV)	0.12810°	0.15%	0.47%
VT 3	121.57 ±0.11021V	3.9830	3.86 (mV)	0.31806°	0.17%	1.12%
Current Transducer 1	17.22 ±0.01159A	0.41477	610.07 (μV)	1.6692°	0.26%	5.84%
CT 2	16.836 ±.020748A	0.40182	784.37 (μV)	1.6229°	0.35%	5.68%
CT 3	16.803 ±0.02136A	0.39044	488.17 (μV)	1.7366°	0.23%	6.07%

PMU to PDC communication compliance to the IEEE standard was also tested and validated. This compliance was accomplished with the exception of reporting fraction of seconds and warning of an upcoming leap second. These capabilities have not yet been added. In addition, the PMU can receive, but not yet respond to, PDC commands other than the initial two packets associated with the PMU-PDC handshake. Remote control of PMU from PDC is functionality that is planned for future work.

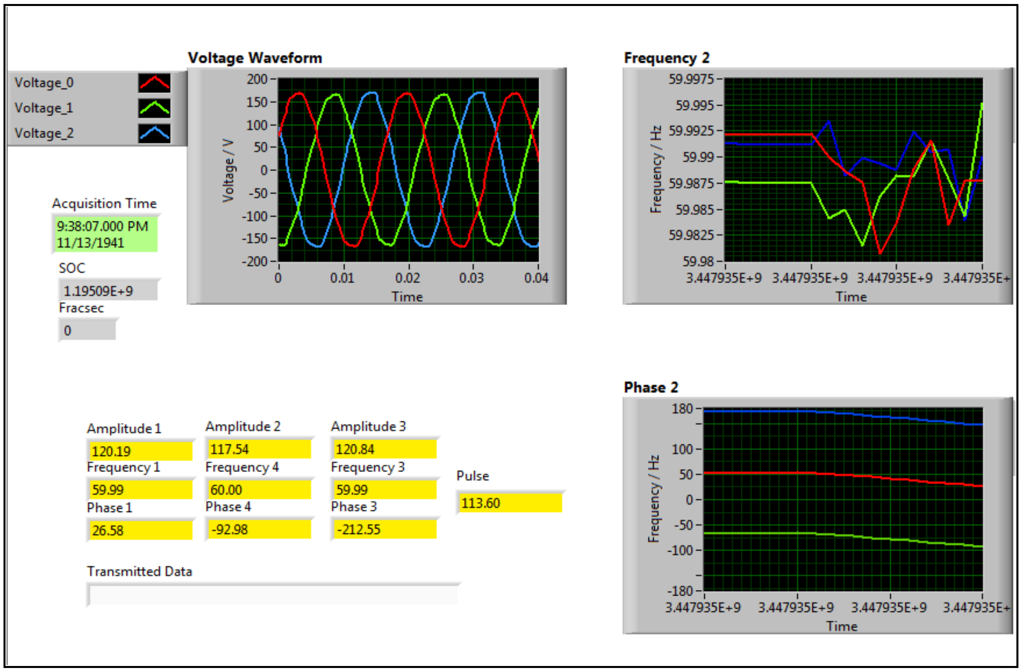


Figure 7. OpenPMU graphical user interface

For final system testing of the PMU-WAMS, the availability and integrity of data passing between the PMU, PDC, and the PDC GUI was examined. Testing confirmed that data sent by the PMU was the same data received by the PDC, and the data being displayed on the PDC GUI was the same data the PMU had originally sent. The connection between the PMU and PDC was verified by monitoring traffic between the two through Wireshark [10]. The validation of this test can be seen in Figure 8, which shows a screenshot of Wireshark on the PMU side sending data to the PDC's IP address and a screenshot of Wireshark on the PDC side showing that the PDC is accepting packets from the PMU's IP address. Once a piece of data left the PMU, the data packet was opened up and compared to IEEE C37.118 which dictated how the packet should have been structured. Once this packet was translated from hex to decimal, it was compared to the data sent by the PMU packet to the data updated on the actual PDC and MySQL database. In this way, there was confirmation in the integrity of the data. Figure 10 shows that it received valid data from the PMU for the voltage of the third phase (single-phase sampling was conducted for this test), corresponding to approximately 120V rms.

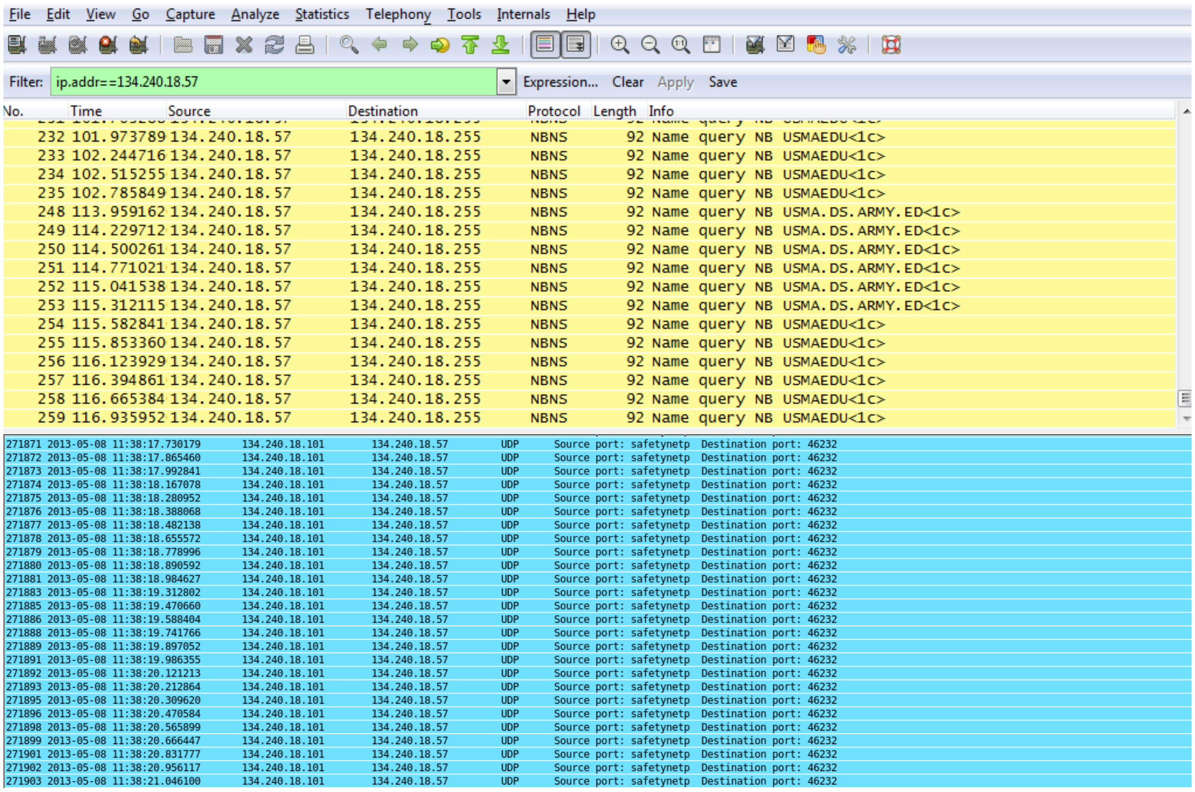
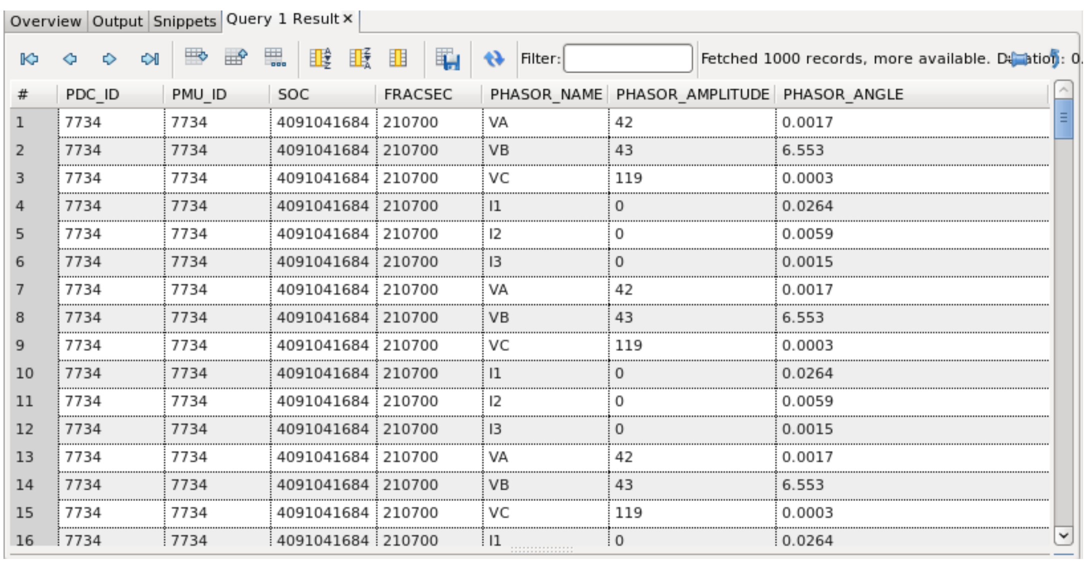


Figure 9. wireshark validation of PMU-PDC communication



#	PDC_ID	PMU_ID	SOC	FRACSEC	PHASOR_NAME	PHASOR_AMPLITUDE	PHASOR_ANGLE
1	7734	7734	4091041684	210700	VA	42	0.0017
2	7734	7734	4091041684	210700	VB	43	6.553
3	7734	7734	4091041684	210700	VC	119	0.0003
4	7734	7734	4091041684	210700	I1	0	0.0264
5	7734	7734	4091041684	210700	I2	0	0.0059
6	7734	7734	4091041684	210700	I3	0	0.0015
7	7734	7734	4091041684	210700	VA	42	0.0017
8	7734	7734	4091041684	210700	VB	43	6.553
9	7734	7734	4091041684	210700	VC	119	0.0003
10	7734	7734	4091041684	210700	I1	0	0.0264
11	7734	7734	4091041684	210700	I2	0	0.0059
12	7734	7734	4091041684	210700	I3	0	0.0015
13	7734	7734	4091041684	210700	VA	42	0.0017
14	7734	7734	4091041684	210700	VB	43	6.553
15	7734	7734	4091041684	210700	VC	119	0.0003
16	7734	7734	4091041684	210700	I1	0	0.0264

Figure 10. MySQL database results

5. Conclusion

This paper presented the development and testing of a PMU-WAMS at the United States Military Academy (USMA). The primary purpose of this system is for education and research. Open source tools were utilized in this effort to quickly develop the system and at low cost. To be more specific, OpenPMU was used as a starting point for the PMU and iPDC for processing and storing data. The WAMS in this work adheres to the IEEE C37.118 synchrophasor standard in most aspects and, in addition, features improvements over the available open source tools including a graphical user interface to the PDC, and additional data processing. Future work includes more thorough testing and validation of compliance with the IEEE C37.118 standard, construction of additional PMUs, adding functionality to the PDC GUI, and deployment of the PMU-WAMs at USMA.

6. References

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