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# A State-of-the-Art PMU and MATLAB Based GUI Development towards Power System State Estimation on Real Time Basis

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**ABSTRACT: The main aim of this paper is to monitor the phasors of voltage and current waveforms and to calculate the real and reactive power consumption at the different bus ends of a transmission system using state-of-the-art microcontroller based Phasor Measurement Unit (PMU). Each PMU is designed and developed to acquire the samples of voltage and current signals of the line ends in a synchronized time reference frame. Each of them computes the peak values of each signal and the real and reactive power consumption at each of the ends utilizing these samples only along with their direction of flow. The individual voltage and current phasors at each of the ends are also detected from the zero crossing instants of the respective signals with respect to the synchronization pulses. The data packet containing the information regarding phase angles, peak values, active and reactive power from the PMUs are collected and stored in a PC using a centralized Intelligent Electronic Device (IED). A MATLAB based front end graphical user interface (GUI) is developed to acquire these data using the PC's serial port. The IED coordinates all the time synchronization pulses to each PMU in multicast mode and maintains a sequential routing for the data collection from them in a unicast mode of networking. The overall functioning of the PMUs, IED and the GUI is tested in a laboratory model of the power system and satisfactory performance is obtained.**

***Index Terms—*** PMU, IED, GUI, Time synchronized pulses, Active Power, Reactive Power.

## I. INTRODUCTION

The conventional electric power industry is essentially a regulated industry with bulk generation, economic transmission over long distances and efficient distribution for domestic and industrial applications. The necessary control and protection devices are also provided to maintain its reliability, stability and efficiency. However, the latest Electricity Act, as well as, the use of modern technologies for control, communication and protection purposes, have opened up huge opportunities to both the suppliers and consumers regarding generation, distribution, import and export of electricity and sharing of the power transmission system. As a result, the power industry has started its restructuring. This has not only encouraged competition in the electric industry to tackle monopoly but has also assured the consumer of good quality power supply, on demand basis, at a competitive price. Among all the state-of-the-art technologies in building a modern power grid, the phasor measurement unit (PMU) is an important and promising one [1].

Phasor measurement units (PMUs) are high speed power system devices that provide synchronized measurements of real-time phasors of voltages and currents [2, 3]. They can be further used to calculate voltage and current magnitudes, phase angles, real and reactive power flows etc. The synchronization is usually achieved by the same-time sampling of voltage and current waveforms using timing signals from the Global Positioning System (GPS) satellite [3]. A detailed insight shows that a PMU runs of its own sampling time which can be synchronized by the common time reference frame with the utilization of a PLL system. Synchronized phasor measurements elevate the standards of power system monitoring, control, and protection to a new level [3]. The Phasor Measurement Unit (PMU) technology provides phasor information (both magnitude and phase angle) in real time [4]. The advantage of referring phase angle to a global reference time is helpful in capturing the wide area snap shot of the power system [4]. Effective utilization of this technology is very useful in mitigating blackouts and learning the real time behavior of the power system [4]. Since the bus voltage angle of a power system is very closely linked with the behavior of a network, its real time measurement is a powerful tool for operating a network [5, 6, 7].

In this work, the authors have tried to develop a monitoring system with the help of a microcontroller based PMU and a MATLAB based GUI. The PMU acquires the samples of voltage and current signals at the line ends in a synchronized time reference frame and computes the active and reactive power consumption at the respective ends. The individual voltage and current phasors at each of the ends are detected from the zero crossing instants of the respective signals with respect to the synchronization pulses. The data packet containing the information regarding phasor angles, peak values, active and reactive power from the PMUs are collected and stored in a PC using a centralized Intelligent Electronic Device (IED). A MATLAB based front end graphical user interface (GUI) is developed to acquire these data using the PC's serial port and a dedicated communication channel. The IED coordinates all the time synchronization pulses to each PMU in multicast mode and maintains a sequential routing for the data collection from them in a unicast mode of networking.

## II. MATERIALS AND METHODS

### *A. Fundamentals of PMU*

A pure sinusoidal signal represented as

$$x(t) = X_m \cos(\omega t + \varphi) \quad (1)$$

The phasor representation of this sinusoid is given by

$$x(t) = \frac{X_m}{\sqrt{2}} e^{j\varphi} = \frac{X_m}{\sqrt{2}}(\cos\varphi + j\sin\varphi) \quad (2)$$

It can be therefore, concluded from equation (2) that the signal frequency, $\omega$, is not explicitly stated in the phasor representation. The magnitude of the phasor is the rms value of the sinusoid $\frac{X_m}{\sqrt{2}}$ and its phase angle is φ [7].

The concept of PMU technology provides real time phasor information of voltage and current signals by acquiring their samples in a time synchronized reference frame. It helps in measuring, as well as, monitoring the magnitudes and phase angles of the voltage and current signals of different buses over a distributed transmission network. The information regarding the amount of power flow and the current injected at different nodes of a transmission network can also be obtained. This will help the system operators to maintain the healthiness of the network. Thus, PMU demands the measurements to be made at common sampling instants so that a comparison of the signal magnitudes and angles between them at different buses can be made. The synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from different common time reference frame, such as the Global Positioning System (GPS) Satellite or any other reference timing signal generator.

### *B. Sample Shifting Technique*

The information about the active and reactive power, consumed at the sending and receiving ends of the transmission line, is obtained by utilizing the voltage and current samples using the Sample Shifting technique. One important advantage of this method is that it does not require the computation of power factor angle between the voltage and the current signals [8].

*Calculation of Active Power (P)*

If the voltage and current signals are sinusoidal in nature with the current lagging the voltage signal by an angle $\phi$, then the two signals can be expressed as follows:

$$v(t) = V_m \sin\omega t$$
$$i(t) = I_m \sin(\omega t - \phi)$$

In such a case the expression for the instantaneous power becomes

$$\begin{aligned} p(t) &= v(t)\, i(t) \\ &= V_m I_m \sin(\omega t)\sin(\omega t - \phi) \end{aligned} \quad (3)$$

Since the average value of the instantaneous power is called as the active power, its equation can be expressed as:

$$\begin{aligned} P = P_{avg} &= \frac{1}{2\pi}\int_0^{2\pi} p(t)\, d(\omega t) \\ &= VI\cos\phi \end{aligned} \quad (4)$$

Thus, it can be concluded from equation (4) that the active power, P, is basically the average of the products of instantaneous voltage and current samples over a complete cycle. In other words, equation (4) can be modified as,

$$P_{avg} = P = VI\cos\phi = \frac{1}{N}\sum_{n=1}^{N} v_n i_n \quad (5)$$

where, $v_n$ and $i_n$ are the samples of the instantaneous values of the voltage and current signals at the nth instant respectively and N is the total number of samples over a full cycle. The active power is thus measured using equation (5) following the methods as described in [8].

*Calculation of Reactive Power (Q)*

The reactive power, Q, can also be calculated if the samples of voltage and current are known. The product of voltage and current samples at an instant, shifted by 90 degrees, gives the reactive power at that instant.

$$\begin{aligned} Q &= VI\sin\phi \\ &= VI\cos(90 - \phi) \\ &= \frac{1}{N}\sum_{n=1}^{N} v_n i_{-90^o n} \end{aligned}$$

where, $v_n$ and $i_{-90^o n}$ are the sample values of voltage and $90^o$ shifted current signals and *N* is the total number of samples over a full cycle. Using the above equation reactive power (*Q*) is measured from the samples only as described in [8].

### *C. Sensing of Direction of Power Flow*

With deregulated power system, electric energy is now being import or export as the situation demands. The identification of export or import of power is done with the sensing of direction of power flow.

Sensing of direction of power flow is done from the sample values of the voltage and current signals only. The following logic is implemented to detect the power flow direction without employing any kind of direction sensing hardware element.

The direction of power flow can best be understood from the fig.2 in which the phasors of voltage and current signal are shown.

Considering the voltage phasor as a reference phasor i.e. V<0°, the current phasor may be at any angle within -90°< θ <90° for a particular direction of power flow. This flow may be termed as forward direction of power flow i.e. from power grid to the load with either lagging or leading load angle.

For backward direction of power flow, the current phasor will be in the opposite direction to that of the forward direction i.e. the phasor angle will be within 90°< θ <-90° w.r.t. the same voltage phasor. It is also illustrated in Table-I.

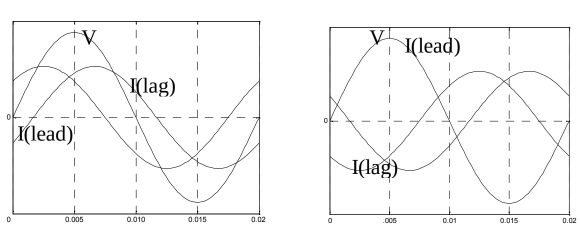
From the respective voltage and current waveforms, as shown in fig.2, the load angle θ can be evaluated from their zero crossing instants. The lagging or leading states will be computed from the slope of the waveforms. As it is shown in the fig.2, for lagging load angle within -90°<θ<0° the zero

crossing instant of current waveform falls within 0°<θ<90° from that of voltage waveform considering their positive slope only. Similarly, for leading load angle within 0°< θ <90° the zero crossing instant of current waveform falls within 270°< θ <360° for the same measuring condition. This is true for forward power flow.

On the other hand, for reverse power flow, for lagging load angle within -90°<θ<180° the zero crossing instant of current waveform falls within 180°<θ<270° and for leading load angle within -180°< θ <-90° the zero crossing instant of current waveform falls within 90°< θ <180° for the same measuring condition.

**Table 1. Table showing the power direction for different load angles.**

| Power Direction | Load Angle range | Positive slope zero crossing angles | Quadrant |
|---|---|---|---|
| Forward | 0°<θ<-90° (lag) | 0°<θ<90° | First |
| Forward | 0°<θ<90° (lead) | 270°< θ <360° | Fourth |
| Reverse | 90°<θ<180° (lag) | 180°<θ<270° | Third |
| Reverse | -180°< θ <-90° (lead) | 90°< θ <180° | Second |




(a) (b)

**Fig.1.** Voltage and current waveforms for (a) positive (b) negative power flow in lag or lead power angle condition.

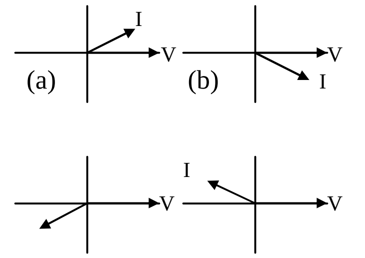



**Fig.2.** Voltage and current phasors for positive power flow in (a) & (b) and negative power flow in (c) & (d) for lead and lag power angle respectively.

*D. Phasor and Power Measurement details in a PMU*

Figure 3 shows the schematic diagram of the PMU block. The voltage and current signals at the ends of the transmission line are stepped down using potential and current transformers respectively before they are sampled by the ADCs of the PMUs. For a three phase transmission line, six numbers of ADCs are employed – three of them sample the respective phase voltages and the remaining three ADCs sample the respective phase currents.

The IED transmits a "synchronizing command" data packet @ 20 fps in time synchronization with the GPS in multicast mode to all the PMUs. The microcontroller in the PMU generates a reference clock pulse on receipt of the synchronizing command. As shown in figure 4, $T_{ref}$ denotes the period between the successive "synchronizing commands". This reference clock pulse of 10Hz is fed to a PLL in order to get the sampling frequency of the ADCs at 1kHz, the period of which is shown by $T_{ADC}$ .The sampling instant of all the PMUs will then be the same and in phase with the synchronizing command. The microcontroller computes and stores the peak values, phase angles, active and reactive power for one complete cycle of the input signal waveform.

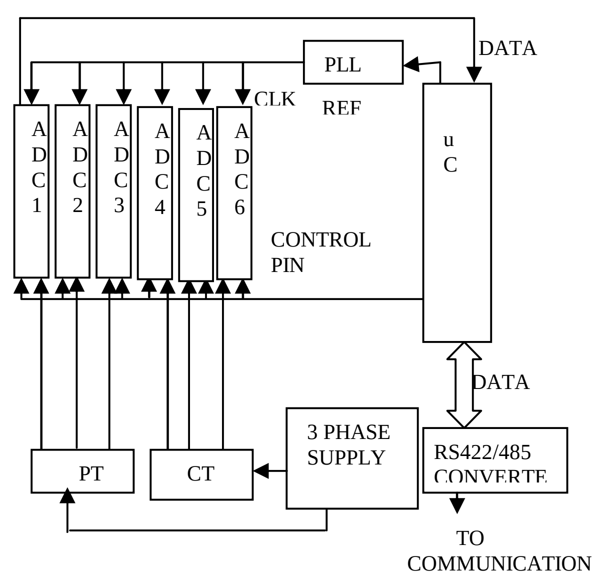



**Fig.3.** Schematic diagram of the PMU Block.

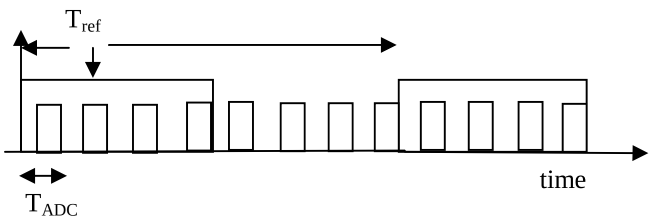



**Fig.4. S**howing reference clock pulses and the pulses generated from the PLL.

While the maximum value of the signal can be obtained by comparing the sampled values with one another, the phase angle difference between any two signals is determined from the zero crossing instants of the two signals on either the rising or the falling edges. The active and reactive power is calculated using the Sample Shifting technique. These data are sent to the IED for their storage and display in the PC using RS422/ 485 protocol, only when the "data request command" is sent to the PMU. Provision has also been made in the IED for acquisition of all the samples of the voltage and current signals if continuous monitoring of voltage and current signals is required if some abnormal conditions prevail in the network.

*E. Organization of the PMU at different Transmission Lines*

Figure 5 shows the arrangement of PMUs at different transmission lines in a power system. All the PMUs communicate with the IED through the same communication channel. The IED sends the "synchronizing command" @ 20 fps to all the PMUs of one zone continuously in a multicast mode. The PMUs sample the signals for one complete cycle of the signal and wait for the next "synchronizing command". The PMUs wait for the "data request" command along with the PMU ID number for transferring the data to the IED for its storage. Only the PMU whose ID number matches with that of the IED sends its data to the IED for its storage. In this way, only one PMU communicates with the IED at a time.

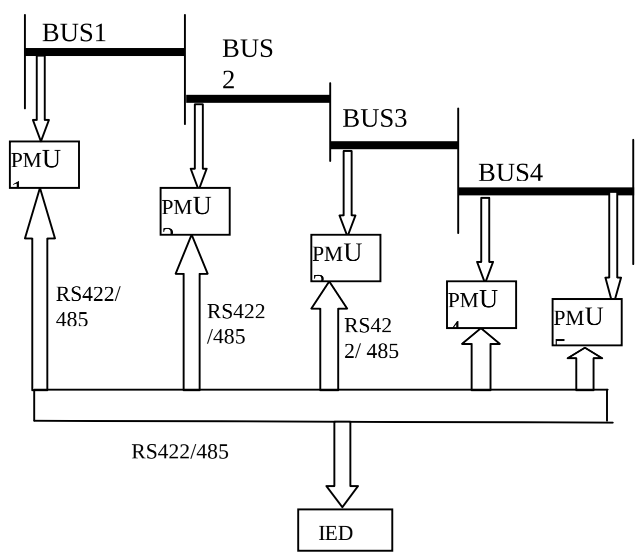



**Fig.5.** Arrangement of PMUs in a Power System.

*F. IED and Synchronization*

The basic purpose of the IED is to establish coordination among the different PMUs installed at different locations and the PC. The coordination among the PMUs is done with the help of wired network communication using RS422/485 protocol. Using RS485 protocol the maximum distance between the IED and the PMU can be up to 12 km. The microcontroller in the IED communicates with the PC using RS232 protocol, the schematic diagram of which is shown in figure 4. IED sends a "synchronizing command" data packet to all the PMUs for time synchronized sampling of the signals by the respective PMUs. It also sends a "data request" packet to the PMU, by mentioning the PMU ID number within the packet, in order to acquire the data. The PMU responds to this request only when its own ID number is matched, by transmitting the data packet consisting of phasor angles, peak values, active and reactive power to the PC for its storage and analysis. The next PMU data will be acquired in a similar technique by changing the ID number in the "data request" packet, only when the previous one will be completed. In this way the PC collects the data packet of all the PMUs within the time interval between the successive "synchronizing commands".

As shown in the figure 6, the microcontroller within the IED receives a GPS reference signal and generates a "synchronizing command" packet @ 20fps for the required synchronized data acquisition by the PMUs. The microcontroller also receives the GPS real time clock and sends the time to the PC. The PC stores the data from all the PMUs as well as this time information in a server such that the power system parameters from different zones can be monitored with respect to the real time clock.

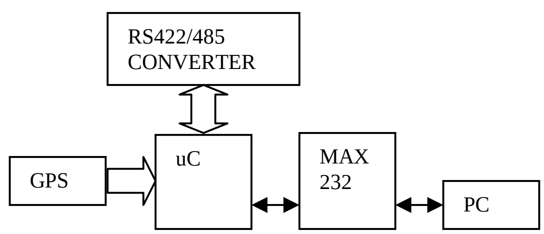



**Fig.6.** Schematic diagram of the Intelligent Electronic Device (IED).

*G. Communication Bandwidth*

The sampled values of the signal (voltage / current) are transmitted to the IED via the communication channel by means of serial communication. The sampling rate of the ADC is selected at 1 KHz. This gives 20 samples of a 50 Hz signal (voltage / current) in one complete cycle of the waveform. Thus, every communication channel carries 20 bytes of a signal in 20 millisecond duration. If the sampling rate is increased to 10 KHz, 200 bytes / cycle will be transmitted serially through every channel. In other words, the number of transmitted bytes is directly proportional to the sampling frequency (f).

If the PMU technology is implemented in a single phase system to measure the voltage and current signals, the data rate will be 20 Kbps. For a three phase system, six numbers of ADCs will be required to transmit the voltage and current signals. Hence, the data rate will be 60 Kbps for such a system. So, the number of transmitted data bytes increases if the number of signals (s) or the number of phases (n) of the system is increased.

In a power system, the PMUs may be located at different points. The IED may be designed in such a way that it acts as a centralized data collection system to collect the data from different PMUs. Thus, the communication speed of the serial channel is the main constraint. The communication speed must be sufficiently high enough to collect all the data from the PMUs without any data loss.

Mathematically, the number of transmitted data bytes (B) can be represented as:

$$B = f \times n \times s$$

The state of a transmission line or a bus at its sending or receiving ends can be determined using the peak values of voltage and current, active power, reactive power and power factor at its respective ends. Hence, only six bytes of data need to be transmitted from each PMU to the IED. In this way, the IED is able to collect data from more number of PMUs without stressing the communication speed. The information collected from the different PMUs can be stored and displayed in the PC using a MATLAB based GUI.

## III. EXPERIMENT RESULTS

Figure 7 shows the experimental set up of the hardware that has been used in the laboratory to implement a PMU. For testing the performance of the PMUs, two of them have been stationed at two different plug ends in the laboratory and the corresponding voltage data were acquired and displayed in the PC as shown in figure 8.

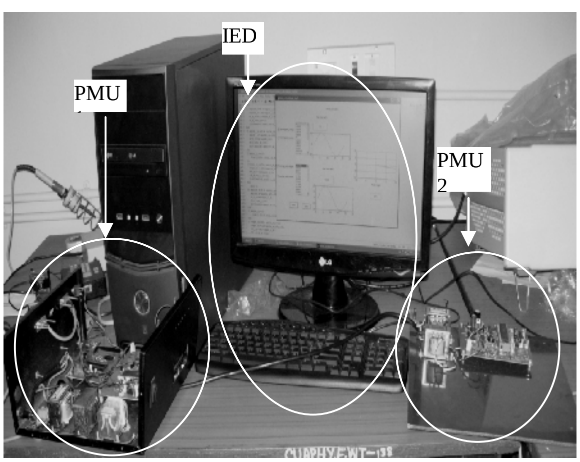



**Fig.7.** Experimental setup of the hardware along with the results obtained.

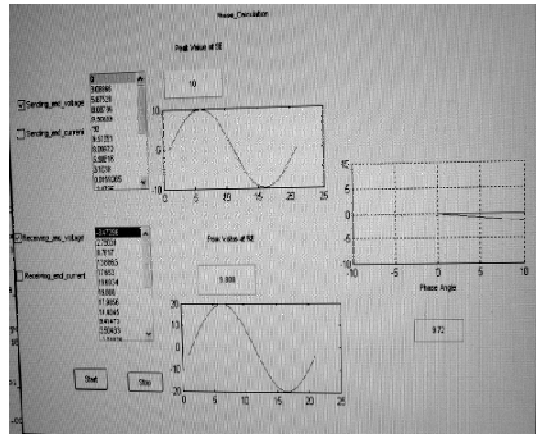


**Fig.8.** Front End of MATLAB based GUI displaying the voltage waveforms of the PMUs.

The waveforms of the voltages as well as the phase angle between the two waveforms at the two different plug ends are displayed in the GUI. Provision has also been made in the GUI for the corresponding phasor representation of the two signals. Table I shows the experimental data obtained for one complete cycle of the voltage waveforms that have been measured by the respective PMUs.

## IV. DISCUSSION

The uniqueness of the proposed system is that a state-of-the-art microcontroller based PMU and IED are developed and tested in the laboratory with satisfactory results. The IED generates the time synchronization pulses @20 fps with respect to the GPS and transmits it to all the PMU for their synchronization. The PMU runs of its own clock (@ 1 kHz) with time synchronized pulses from IED. The phase angle is calculated from the voltage or current samples of both the ends by comparing the zero crossing instants of the respective signal samples. A rough estimation of the angle can be evaluated in this way since the samples do not always fall on the zero line. For exact measurement an interpolation technique can be adopted to know the exact zero crossing points. The GPS system in each PMU is avoided here by sending the time synchronized pulses with respect to the GPS from the IED only. This reduces the cost of using GPS receiver with each PMU.

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