Journal of Power and Energy Engineering, 2024, 12, 34-47
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

Determination of Total Vector Error of the Phasor Measurement Unit (PMU) Using the Phase Angle Error of a Constant Amplitude Voltage Signal

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How to cite this paper: Musonda, G., Zulu, A. and Lubobya, C.S. (2024) Determination of Total Vector Error of the Phasor Measurement Unit (PMU) Using the Phase Angle Error of a Constant Amplitude Voltage Signal. *Journal of Power and Energy Engineering*, **12**, 34-47.
https://doi.org/10.4236/jpee.2024.1211002

Received: October 1, 2024
Accepted: November 15, 2024
Published: November 18, 2024

Abstract

This paper investigates the effect of the Phase Angle Error of a Constant Amplitude Voltage signal in determining the Total Vector Error (TVE) of the Phasor Measurement Unit (PMU) using MATLAB/Simulink. The phase angle error is measured as a function of time in microseconds at four points on the IEEE 14-bus system. When the 1 pps Global Positioning System (GPS) signal to the PMU is lost, sampling of voltage signals on the power grid is done at different rates as it is a function of time. The relationship between the PMU measured signal phase angle and the sampling rate is established by injecting a constant amplitude signal at two different points on the grid. In the simulation, 64 cycles per second is used as the reference while 24 cycles per second is used to represent the fault condition. Results show that a change in the sampling rate from 64 bps to 24 bps in the PMUs resulted in phase angle error in the voltage signals measured by the PMU at four VI Measurement points. The phase angle error measurement that was determined as a time function was used to determine the TVE. Results show that (TVE) was more than 1% in all the cases.

Keywords

Phasor Measurement Unit (PMU), Phase Angle Error, Total Vector Error (TVE), State estimation, Time Source Error, Constant Amplitude Signal

1. Introduction

Modern power system management has placed emphasis on higher utilization of the power grid, and monitoring of its dynamic behaviour. The electricity power grid relies on traditional Supervisory control and Data Acquisition (SCADA) systems to provide supervision and control functions of the power grid elements. The shortfalls of SCADA are the inability to provide real-time data and inferior update rates that Wide Area Monitoring Protection and Control (WAMPAC) systems provide. Typically, most SCADA systems provide data measurements once every 2 or 4 seconds, and this affects the appropriate power system observability as well as the accurate analysis of the system's dynamic events. [1] Therefore, by design, SCADA has limited capability to support higher utilization of the power system and to monitor its dynamic behaviour.

The challenge of existing WAMPAC systems is the distortion in time tagging of data frames and poor system synchronization in instances of loss of the GPS signal, line frequency variation and communication network bandwidth limitations. The PMU is the unit used for the extraction of time-stamped phasor quantities in WAMPAC systems and the unit through which error is generated by the loss of the GPS signal for example. When the GPS signal is lost, the PMUs rely on their local oscillator to compute synchro-phasors. In most PMU applications, a drift in the local oscillator frequency normally occurs due to temperature variations and mechanical vibrations, thus providing inaccurate time stamps for synchro-phasor computation, which is reflected in the form of errors in the phase angle computation of the measured quantities [2]. Phase angle error can also be measured in terms of timing error in the measured quantities. Under these conditions, accurate monitoring and control of the power system and its parameters cannot be realized.

The most reliable approach to power grid monitoring and control is the closed-loop control method. The PMU is the core element in the WAMPAC closed-loop control system architecture. Measurements from PMUs are obtained from widely dispersed locations, synchronized with respect to the GPS clock [3]. This is impractical if the phasor quantities are not accurately time-stamped. WAMPAC systems perform real-time monitoring of the power grid dynamic behaviour through the application of the closed-loop control method. However, in the absence of the GPS signal to the PMU, time delay of the control network is likely to deteriorate the control effect and even leads to system instability [4].

2. Related Works

In [5] Ravi Shankar *et al.* showed that in practical on-field applications of commercial PMUs, the required accuracy of the time source should be better than the 31.8 μs limit mentioned in the IEEE C37.118.1 standard for synchrophasor measurements in Power Systems. The results showed that even a time source error of 10 μs is sufficient to make the TVE to be higher than 1%.

In [6] Subin Koshy *et al.* uses discrete Fourier analysis (DFT) of the input signal to the PMU wherein the rms value of magnitude and angle is calculated in each period of the selected sampling window. This work recognized the importance of external time source in controlling the sampling rate of phasor quantities. It goes on to propose DFT analysis of the sample signal to correct time source error.

In [7] Marco Agustoni *et al.* investigated the use of a measurement chain for synchrophasor estimation based on digital inputs: an instrument transformer, a stand-alone merging unit (SAMU) and a phasor measurement unit (PMU) to correct time source error. The results show that integration of online time quality management along with the synchrophasor measurement mitigates time source error.

[8]-[15] Jie Zhang *et al.* proposed the design of a software based phasor measurement method that utilizes soft synchronization with temporal pulse signals from GPS and mobile communication stations, offering a simpler and cost-effective alternative. The results showed that a software code with temporal GPS pulse signals can effectively correct phase angle error caused by the time source error.

This research has established a direct relationship between the signal sampling rate with the phase angle error of measured quantities. It has provided a clear understanding of time source error in relation to the sampling rate of signals and the phase angle error. Specifically, the phase angle error outcome at different measurement points for sampling rates of 24 bps and 60 bps for a constant amplitude voltage signal is established and converted to TVE %. Variation in the sampling rate from 24 bps to 60 bps resulted in timing error ranging between 35 μs to 72 μs. The TVE% outcome from this work correlates with the findings in the work done by [5]-[8]. These outcomes suggest time source error can be corrected through correct sampling of signals, DFT analysis of sampled signals and perhaps online time quality management. The research highlights the need to maintain a TVE below 1%. It further validates the effect of time source error on the performance of the PMU.

3. Literature Review

PMU's measure positive sequence voltages and currents on the transmission grid. Time synchronization allows synchronized real-time measurements of several remote measurement points on the grid, these are also referred to as synchro-phasors and are considered one of the most essential measuring devices in the future of power systems. Synchronization is achieved by time sampling of voltage and current waveforms using timing signals from the Global Positioning System (GPS) Satellite. This allows accurate comparison of measurements over widely separated locations as well as potential real-time measurement-based control actions [9]. A Phasor Measurement Unit can be a dedicated device, or can be incorporated into a protective relay.

The Phasor measurement unit is made up of the analog input, Anti-aliasing filter, Analog-to-digital (A/D) Converter, Phase locked oscillator, Phasor Microprocessor, modem and GPS antenna. **Figure 1** shows a typical synchronized phasor measurement system configuration block diagram.

The GPS signal is received by the receiver, that produces a phase-locked sampling pulse to the A/D converter. A complex number is used to represent the sampled data of the input analog signal waveform. In the three-phase system, the three phasors are combined to produce the positive sequence measurement. Any computer-based relay which uses sampled data is capable of developing the positive sequence measurement. By using an externally derived synchronizing pulse, the measurement could be placed on a common time reference. Most PMUs use the external time-source signal not only to define the full second transition and thus the measurement time-stamp, but also to discipline the internal clock [7].

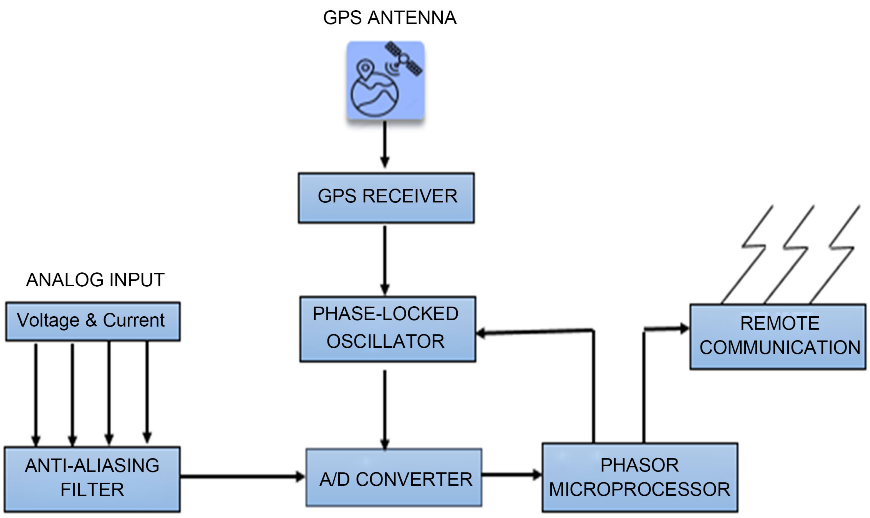

Figure 1. PMU block diagram.

3.1. Signals Received by PMUs

Phasor technology and the Phasor Measurement Unit (PMU) [2] is a valuable measurement technology in the power system for monitoring the condition of transmission and distribution networks. The phasor of the 50 Hz signal component is obtained based on the digitally sampled analog voltage waveform that is synchronized with the clocking signal from the GPS receiver in distributed locations as shown in **Figure 2**. The accuracy of a phasor estimate from a PMU is measured in terms of the Total Vector Error (TVE). The TVE for an operational PMU under steady-state conditions should not exceed the 1% or 0.01 pu mark. For purposes of determining the phase angle error of the PMU, an alternating Current (AC) signals can be represented by;

$$x(t) = X_m \cos(\omega t + \varnothing) \tag{1}$$

where X_m is the signal's peak value and $\omega = 2\pi f$ is the angular frequency and $\varnothing$ is the initial phase-angle.

The signal's phasor representation can be written as:

$$X = \frac{X_m}{\sqrt{2}} e^{i\varnothing} = \frac{X_m}{\sqrt{2}} (\cos\varnothing + i\sin\varnothing) = X_r + iX_i \tag{2}$$

where $\frac{X_m}{\sqrt{2}}$ is the RMS value, X_r is the real part and iX_i is the imaginary part of the signal [10].

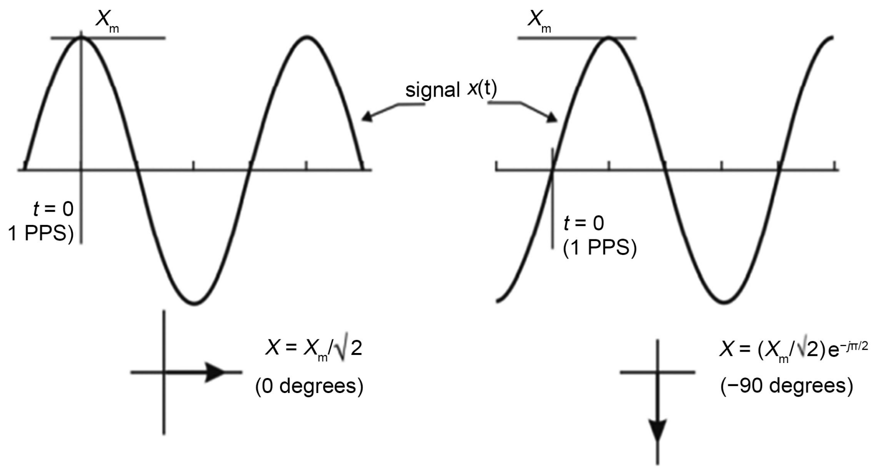

Figure 2. Synchrophasor representation.

When the signal is in this form the amplitude and phase can be calculate by using the following equations [11];

$$X_{amp} = \sqrt{\left(X_{rms}\cos\varnothing\right)^2 + \left(X_{rms} i \sin\varnothing\right)^2} = \sqrt{X_r^2 + iX_i^2} \quad (3)$$

$$\varnothing(t) = \tan^{-1}\frac{\sin\varnothing}{\cos\varnothing} = \tan^{-1}\frac{X_i}{X_r} \quad (4)$$

Assuming no magnitude errors in the synchro-phasor estimate, then a 1% TVE corresponds to a phase angle error of 0.573^0. In terms of time, this is about 31.8 µs at the system frequency of 50 Hz [5]. In order to achieve a TVE of below 1% or timing errors of less than 31.8 µs in a 50 Hz system, only GPS, IRIG-B and IEEE 1588 PTP is recommended in synchro-phasor applications [5]. For constant amplitude signals, the phase angle error in degrees is given by:

$$\text{Phase angle}\left(^\circ\right) = \left(\frac{\text{Time error}(s)}{\text{Period}(s)}\right) \times 360 \quad (5)$$

3.2. Signal Acquisition and Conditioning Module

The input data of the PMU are a component obtained from the electrical signals from the power systems; these are 3-phase voltages and currents. From the perspective of transmission systems, voltages and currents signals are obtained from the substation equipment—the secondary of the Voltage Transformer (VT) and a Current Transformer (CT). The input signals to the signal acquisition and condition module is stepped-down to match the low-power dissipation components of the module. The three phase voltages of the VT are applied to the PMU. Most of the microcontroller ADC take voltages of up to only 3.3 V [12]. The data acquisition module is responsible for obtaining voltage or current waveforms data for the test. The Data Acquisition and Conditioning Module (DAM) can be implemented in the form of either Hardware or Software. Sampling of the three phase signals will be initiated by the Microprocessor after receiving 1 pulse per second (1 PPS) signal from the GPS module [13].

The three-phase signal acquisition and conditioning module is separated into two sections: The Line voltage measurement interface and Line frequency measurement interface.

3.3. Signal Processing Module

The Phase Estimation Module (PEM) is one of the major component of the PMU implementation. It is responsible for applied voltage phase angle processing by means of the phase estimation algorithm that runs on it. The algorithm can be of two types; Static State Estimation or Dynamic State Estimation.

In Static State Estimation (SSE), estimates are obtained from the present state measurements made at the system buses at a more significant interval of time, ranging from few seconds to minutes [14]. To reduce the complexity of computation associated with static state estimation, the estimates are updated only in a few minutes. This brings about a limitation of the SSE – that it cannot be used as a real–time monitoring tool of the power system [15]. The estimates obtained in SSE are not real time and simply illustrates the quasi-static representation of the power system.

In Dynamic State Estimation (DSE), time-synchronized data from PMUs is used to provide exact and real-time state of a power system. As a consequence, an erroneous or a missing synchronization may affect not only the reporting time reference and thus the correct aggregation with other PMU measurements, but also the estimated quantities, particularly the phase angle and its derivatives [7]. That is, if the state vector at an instant of time "t" is known, then the dynamic state estimation model can be used to predict the state vector of the power system at the next time instant, "t +1" [6]. One such promising alternative is soft synchronized sampling. This approach corrects timing errors between two consecutive PPS signals using interpolation techniques, eliminating the need for frequent adjustments of the ADC [8]. The disadvantages of DSE and SSE are highlighted in **Table 1** below.

Table 1. Disadvantages of SSE and DSE.

No.	State Estimation	
	Dynamic State Estimation (DSE)	**Static State Estimation (SSE)**
i.	Poor PMU Placement	No time synchronization
ii.	Inefficient Data Processing Algorithm	Skewed and latency in data
iii.	Inaccurate data detection	Data is not time stamped

3.4. GPS Receiver Module

Accurate time synchronization is required to offer the time-stamp of the signals taken and managed by the PMU. If a reliable GPS signal is available, the Analogue-to-digital converter (ADC) is used to convert the voltage waveform into numerical values sampled at controlled intervals by an independent local oscillator. In this case, the sampling clock is not locked to the GPS signal. The PMU should perform all the measurements and report the results at a constant reporting rate, expressed in terms of frames per second [16]. Devices based on synchrophasor technology must handle measurements at least at the mandatory reporting rates of 10, 25, and 50 frames per second [13]. However, the sampling data appears to be in synchronism with GPS signal because of the running function on the microprocessor controlling the ADC. Inherently, a clock drift occurs in this approach. Therefore, interpolation of sample points to fit specified time values is recorded and utilized by the phasor estimation algorithm to correct for sampling clock drift.

The Data Acquisition can also be constructed such that internally generated sampling clock is synchronized with the GPS signal. This ensures that the ADC samples the waveforms at predetermined instances thereby ensuring that there is no sampling clock drift.

3.5. Communication Interface Module

The communication interface module provides the external communication functions of the device. When the proposed PMU was implemented, a reference implementation of IEEE C37.118.2, but the Open PMU project prefers a more open communication module with security built into its design.

Microprocessor after receiving 1 pulse per second (1 PPS) signal from the GPS module [17].

The three-phase signal acquisition and conditioning module is separated into two sections: The Line voltage measurement interface and Line frequency measurement interface.

3.6. Hardware Implementation of the DAM

DAM implementation is achieved by means of an analogue-to-digital converter (ADC) which is normally connected to an external time source. This approach has the advantage of high process speed compared to the software implementation method.

3.7. Software Implementation of DAM

In this application, a virtual sampling procedure in a numerical environment is used, e.g., MATLAB/Simulink, PSSE/Python, or LabVIEW.

4. Methodology

The Simulink model for determination of the TVE error was configured as shown in **Figure 4** below.

In this experiment, two (2) three-phase voltage sources with series RL branches are used to provide the system voltage and current. Three-phase Pi sections are utilized at three points on the system in order to obtain an extended frequency response. 25 Km distributed line parameters are used to represent the transmission line parameters. A resistance branch is included to the model to account for transmission line losses. Voltage phase values are measured at bus 1, bus 2, bus 3, bus 4 and bus 5 respectively. The three-phase VI measurement link is configured to read the voltage and current phasor for input to the phasor measurement unit (PMU). The PMUs are located at buses and feeders in power system substations [18]. PMU reference voltage is set at 400 V, 50 Hz. The fault signal in the system is sampled at 64 cycles standard. The control voltage phasor is read at 50 Hz, 24 cycles per second to determine the total vector error (TVE).

In order to establish the relationship between the GPS signal and the internal sampling clock, a 1 pu (0.02 s) magnitude error signal is injected at bus 4 and bus 5 of the IEEE-14 bus system. The PMU block uses a Phase-Locked Loop (PLL) to determine the fundamental frequency and a Positive-Sequence measurement over a running window of one cycle of the fundamental frequency. The IEEE-14 bus system, shown in **Figure 3**, was used in the experiment. The simulations were done on the IEEE-14 bus system in MATLAB/Simulink as shown in **Figure 4**.

5. Results and Discussion

To observe the phase-angle shift in the Voltage signals, a fault is introduced at 0.98 for 1 cycle and removed at 1 second at bus 4 and bus 5. The fault introduced is a pulse signal of duration 0.02 seconds. The results observed on the three-phase oscilloscope are shown in **Figures 5-12** below. **Table 2** shows the positive sequence time measurement taken for two distinct sampling rates; 24 bps and 64 bps at buses 2 - 5 respectively. Timing error is determined from the measured quantities and converted to the phase angle error equivalents. TVE% is computed as shown in **Table 2**. From the results it can be seen that is TVE above 1% maximum threshold according to the IEEE C37.118.2. A TVE above 1% indicates that there are serious timing stamping errors on the grid and accurate control actions could be impossible to implement.

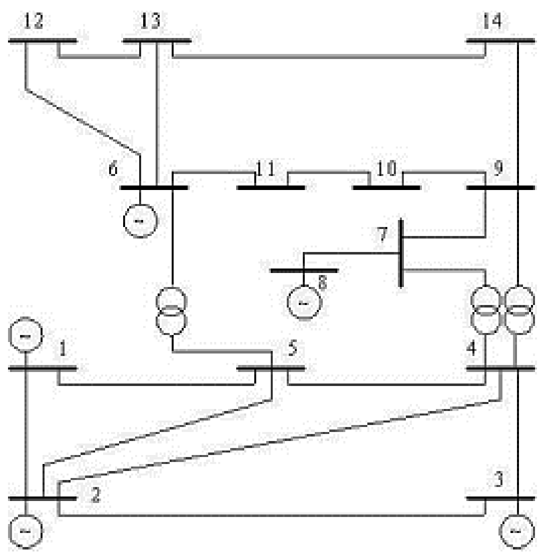

Figure 3. IEEE 14 bus system.

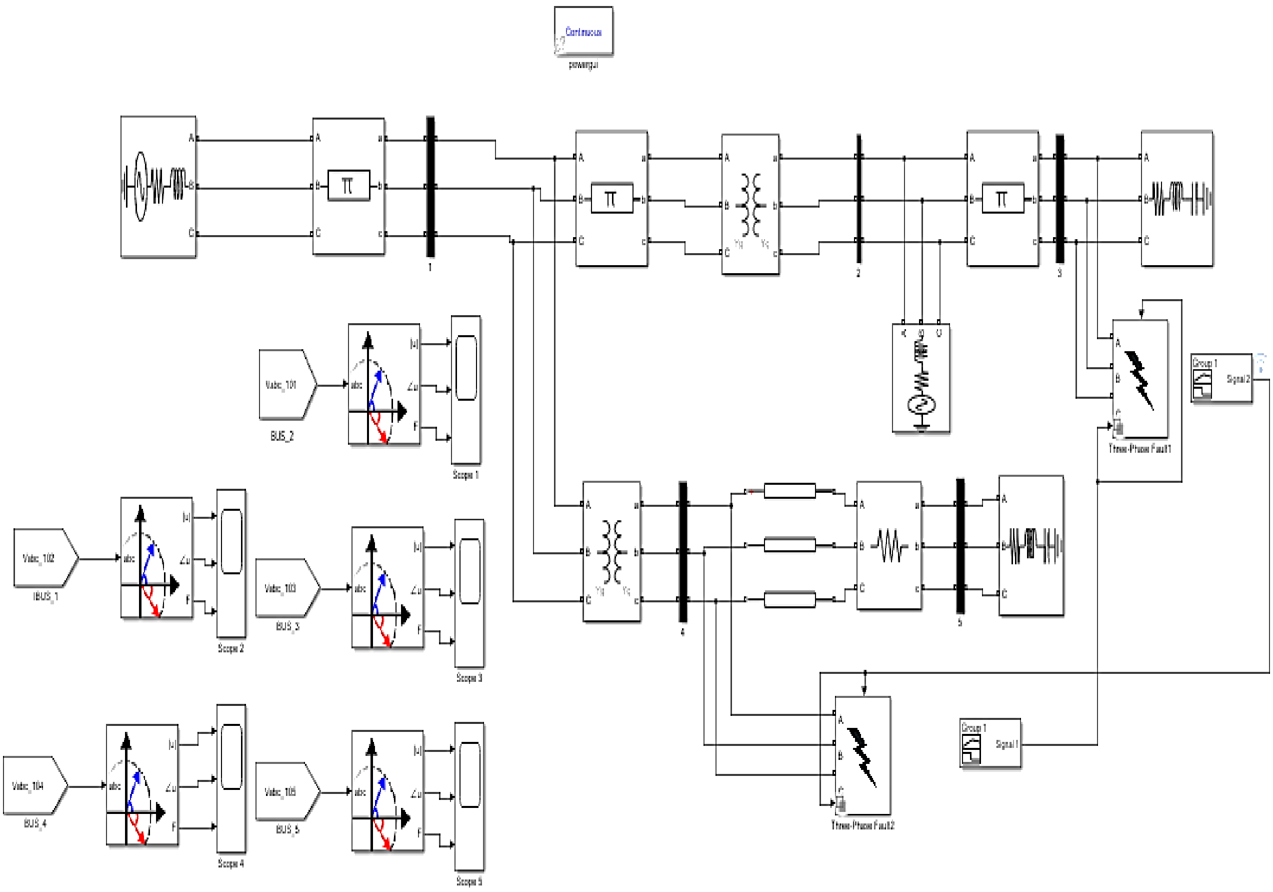

Figure 4. IEEE 14-bus Simulink model (section).

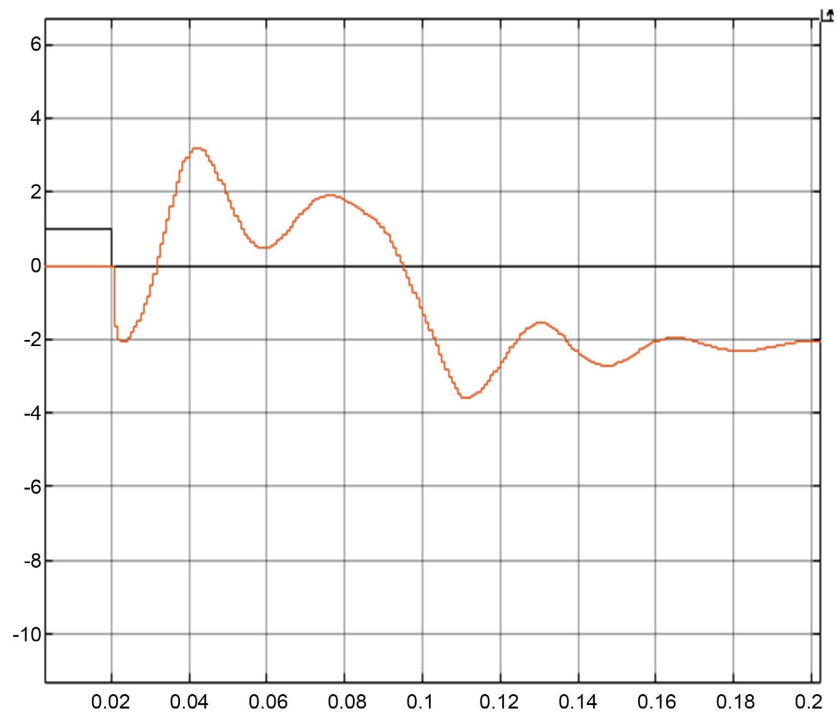

Figure 5. Synchrophasor waveform at bus 2 (24 bps).

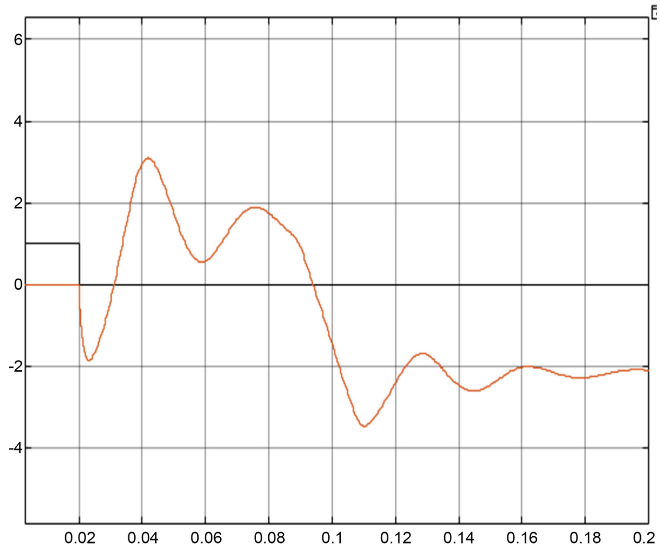

Figure 6. Sychrophasor waveform at bus 2 (64 bps).

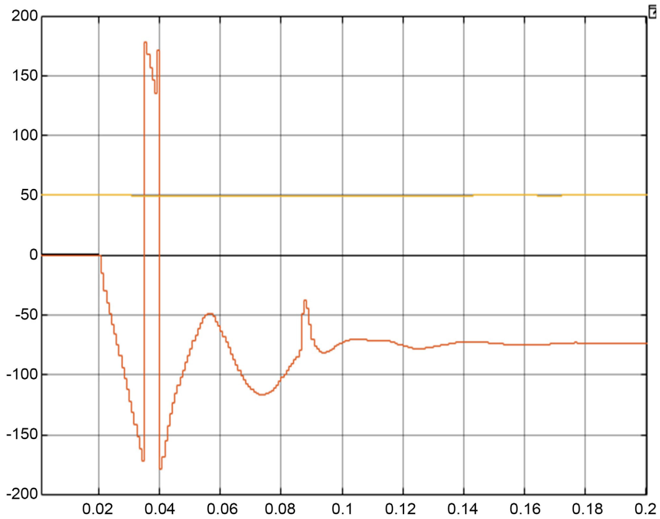

Figure 7. Synchrophasor waveform at bus 3 (24 bps).

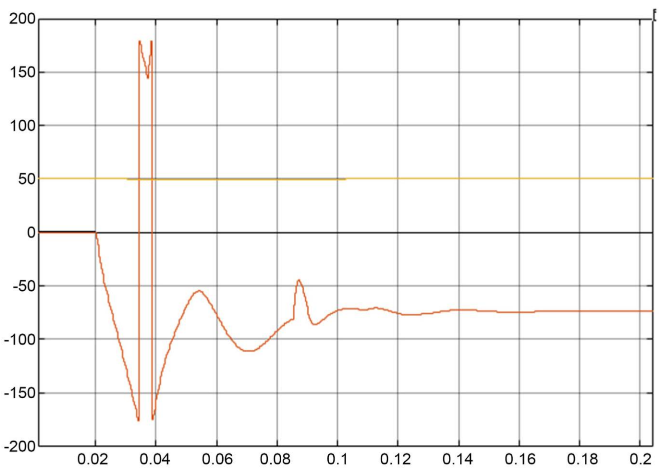

Figure 8. Synchrophasor waveform at bus 3 (64 ps).

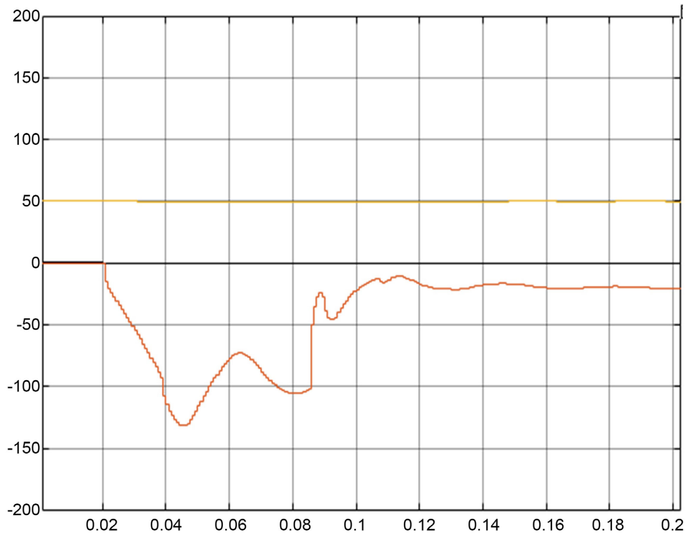

Figure 9. Synchrophasor waveform at bus 4 (24 bps).

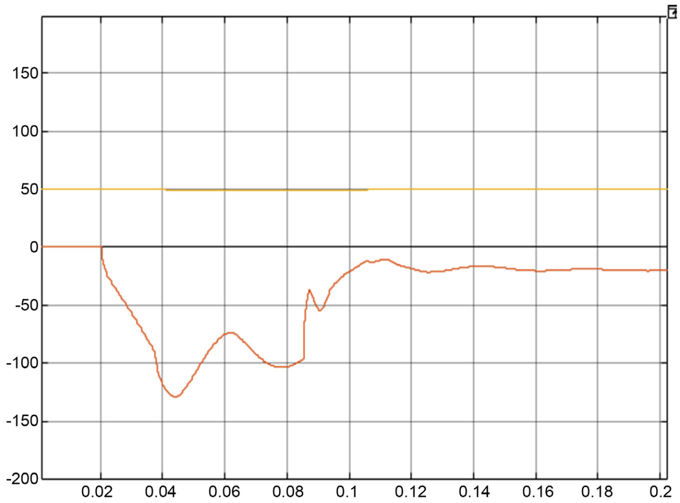

Figure 10. Synchrophasor waveform at bus 4 (64 bps).

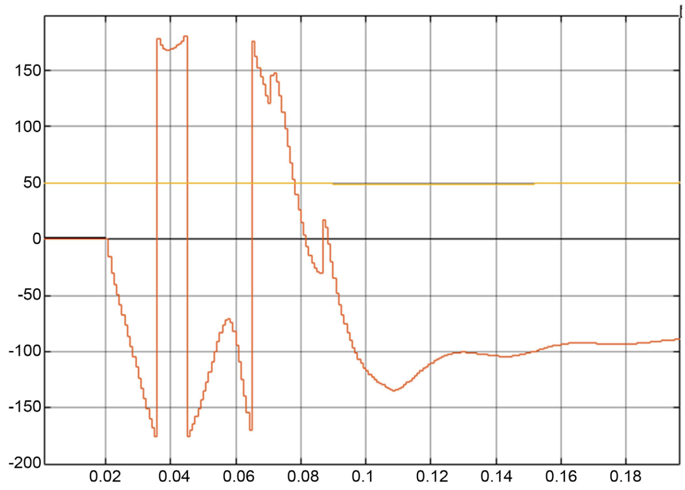

Figure 11. Synchrophasor waveform at bus 5 (24 bps).

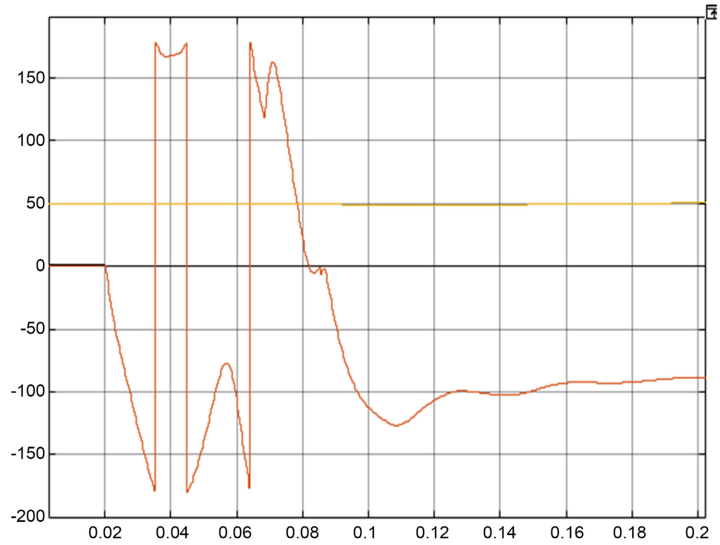

Figure 12. Synchrophasor waveform at bus 5 (64 bps).

Table 2. Phase Angle Error (PAE) and Total Vector Error (TVE) estimation.

Bus No.	Sampling Rate				
	Positive-sequence time measurement (24 bps)	*Positive-sequence time measurement (64 bps)*	*Timing error Δs (μs)*	*Phase angle error (˚)*	*TVE %*
2	729.642 ms	729.693 ms	51	0.918	1.6
3	729.958 ms	730.000 ms	42	0.756	1.319
4	729.966 ms	730.001 ms	35	0.630	1.099
5	729.989 ms	730.061 ms	72	1.296	2.26

6. Conclusions

Time synchronization of PMUs measurement using the 1 pps GPS signal is very critical to the state estimation of the power system parameters. The absence of the 1 pps signal affects the sampling rate and consequently the time estimation (time-tagging) of voltage and current error signals resulting in TVE higher than 1%.

It is seen that a change in the sampling rate from 60 bps to 24 bps in the PMUs produced TVE above 1%. This is a result of a loss in the 1 pps GPS signal. The MATLAB/Simulink simulation demonstrates that for a constant amplitude signal, different sampling rates will result in phase angle error in the measured voltage signals. The phase angle error measurement that was determined as a time function affects time tagging of synchro phasors. Disturbances on the grid can be known by using the rate of change of phase angle [19]. In practice, phase angle errors result in inaccurate control actions on the power grid. The resulting TVE of above 1% is outside the threshold recommended by IEEE C37.118.2 standard. It is therefore, required that a cluster of PMUs remain synchronized even after the GPS signal is unavailable to one or all the PMUs. This ensures that signals are sampled at the same rate and accurate control actions are in place on the power grid.

It has been established that the external clock signal does not only ensure timing synchronization of PMUs but also maintains the TVE within the prescribed limits. A state estimation algorithm can be used to discipline the internal clock in order to ensure accurate time stamping of phasor quantities. A dynamic state estimation software can be deployed to run on the PMU microprocessor unit to effect phase angle estimation of phasor quantities.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Muhayimana, O. and Toman, P. (2022) A Review on Phasor Measurement Units and Their Applications in Active Distribution Networks. 2022 *IEEE PES/IAS PowerAfrica*, Kigali, 22-26 August 2022, 1-5.

[2] Chenine, M. and Nordström, L. (2017) Investigation of Communication Delays and Data Incompleteness in Multi-PMU Wide Area Monitoring and Control Systems. 2009 *International Conference on Electric Power and Energy Conversion Systems*, (*EPECS*), Sharjah, 10-12 November 2009, 1-6.

[3] Sharmaa, R.B. and Dholeb, G.M. (2016) Wide Area Measurement Technology in Power Systems. *Procedia Technology*, **25**, 718-725.

[4] Liao, J.P. and He, C. (2014) Wide-Area Monitoring Protection and Control of Future Power System Networks. 2014 *IEEE Workshop on Advanced Research and Technology in Industry Applications* (*WARTIA*), Ottawa, 29-30 September 2014, 903-905. https://doi.org/10.1109/wartia.2014.6976419

[5] Singh, R.S., Hooshyar, H. and Vanfretti, L. (2015) Assessment of Time Synchronization Requirements for Phasor Measurement Units. 2015 *IEEE Eindhoven PowerTech*, Eindhoven, 29 June-2 July 2015, 1-6.

[6] Koshy, S., Sunitha, R. and Cherian, E.P. (2018) A PMU Model for Dynamic State Estimation of Power Systems. 2018 2*nd International Conference on Power*, *Energy and Environment*: *Towards Smart Technology* (*ICEPE*), Shillong, 1-2 June 2018, 1-6.

[7] Agustoni, M., Castello, P., Frigo, G. and Gallus, G. (2023) Time Synchronization Sensitivity in SV-Based PMU Consistency Assessment. *Metrology*, **3**, 99-112. https://doi.org/10.3390/metrology3010006

[8] Zhang, J., Tang, C., Liu, C., Wang, H., Duan, J.F. and Tang, S.H. (2023) Phasor Measurement Method Based on Soft Synchronized Sampling with Temporal Pulse Signal Reference. *Frontiers in Energy Research*, **11**, Article ID: 1302869.

[9] Raikwal, S. (2015) Wide Area Monitoring, Control and Protection of Power System. *International Journal of Computer Applications*, No. 3, 18-21.

[10] Björkhem, F., Boivie, J., Jolhammar, M.T. and Nour, O.M. (2024) Implementation of a Phasor Measurement Unit in MATLAB. Department of Electrical Engineering, Uppsala University.

[11] Bart, Q. and Tzoneva, R. (2018) An FPGA-Based Implementation of a Hilbert Filter for Real-Time Estimation of Instantaneous Frequency, Phase and Amplitude of Power System Signals. *International Journal of Applied Engineering Research*, **13**, 16333-16341.

[12] Raju, V.V.R., Shree, K.H.P. and Kumar, S.V.J. (2021) Development of Cost-Effective

Phasor Measurement Unit for Wide Area Monitoring System Applications. *International Journal of Electrical and Computer Engineering* (*IJECE*), **11**, 4731-4739. https://doi.org/10.11591/ijece.v11i6.pp4731-4739

[13] Castello, P., Muscas, C., Pegoraro, P.A. and Sulis, S. (2018) A Monitoring System Based on Phasor Measurement Units with Variable Reporting Rates. *Acta IMEKO*, **7**, 62-69.

[14] Blood, E.A., Krogh, B.H. and Ilic, M.D. (2008) Electric Power System Static State Estimation through Kalman Filtering and Load Forecasting. 2008 *IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the* 21*st Century*, Pittsburgh, 20-24 July 2008, 1-6. https://doi.org/10.1109/pes.2008.4596742

[15] Huang, Y., Werner, S., Huang, J., Kashyap, N. and Gupta, V. (2012) State Estimation in Electric Power Grids: Meeting New Challenges Presented by the Requirements of the Future Grid. *IEEE Signal Processing Magazine*, **29**, 33-43. https://doi.org/10.1109/msp.2012.2187037

[16] Femine, A.D., Gallo, D., Landi, C. and Luiso, M. (2019). A Design Approach for a Low-Cost Phasor Measurement Unit. 2019 *IEEE International Instrumentation and Measurement Technology Conference* (*I*2*MTC*), Auckland, 20-23 May 2019, 1-6. https://doi.org/10.1109/i2mtc.2019.8826889

[17] Ponnala, R., Chakravarthy, M. and Lalitha, S.V.N.L. (2022) Effective Monitoring of Power System with Phasor Measurement Unit and Effective Data Storage System. *Bulletin of Electrical Engineering and Informatics*, **11**, 2471-2478. https://doi.org/10.11591/eei.v11i5.4085

[18] Jain, A., Bhardwaj, A., Kumar, S. and Bhullar, S. (2018) Implementation Techniques for Frequency & Phasor Estimation in Phasor Measurement Units (PMUs). 2018 3*rd International Conference on Internet of Things*: *Smart Innovation and Usages* (*IoT-SIU*), Bhimtal, 23-24 February 2018, 1-6.

[19] Ren, J. and Kezunovic, M. (2011) Real-time Power System Frequency and Phasors Estimation Using Recursive Wavelet Transform. *IEEE Transactions on Power Delivery*, **26**, 1392-1402. https://doi.org/10.1109/tpwrd.2011.2135385