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Development of Phasor Measurement Units for Real Time Monitoring of Distribution Systems

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Abstract
This paper presents the design and development of a cost effective phasor measurement unit (PMU) for real time monitoring of power network operation. The development of PMU in the Nigerian market will opens up many possibilities for future development to supports ultimate adoption of smart grid. In particular, it will support increased integration of distributed generations. Distributed generation allows for the use of small, sustainable sources to supplement or be the sole power source of small areas. This capability is a key to the spread of sustainable power development. The prime objective of the paper is to acquire accurate power system data to support critical corrective decision by the control room operators and regional administrators. Hence, there is need for the design of a faster automatic control to counteract disturbances on the grid. The web-based phasor data concentrator (PDC) allows for many tasks to be executed using the personal computer and the Internet. This paper, proposed a system that can eliminate the manual operation/interaction between the grid and the control room operators. The device was designed in compliance with the IEEE Standard C37.118, in order to ensure compatibility with existing phasor data concentrators and visualization software.

Keywords: Control room, critical corrective decision, distributed generation, phasor data concentrators, phasor measurement unit, sustainable sources and Smart grid.

1.0 INTRODUCTION
Nigeria being one of the most populated countries in Africa, only about 40% of its populace is connected to the national grid. Nigeria produces closed to 8 MW of electricity but also experiences blackouts. From the investigation carried out by the Nigerian Electricity Regulatory Commission (NERC), the blackout can be confined to a small region, if the operators can know the condition of the overstressed and failing lines. Since this investigation, measures were put in place on how to improve real-time monitoring of the Nigeria's transmission and distribution network, to enable the system operators to predict and counteract disturbances. Increased in situational awareness can also allow the dynamic calculation of maximum load ratings based on the environmental conditions. Overall, improved monitoring allows utilities to provide power to customers in a more efficient, more reliable, and safer way [1].

Power system monitoring simply involves taking readings or measurements from power systems at specified time intervals while these systems were in service. Measurements of specific parameters on power systems are carried out by specific devices. One of such device is the phasor measurement unit (PMU) being a key tool in providing situational awareness, thereby increasing the reliability of the power system network [2]. A PMU is a device designed for measuring basic system parameters; bus voltage, current and frequency, as well as the synchronized voltage and current phasors, with optimum accuracy and speed. PMU samples the voltage and/or current signals to calculate voltage and/or current phasor(s), deviation from nominal frequency and the rate of change of frequency, with exact time stamp associated with each measurement. Increasing the number of PMUs installed in the network, it improves the resolution of data available to control room operators. It also creates the possibility for implementation of automatic control systems to correct disturbances or failures. However, these devices are expensive; thus they are difficult to install [3]. To install a PMU into the network, a dedicated communication networks for data feedback to the central processors, known as phasor data concentrators (PDCs) are required.

The future of power system depends on the quality of network data available to the operators. The main task of PMU is to measures electrical waves on the electrical power system using a common time source for synchronization by global positioning system (GPS) satellites and respectively receiving universal time coordination (UTC) signals. The advantages of PMU comes from its unique ability to provide synchronized phasor measurements of voltages and currents from widely dispersed locations in an electric power grid. PMUs were first introduced in 1980s, and since then have become the ultimate data acquisition device, which can be used for wide area measurements with many applications that are currently under development around the world [4, 5].

PMUs were designed for measurements at 50/60 Hz AC waveforms (voltage and current) typically at a rate of 48 samples per cycle. The voltage and current waveforms were digitized by an analogue-to-digital converter for each phase. A phase-locked-loop oscillator along with a GPS reference source provides the needed high-speed synchronized sampling with 1 microsecond accuracy. PMUs can be connected to a multiple time sources including non-GPS references provided that all the sources were calibrated and synchronized. The combined action of the system can be transmitted to a local or remote receiver at rate up to 120 samples per second [6].

PMU system is preferred to the traditional SCADA and EMS systems because it can be use to measures both analog and digital input. It also has high resolution (60 samples per seconds), dynamic/transient observability, and most importantly, it is time stamped. Therefore, PMU is widely use in power system monitoring and control [7].

2.0 LITERATURE REVIEW

2.1 Theoretical Background

PMUs technology provides phasor information (both magnitude and phase angle) in real time. Effective utilization of this technology is very useful in mitigating blackouts as well as getting the real time behavior of the power system. With the advancement in technology, the microprocessor based instrumentation such as protective relays and disturbance fault recorders (DFRs) were incorporated in the PMU module along with other important features.

The system block diagram is shown in Figure 1. The analog inputs to the device are currents and voltages obtained from the secondary windings of current and voltage transformers. The phase currents and voltages were used so that the positive sequence measurement can be carried out. The current and voltage signals were converted to voltages with appropriate shunt or instrument transformers to match with the requirement of the analog to digital converters in the Arduino. The sampling rate chosen for the sampling process will dictates the frequency response of the anti-aliasing filters. Anti-aliasing filters will ensure that all the analog signals have the same phase shift and attenuation, thus assuring that the phase angle differences and relative magnitudes of the different signals remains unchanged.

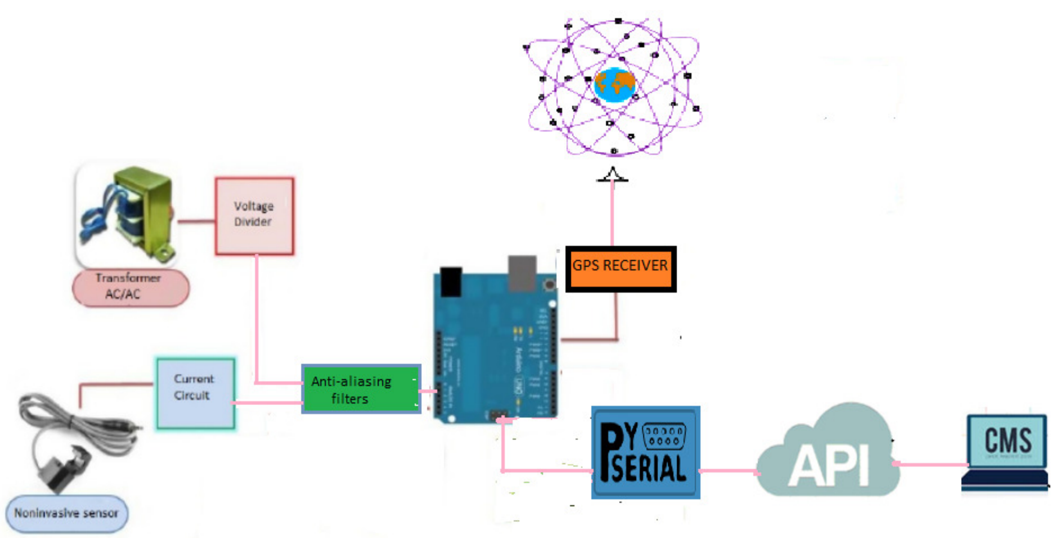

Figure 1: Block Diagram of the System [6]

The GPS will be used to determine the coordinate of the receiver. The pulses received by any receiver on earth will be the same with all other receivers. The PMU data will be obtained using the developed Arduino sketch C++ program, uploaded on the Arduino board. The data recorded by the PMU are time, power factor, voltage, current, real power, apparent power, frequency and energy. The equations used for the computation of these parameters were included in the C++ library and will also be installed in Arduino IDE.

2.1.1 IEEE Standards for PMU

The IEEE standard for PMU was approved by the IEEE-SA Standards Board (2005) and also by the American National Standards Institute (2006). This standard contains definition for synchronized phasor measurement, methodology of quantifying these measurements, and specifications for quality test. Definition of data transmission formats for real-time data reporting is also contained in this standard. The IEEE C37.118-2005 standard gives a better description of synchrophasor measurement. This standard introduces the mathematical definition of a synchrophasor from a pure sinusoidal waveform.

$$X(t) = X_m \cos(\omega t + \phi) \quad \ldots (1)$$

$$X = X_r + X_i = \left(\frac{X_M}{\sqrt{2}}\right)e^{j\phi} = \frac{X_m}{\sqrt{2}}(\cos\phi + j\sin\phi) \quad \ldots (2)$$

Where, $\frac{X_m}{\sqrt{2}}$ is the rms value of the signal X (t) and $\emptyset$ is the instantaneous phase angle relative to a cosine function at nominal system frequency synchronized to UTC". This angle is 0^0 when the maximum of X (t) occurs at the UTC second rollover (1PPS time signal), and -90^0 when the positive zero crossing occurs at the UTC second rollover as shown in Figure2

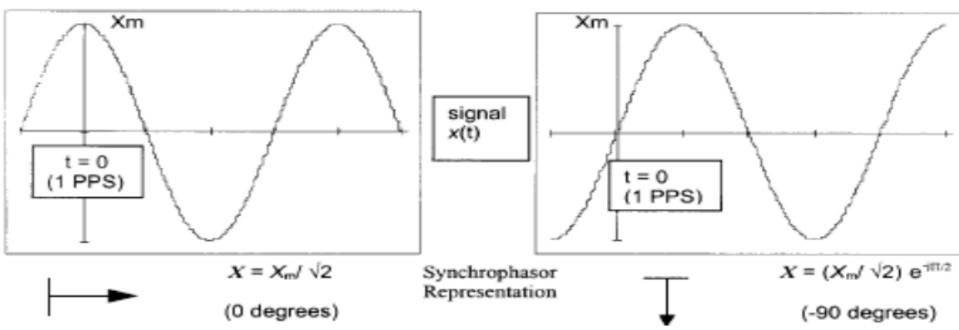

Figure 2: Synchrophasor Representation[6]

2.2 Review of Pertinent Literatures

In [5], a modeling for a complete scenario of a proposed wide area measurement system (WAMS) based on synchronized phasor measurement units (PMUs) technology with the access of a broadband communication capability was presented. The purpose was to increase the overall system efficiency and reliability for all power stages via significant dependence on WAMS as distributed intelligence agents with improved monitoring, protection, and control capabilities of power networks. The developed system was simulated using the Matlab/Simulink program. The power system consists of a 50 kW generation station, 20 kW wind turbine, three transformers, four circuit breakers, four buses, two short transmission lines, and two 30 kW loads. The communication system consists of three PMUs, located at generation and load buses, and one phasor data concentrator (PDC). The proposed system was tested under two possible cases; normal operation and fault state. The simulation results confirm the validity of the proposed WAMS technology for smart grid applications.

In [6], an inexpensive PMU that takes measurements at the distribution level of the power grid around an ATMEL's Arduino Uno328 based microcontroller and integrated real time GPS module and ESP8266 Wi-Fi module were developed. The hardware architecture design was made to communicate measured values of current and voltage phase angles and magnitudes to a central database via the internet, based on specified IEEE regulations (Standards C37.118.1 and C37.118.2). The system achieved frequency, voltage, current and power factor of percentage errors 0.58, 0.34, 0.62 and 0.012 respectively which are within the acceptable limits. However, despite the good resolution of the data available at the control room for the operators to work with, response time for subsequent data is of high concern. Arduino runs code from top to bottom, so it does not allow multiple operation at a time, hence delay in response.

In [7], presented a review of microcontroller-based PMU with and without GPS. The work summarized the differences between with and without GPS, where PMU with GPS system reveals higher advantages because of its simplicity and cost effectiveness.

In [8], the performances of a prototype PMU based on a synchrophasor estimation algorithm conceived for the monitoring of active distribution networks were described. Also, its experimental application during some intentional islanding and reconnection tests of an urban medium voltage power network were discussed. With respect to typical applications in transmission networks, the use of PMUs in distribution networks requires very low values of total vector error (TVE), which involves particular low values of phase errors of the synchrophasor estimates. The work developed dedicated PMUs to monitor experimental tests carried out to assess the capability of a urban distribution network to operate autonomously when fed by a local 80 MW combined-cycle power plant. The information provided by the installed PMUs significantly facilitate the operator maneuvers and appear to be useful for the development of an improved control and management system of the active distribution network.

In [9], the open PMU, being an alternative to the commercial products was proposed. Compliance testing of the proposed system was taken under both nominal and dynamic conditions and it was found that the Open PMU complies with IEEE Standard for total vector error (TVE) under 99% of measurements during nominal conditions.

In [10] proposed a system aimed at designing a cost-effective PMU device as per IEEE standard C37.118.1-2011. The proposed system worked in two steps; in first step, Balanced 3-phase voltage wave-forms were first simulated in MATLAB and parameters specified by the standard were computed using the recursive DFT algorithm, and in second stage, the whole algorithm was ported to C language which was used to program Arduino Due –the micro-controller platform used.

In [11], a review of synchrophasors for distribution applications was carried out. The work discussed both existing and future applications for synchrophasor technology in distribution systems. Monitoring, control, and protection applications were considered, including visualization, component monitoring, and high-speed applications. The time-synchronized and streaming characteristics of synchrophasors to address distribution concerns and understanding of the capabilities and limitations were considered. The work also suggested that advancements in IEDs increase the available locations of PMU technology. Locations out on the feeder have PMU capabilities; data rates of synchrophasor technology are an order of magnitude higher than the traditional SCADA, by providing improved visibility of more transient conditions. Applications should be matched to data rate and type in order to optimize communication.

In [12], constructed a PMU for power system applications. This work utilized off-the- shelf components to estimate power system parameters such as voltage magnitude, phase angle and frequency with main design information extracted from the Open PMU group and the IEEE C37.118-2011 standard. The functionality of the PMU was tested by comparing measured result of voltage magnitude, phase angle and frequency of a balanced three phase signal from a rapid prototyping system with estimated results from PMU. The conducted experiments confirmed that the PMU could estimate voltage magnitude, phase angle and frequency approximately equal the measured quantities of the input signal.

In [13], proposed a GPS based phasor measurement techniques in power system. In the system, voltages and currents were the analog inputs taken from the secondary winding of the three-phase voltage and current transformers. Included was Anti-aliasing filter to limit the bandwidth to satisfy the Nyquist criterion and also used to filter out the input frequencies that are higher than the Nyquist rate.

In [14], carry out the design of a GPS- free smart phone-based power grid frequency and angle monitoring system. In this systems, primary synchronization signal in the 4G long term evolution (LTE) cellular network was proposed, which is the network time protocol (NTP) as the synchronization sources, an alternative of GPS signal. The extendibility of the smart phone platform enables more functionality to be further integrated into the system. Effectiveness of the system on frequency and angle monitoring system was verified when compared with frequency disturbance recorder (FDR).

In [15], proposed a method for detection and classification of multiple events in an electrical power system in real time. They classified the events into three: islanding, high frequency events (loss of load) and low frequency events (loss of generator). This method is based on principle component analysis of frequency measurement. A gain, the method employs a moving windows approach to combat the time varying nature of power systems, thereby increasing overall situational awareness of the power system. The reliability of the proposed method was demonstrated using numerical case studies including both real data collected from UK power system and simulated case studies constructed using dig silent power factory for islanding events as well as both losses of loads and generation dip event.

In [16], implemented a PMU with an optical sensor for signal acquisition that will replace the traditional transformers. In the work, the accuracy of frequency, angle, and amplitude were evaluated via experiments. The optical sensor-based PMU achieved the accuracy of 9.03×10-4Hz for frequency, 6.38×10-3radian for angle, and 6.73×10-2V for amplitude with real power grid signal. The total vector error (TVE) of OS-PMU is as small as 0.31%, which is sufficient to fulfill the 1% requirement of IEEE synchrophasor standard C37.118.1.

In [17], highlighted the theoretical benefits of synchronized-measurement technology for power-grid applications. The work explained the ability of PMUs to directly obtain angle differences which allows operators to reduce error margins and operate transmission corridors closer to their real stability limits while maintaining a safe. Again, Direct utilization of PMU data may achieve vastly improved system performance over current methods for planned system separation. Using synchronized phasor measurement, certain relays and protection schemes could be made to adapt to the prevailing system conditions, thereby enhance their performance. The PMUs are well suited for on-line monitoring of angles, and thus can be helpful as “eyes and ears” for the operator during a power restoration. PMU technology seems very promising in monitoring and detecting islanding of DG and micro grids. However, low-cost design and model may need to be developed for wider penetration which was not achieved in this work

As evident in the foregoing literature, there exists a need to build a cost-effective, microcontroller based PMU that can report the voltage and current Phasor, satisfying the IEEE PMU standards [18] when put to operation as the proven building block of a smart Grid. This paper deals with the design and development of an inexpensive PMU using open hardware platform (Arduino) and open source software platform (python) as per existing IEEE standard for synchrophasor measurement (C37.118.1-2011std) [19]. The proposed PMU will estimate voltage and current phasors using 64 point discrete Fourier transform (DFT). A low cost microcontroller (ArduinoAtmega 328) will be used as a computational unit. Each Phasor will be time stamped with time sourced from GPS. The local communication will be achieved using Universal Asynchronous Transmitter and Receiver (UART) which is a type of serial communication. The Phasorwill be transmitted to remote location via transmission control protocol (TCP) over Ethernet.

3.0 METHODOLOGY

3.1 System Design

The various components of the PMU system were designed based on the task before hand in this section.

3.1.1 Synchrophasor Definition

Alternating Current (AC) is mathematically represented by a cosine wave,

$$x = A\cos(2\pi f_{AC} t + \varphi) \quad (1)$$

where $f_{AC} = 50Hz$ in Nigeria. AC can be represented as a simplified quantity called a phasor. When representing a cosine as a phasor, it is assumed that the frequency of the signal remains the same. Therefore, the variable quantities are magnitude and phase. For AC, magnitude is commonly defined as the root mean square of voltage. Equation (1) becomes

$$X = \frac{A}{\sqrt{2}}\angle\phi \quad (2)$$

Establishing phase requires either a signal or time reference. Synchrophasors calculate phase using an absolute time reference. The synchrophasor is defined to be 0° if the cosine has a maximum crossing during the pulse and 90° if the cosine has a zero crossing at the pulse. Values between 0° and 90° are calculated according to the selected phasor estimation algorithm.

3.1.2 Performance

The performance requirements for this project are drawn from the IEEE Standards for Synchrophasor Measurements for Power Systems. The performance standard P, for fast response with no explicit filtering is adhered to in this paper.

The device is broken down into different component parts as shown in Figure 3. The measurement source is a 240 V residential outlet. A step down circuit lowers the voltage of the measurement source into the range of the A/D converter. This circuit also provides DC power for the other component parts including sensors. The signal passes through an A/D converter that samples in synchronicity with the time source. The time source provides an absolute time reference to the A/D converter and Synchrophasor Estimator (a sketch written in python and C++ programing languages bundled into Raspberry pi).

The Synchrophasor Estimator will calculate the magnitude of digital signal and run it through a phase estimation algorithm. The resulting magnitude and phase estimation will be given a time tag and sent to the cloud via the internet module.

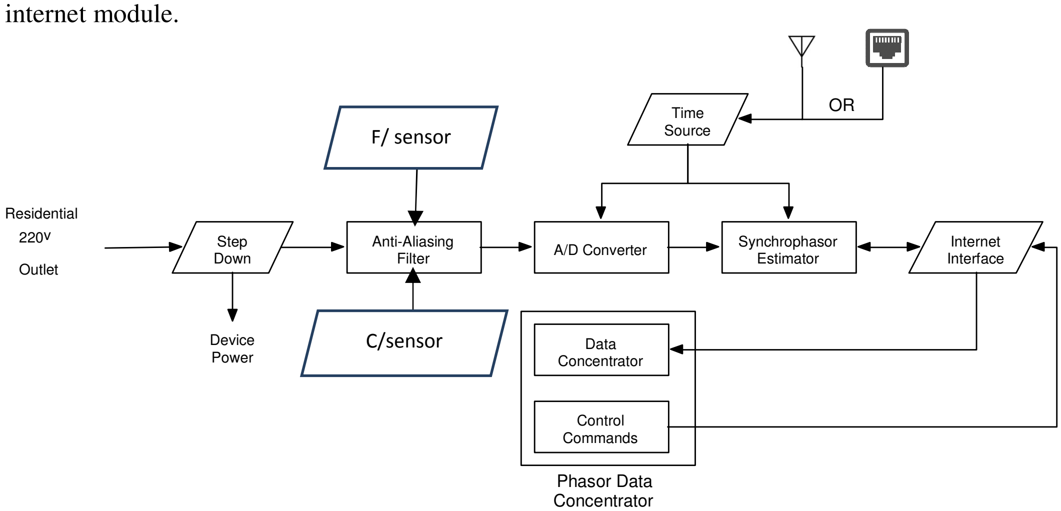

Figure 3: PMU Block Diagram

3.1.3 Step Down and Device Power

Analog to Digital (A/D) converters are not typically capable of measuring signals at 120v, meaning a voltage step down circuit must be designed to reduce the magnitude of the AC signal to match the specified range of the A/D. The device may only have one connection to the power source, meaning the step down circuit must also include a tap and rectification circuit to provide power for the chosen A/D. The chosen process, Raspberry pi, uses power adapter that supply the require voltage. The adapter has over- voltage protection to prevent damage to the device and have an output voltage ripple that meets the constraints of the chosen processor.

3.1.4 Analog Filtering

Since an A/D conversion is being performed, it necessary to have an analog low-pass filter to reduce the bandwidth of the input signal and eliminate aliasing. The cutoff frequency for the low-pass filter should be just above $f_s/2$, the chosen sampling frequency (50Hz or 60Hz, with a reporting rate between 10 sec and 30 sec.).

3.1.5 Timing

Synchrophasors must, by definition, be recorded with respect to an absolute time reference. The absolute reference used by IEEE C37.118.1 is Coordinated Universal Time (UTC). UTC can be obtained from either a GPS receiver or through the internet based Precision Time Protocol (PTP). The time must be accurate within $\pm 26\mu s$ according to the standard. GPS was used for the scope of this paper. Each synchrophasor must be given a time tag according to Coordinated Universal Time (UTC). The time tag consists of three numbers: a System On a Chip (SOC) count, a fraction-of-second count, and a time status value. SOC is specified as a 4-byte binary count of the number of seconds since the Unix epoch, 00:00 January 1, 1970. Occasionally, a leap second must be inserted to keep SOC synchronized with UTC. Time status indicates the reliability of the clock, which can become unsynchronized due to loss of signal.

3.1.6 Measurement

Synchrophasor measurements must be synchronized with the time code source so they can be time-aligned with measurements from other PMUs by a PDC. Reporting rates are also defined in [19] to ensure that multiple PMUs will take measurements at the same rate. The output of the A/D is synchronized with time value of the GPS by the processor, Raspberry pi, using set of instructions written in python code.

a) Reporting Rate

The reporting rate, measured in phasors per second, must be a factor of the nominal system frequency. The reporting rate must be selectable by the user via the device's internet interface. For this project, think speak is used.

b) Phase Estimation

There are two categories of phase estimation algorithms (PEAs): time domain and frequency domain. An example of a time domain PEA is the Weighted Least Squares method. WLS uses a Taylor series expansion of the signal to determine the phase. Variation of the number of terms in the series is studied in an attempt to reduce error. The Interpolated Discrete Fourier Transform (IpDFT) is an example of a frequency domain algorithm. The IpDFT is significantly faster than WLS, but does not perform as well when disturbances occur. The selection of the PEA provided the constraints for the selection of the processor. In this project, Raspberry pi is selected.

c) Total Vector Error

Total Vector Error (TVE) is a measurement of the difference between a perfect theoretical phasor and the actual phasor measured by the PMU. The IEEE Std. C37.118.1 defines TVE as:

$$TVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{X_r(n)^2 + X_i(n)^2}} \tag{3}$$

Where $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the real and imaginary components of the measured phasor and $X_r(n)$ and $X_i(n)$ are the components of the theoretical phasor. The standard specified that TVE must be less than 1%. Sources of TVE include timing inaccuracy, off-nominal signal frequency, and low frequency oscillations.

3.1.7 Communication

Communication between the PMU and PDC takes place via the internet. Data packets will be sent using Transmission Control Protocol (TCP). Data packets are subdivided into frames, each containing a specific piece of data. These data are stored in the cloud and can be assessed anywhere with internet access. In this paper, to make the communication easier, ThingsSpeak was used to store data from the sensors into the cloud and was accessed at different places by just logging in with the right information into ThingsSpeak. Both the raw data and the graphical data were visualized and further analysis was carried out with the features of ThingsSpeak. An account was created via (https://thingspeak.com/) for a user channel in ThinsSpeak and API code was generated. The API code was used in python code bundled in Raspberry PI, which established the connection between Raspberry PI and ThingsSpeak then PI communicate the output of sensors to Thinspeak for visualization and analysis. This can be done by just logging into thing speak account created. The simplified circuit diagram for Raspberry pi input can be seen in Figure 4.

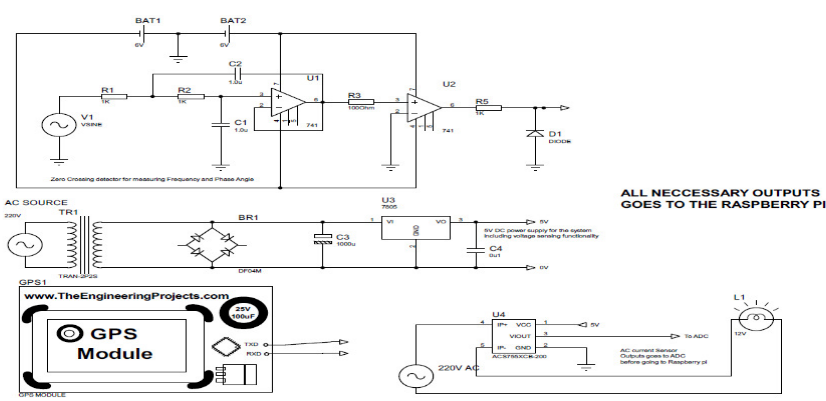

Figure 4: Simplified circuit Diagram for Raspberry pi input.

The device must comply with the Power Holding Company of Nigeria (PHCN) regulations for connection spacing and insulation for 220 V connections. The connection to the wall outlet should be made with standard recommended cable for residential. The cable should be rated such that it withstands voltage above 230 V.

3.2 Component Selection

3.2.1 Computing Platform

The computing platform is the core of the phasor measurement unit. It is responsible for acquiring raw AC voltage waveform data from an Analog to Digital Converter (ADC) in synchronicity with the GPS Pulse Per Second (PPS) time code, computing the magnitude and phase of the signal, packaging the measured data into the IEEE C37.118.2 transmission format and sending the resulting data packet over the internet to a PDC. Many options were considered in the choice of the computing platform for this project, including the well-known Arduino, BeagleBone Black, Raspberry PI and Intel Edison.

An Arduino, while it has an onboard ADC, lacks the computing power of the other SOC based alternatives, requires additional components to connect to the internet and does not have the ability to be reprogrammed remotely, an important consideration when deploying a device in the homes of laymen residents. Intel's Edison platform was considered for its high computing power density (dual core 500 MHz processor), but ultimately rejected due to the scarcity of publicly available documentation. Ultimately, the Raspberry PI is a relatively powerful platform with thorough documentation and an active user base though does not have an onboard ADC, but it ability to multi-process information stands it out among other computing platform. Choosing a platform with an onboard ADC is important because it simplifies the circuitry and reduces the cost of the device. The BeagleBone Black has a number of advantages over the others, It has a 1 GHz processor, a built in ethernet port for internet connection, and an onboard ADC with eight input channels, but ability to multitask, which is a priority for this project is low as compared to Raspberry PI. Therefore, Raspberry PI was considered as a computing platform for this project.

3.2.2 GPS Module

As stated in the Timing section of the Design Requirements, the time source must be accurate within ±26μs in order to achieve the accuracy desired. The NEO6M GPS Module has 2.5m horizontal position accuracy and -161Dbm navigation sensitivity. Though this is not as accurate as timing-specific sources, but it is well within the specifications and budget of the device. Plate I shows the NEO-6GPS Module.

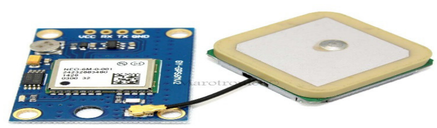

Plate I: NEO-6GPS Module

3.2.3 ThingsSpeak

ThingSpeak is an IoT analytics platform service that allows user to aggregate, visualize, and analyze live data streams in the cloud. User can send data to ThingSpeak from devices, create instant visualization of live data, and send alerts. ThingSpeak enables sensors, instruments, and websites to send data to the cloud where it is stored in either a private or a public channel. ThingSpeak stores data in private channels by default, but public channels can be used to share data with others. Once data is in a ThingSpeak channel, it can be analyzed and visualized, calculate new data, or interact with social media, web services, and other devices.

3.2.4 Raspberry Pi

The Raspberry Pi is a low cost, credit-card sized computer that plugs into a computer monitor or TV, and uses a standard keyboard and mouse. It is a capable little device that enables people of all ages to explore computing, and to learn how to program in languages like Scratch and Python. It's capable of doing everything one would expect a desktop computer to do, from browsing the internet and playing high-definition video, to making spreadsheets, word-processing, and playing games. Raspberry Pi has the ability to interact with the outside world, and has been used in a wide array of digital maker projects, from music machines and parent detectors to weather stations and tweeting birdhouses with infra-red cameras.

It was developed in the United Kingdom by the Raspberry Pi foundation in association with Broadcom. RasPi has evolved through several versions that feature variation in the type of central processing unit, amount of memory capacity, networking support and the peripheral devices support. The Raspberry Pi 3 Model B used in this paper, is the third generation Raspberry Pi. This powerful credit-card sized single board computer can be used for many applications and supersedes the original Raspberry Pi Model B+ and Raspberry Pi 2 Model B. Whilst maintaining the popular board format, the Raspberry Pi 3 Model B brings a more powerful processor, 10x faster than the first generation Raspberry Pi. Additionally, it adds wireless LAN & Bluetooth connectivity making it the ideal solution for powerful connected designs. The features and technical specifications of Raspberry Pi 3 - Model B can be seen in [6]. The selected Raspberry Pi board can be seen in Plate II. After the components selection, the soldering process can be seen in Plate III.

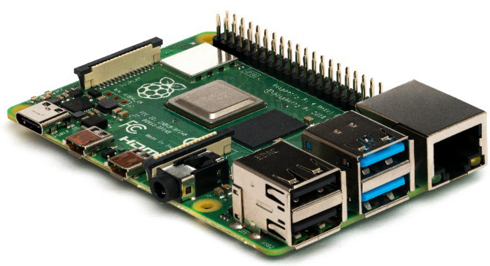

Plate II: Raspberry Pi board

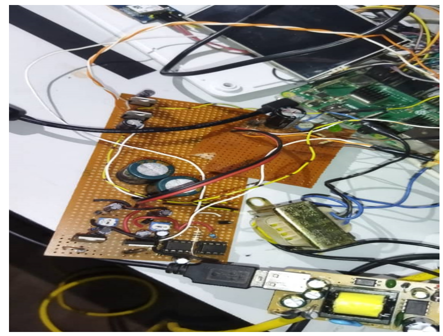

Plate III: Components Soldering in Progress

A phasor measurement unit that measures accurately high speed data was designed, and by taking into consideration the IEEE standard and design safety, a cost effective PMU that allows remote measurement of data was achieved.

4.0 RESULTS

The developed PMU shown in Plate IV was tested in Abubakar Tafawa Balewa University (ATBU) as well as Abubakar Tatari Ali Polytechnics (ATAP) all located within Bauchi metropolis. The GPS location of the two sites is as shown in Plates V and VI. The results obtained from the developed PMU increase the speed and accuracy of the reading, statistics load usage, and reduce labour cost.

a) ATBU Bauchi

The results in Table 1 shows the data collected from the device at Abubakar Tafawa Balewa University, Bauchi for 7 minutes. The logged dated 16th June 2021 between 16:58 pm to 17:05pm at ATBU engineering complex Bauchi,

Table 1: 7 Minutes of PMU Data at ATBU, Bauchi (Yelwa Campus).

Date/Time(UTC)	Voltage	Current	Power	F(HZ)	P(Angle)	Lat.	Long.
2021-06-16 16:58:25 CEST	218.6587	1.130	221.9405	49	8.82	10.278	9.796
2021-06-16 16:58:41 CEST	218.6587	1.096	350.7481	49.5	8.91	10.278	9.796
2021-06-16 16:58:56 CEST	218.6587	1.505	350.4065	49.5	8.91	10.278	9.796
2021-06-16 16:59:11 CEST	218.6587	1.794	237.6571	48	8.64	10.278	9.796
2021-06-16 16:59:27 CEST	218.6587	1.685	347.6731	49.5	8.91	10.278	9.796
2021-06-16 16:59:42 CEST	218.6587	0.961	362.0231	52	9.36	10.278	9.796
2021-06-16 16:59:58 CEST	218.6587	1.658	228.4322	49	8.82	10.278	9.796
2021-06-16 17:00:13 CEST	218.6587	1.730	242.0988	49.5	8.91	10.278	9.796
2021-06-16 17:00:29 CEST	218.6587	1.441	349.3815	49.5	8.91	10.278	9.796
2021-06-16 17:00:46 CEST	218.6587	1.341	243.4654	53.5	9.63	10.278	9.796
2021-06-16 17:01:01 CEST	218.6587	1.249	194.2657	49.5	8.91	10.278	9.796
2021-06-16 17:01:16 CEST	218.6587	1.541	331.6149	49	8.82	10.278	9.796
2021-06-16 17:01:31 CEST	218.6587	1.218	334.0066	47.5	8.55	10.278	9.796
2021-06-16 17:01:47 CEST	218.6587	1.157	248.2487	49.5	8.91	10.278	9.796
2021-06-16 17:02:03 CEST	218.6587	1.629	178.8908	49.5	8.91	10.278	9.796
2021-06-16 17:02:18 CEST	218.6587	1.643	219.8906	49.5	8.91	10.278	9.796
2021-06-16 17:02:33 CEST	218.6587	1.366	276.9486	49	8.82	10.278	9.796
2021-06-16 17:02:48 CEST	218.6587	1.080	300.8651	49	8.82	10.278	9.796
2021-06-16 17:03:04 CEST	218.6587	1.610	262.9403	49.5	8.91	10.278	9.796
2021-06-16 17:03:19 CEST	218.6587	1.235	345.9648	49	8.82	10.278	9.796
2021-06-16 17:03:35 CEST	218.6587	1.435	243.4654	49.5	8.91	10.278	9.796
2021-06-16 17:03:50 CEST	218.6587	1.121	194.2657	49	8.82	10.278	9.796
2021-06-16 17:04:06 CEST	218.6587	1.225	331.6149	49	8.82	10.278	9.796

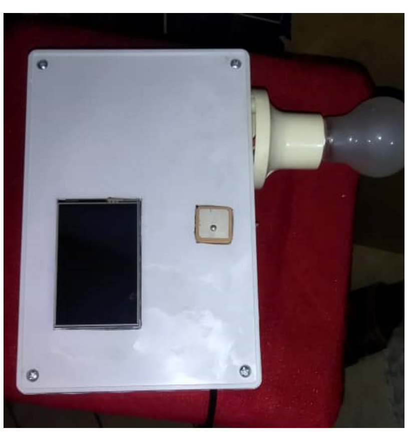

Plate IV: Constructed PMU

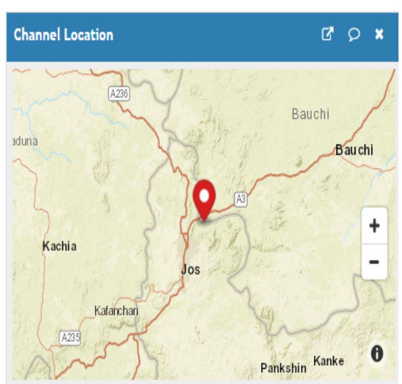

Plate V: GPS Location of ATBU Bauchi

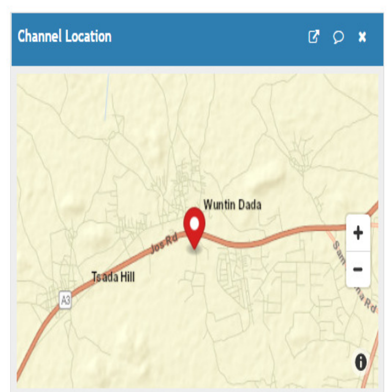

Plate V: GPS Location of ATAP Bauchi

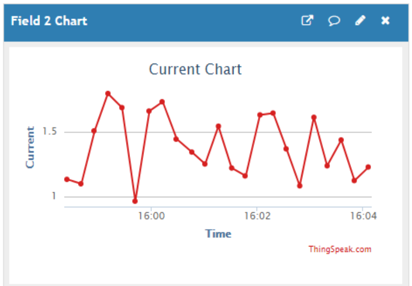

Figure 5: Current chat of ATBU data between 4.00pm and 4.04pm

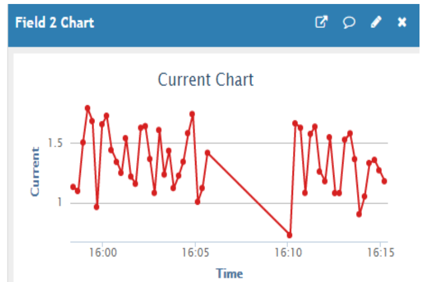

Figure 6: Current chart of ATBU data between 4.00pm and 4.15pm

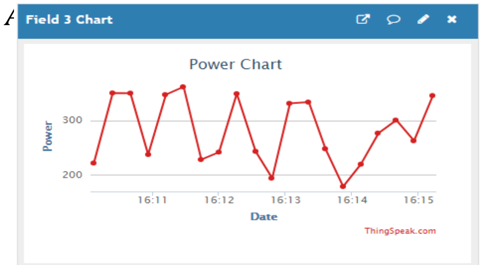

Figure 7: Power chart of data at ATBU between 4.11pm and 415pm

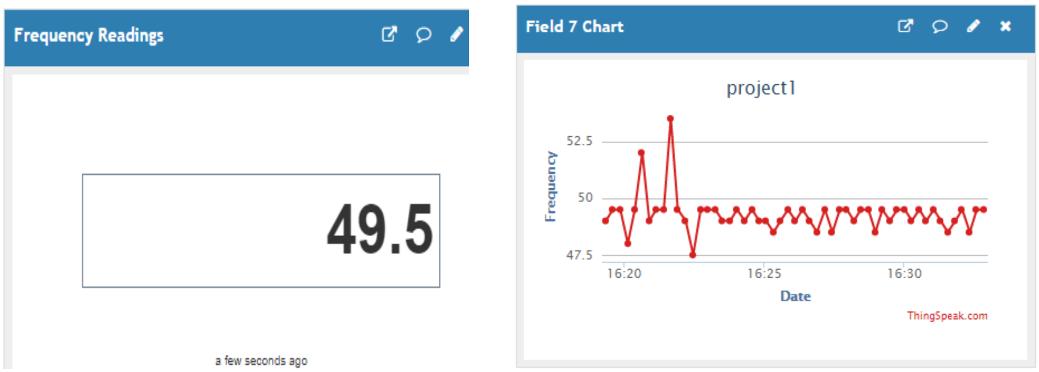

Figure 8: Frequency Chart of ATBU data between 4.20pm and 4.30pm

2021-06-16 17:04:21 CEST	218.6587	1.343	334.0066	48.5	8.73	10.278	9.796
2021-06-16 17:04:37 CEST	218.6587	1.583	248.2487	49	8.82	10.278	9.796
2021-06-16 17:04:52 CEST	218.6587	1.	178.8908	49.5	8.91	10.278	9.796
2021-06-16 17:05:08 CEST	218.6587	1.005	219.8906	49	8.82	10.278	9.796
2021-06-16 17:05:23 CEST	218.6587	1.121	276.9486	49.5	8.91	10.278	9.796

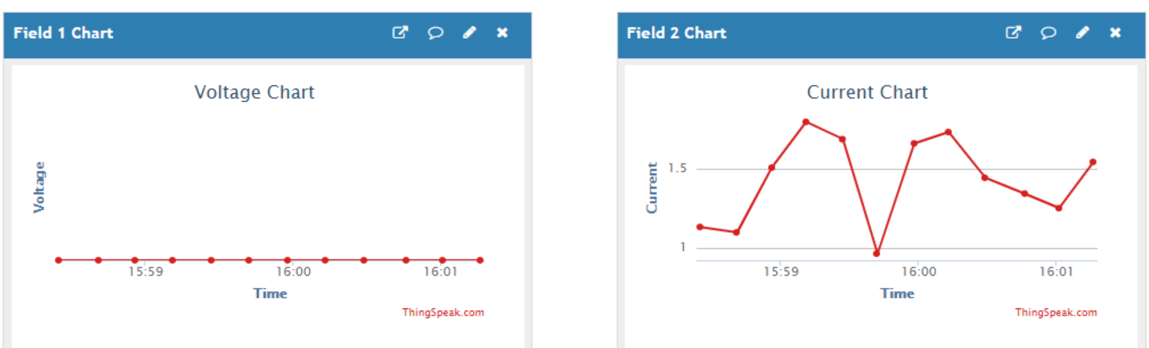

Figure 4: Voltage and Current chart of ATBU data between 3.5pm and 4.01pm

a) ATAP Bauchi (Wuntin Dada Campus)

The results below show the data collected from the device at Abubakar Tatari Ali Politechnics, Bauchi . Table 2 shows 4 minutes logged data on 19th July 2021 between 16:27 pm to 16:31 pm .

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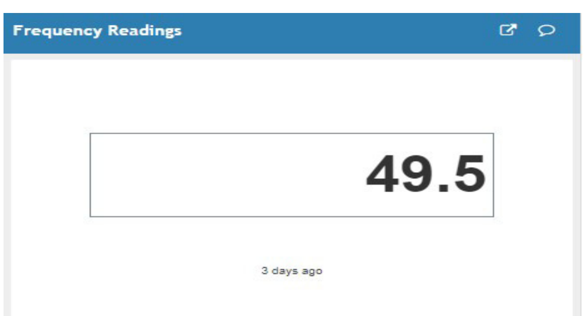
Table 2: 4 Minutes of PMU Data at ATAP, Wuntin Dada, Bauchi

Date/Time(UTC)	Voltage	Current	Power	F(HZ)	P(Angle)	Lat.	Long.
2021-06-19 16:27:48 CEST	218.6587	1.221	280.7	49	9.36	10.311	9.77
2021-06-19 16:28:04 CEST	218.6587	0.757	203.14	48.5	8.82	10.311	9.77
2021-06-19 16:28:19 CEST	218.6587	0.921	194.6	49	8.91	10.311	9.77
2021-06-19 16:28:35 CEST	218.6587	1.005	224.33	49.5	8.91	10.311	9.77
2021-06-19 16:28:51 CEST	218.6587	0.847	185.04	49	9.63	10.311	9.77
2021-06-19 16:29:07 CEST	218.6587	0.797	174.44	49.5	8.91	10.311	9.77
2021-06-19 16:29:22 CEST	218.6587	0.779	170.34	49	8.82	10.311	9.77
2021-06-19 16:29:37 CEST	218.6587	0.994	219.2	48.5	8.55	10.311	9.77
2021-06-19 16:29:53 CEST	218.6587	1.174	284.8	49.5	8.91	10.311	9.77
2021-06-19 16:30:09 CEST	218.6587	1.093	238.34	48.5	8.91	10.311	9.77
2021-06-19 16:30:24 CEST	218.6587	0.747	164.19	49.5	8.91	10.311	9.77
2021-06-19 16:30:40 CEST	218.6587	0.915	213.39	49.5	8.82	10.311	9.77
2021-06-19 16:30:56 CEST	218.6587	0.858	193.58	49	8.82	10.311	9.77
2021-06-19 16:31:12 CEST	218.6587	1.247	258.84	49.5	8.91	10.311	9.77
2021-06-19 16:31:27 CEST	218.6587	1.294	277.97	49.5	8.82	10.311	9.77
2021-06-19 16:31:43 CEST	218.6587	1.072	203.49	48.5	8.91	10.311	9.77
2021-06-19 16:31:59 CEST	218.6587	0.765	173.76	49.5	8.82	10.311	9.77



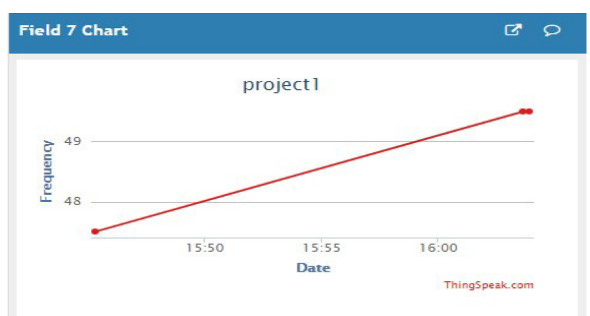


Figure 9: Frequency chart of the PMU data at ATAP, Bauchi

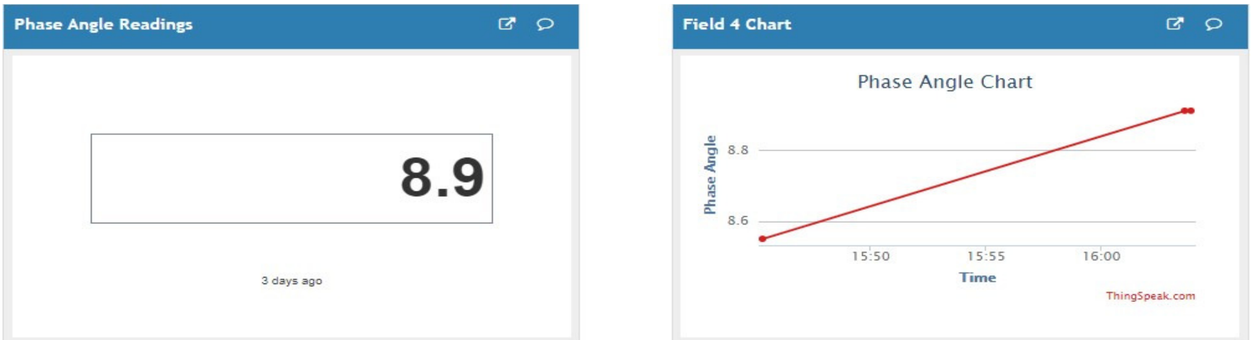


Figure 10: Phase Angle chart of the PMU data at ATAP, Bauchi.

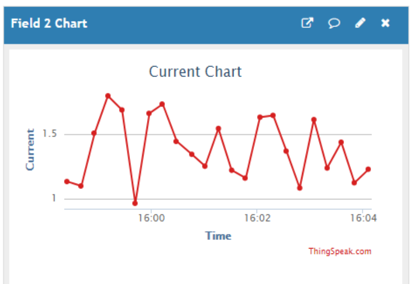


Figure 11: Current chat of ATAP data between 4.00pm and 4.04pm

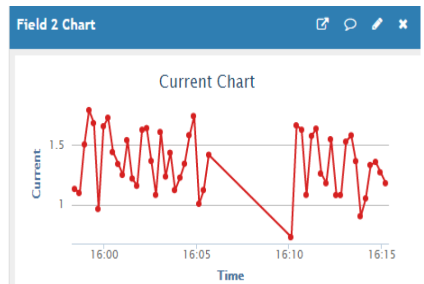


Figure 12: Current chart of ATAP data between 4.00pm and 4.15pm

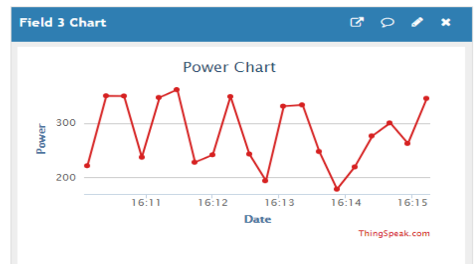


Figure 13: Power chart of data at ATAP between 4.11pm and 415pm

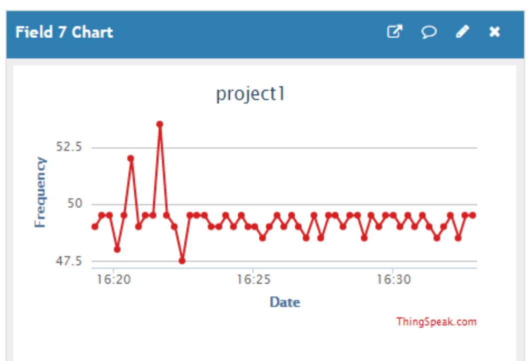
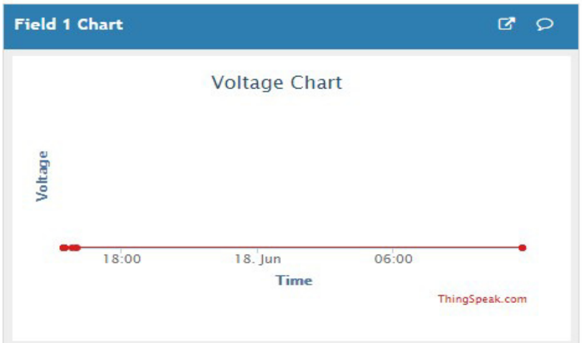


Figure 14: Frequency Chart of ATAP data between 4.20pm and 4.30pm



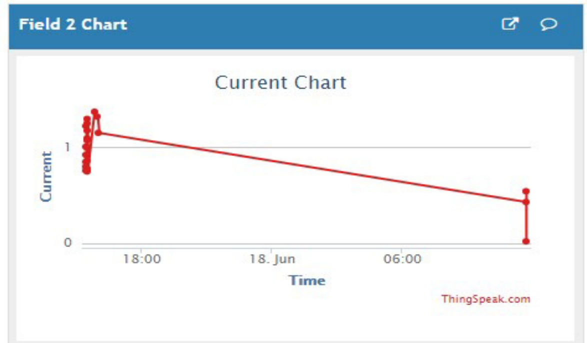


Figure 15: Current and Voltage chart of the PMU data at ATAP, Bauchi.

The plots obtained from the PMU logged data at ATBU Bauchi were correspondingly shown in Figures 5, 6, 7 and 8 for voltage and current against time, power against time, and phase angle against time respectively. Figure 5 shows the voltage and current between 3.58pm and 4.00pm, and figures 5 and 6 shows current behavior at different time intervals. The power chart between 4.11pm and 4.15pm, and frequency chart between 4.20pm and 4.30 are depicted in Figures 7, whilst the Frequency recorded over the period is presented in Figure 8. The average frequency with the recording period is 49.5 Hz.

Table 2 shows 4 minutes logged data on 19th July 2021 between 16:27pm to 17:31pm at ATBU engineering complex Bauchi, with its corresponding channel locations shown in Figure 9. The plots obtained from the PMU logged data are correspondingly shown in Figures 9 to 15 for frequency, phase angle, voltage, current and power against time, power against time. Figure 9 shows the frequency chart between 4.20pm and 4.30pm. The average frequency within the period is 49.5 Hz. Figure 10 shows the Phase angle, having a value of 8.9 pu. The current chart was shown on Figures 11 and 12. The current drops to a minimum value at 16:30:24pm. On Figure 13, the power consumption was ploted against time. The corresponding power at the minimum current is 164.19 W. Figure 14 shows the Frequency recorded between 16:20 to 16:30 pm, whilst the voltage and current recorded within the period of 17:45 pm to 06:25 am were presented in Figure 15.

From the data measured from the PMU device and the theoretical values of voltage magnitude and phase angle, the TVE was obtained by plugging the parameter values, as explained in the PMU design. The parameter values obtained are as follows;

$\hat{X}_r(n) = 218\text{Cos}\ (8.9)$, $\hat{X}_i(n) = 218\text{Sin}\ (8.9)$, $X_r(n) = 230\text{Cos}\ (36.86)$ and $X_i(n) = 230\text{Sin}\ (36.86)$

Inserting these values in Eqn. (1) will gives the TVE value of 0.5%.

5.0 CONCLUSION

A PMU was designed and constructed using a small board computer, Raspberry Pi, with sensors and other components. The device was successfully linked to the cloud where measured data were stored. The measured data include voltage, current, phase angle, frequency and power. And, finally, the data from the PMU were analysed in real-time with data visualization chat available on ThingsSpeak.

The PMU constructed is entirely self-contained with the only external connection to the wall outlet, so there is no further human intervention for it operation after it has been deployed. More so, the data logged are made available on line, which can be accessed from anywhere with internet, especially at the data concentrator. Therefore, the PMU has been able to achieve its fundamental purpose of dynamic power status measurement and monitoring. In addition, the Total Vector Error (TVE) of 0.5% achieved is within the range specified in IEEE standard for Synchrophasor measurement.

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