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A New Implementation of PMU Based on Streamed Values of IEC 61850 Process-Bus

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Abstract

This paper assessing the performance of a simulated PMU fed by streamed measured values as defined in IEC 61850. The PMU is designed and implemented based on the so-called Unscented Kalman Filter algorithm and proposed as a centralized computation tool. The communications among PMUs and central control room is accomplished based on Ethernet network communications. Although that Ethernet-based communications can be appropriate and reliable for many power applications, it is recommended to assess the impacts of its communication network errors such as network bandwidth and clock errors and how their influence on the estimated phasor. This proposed implementation can help power utilities to track any dynamic change and improve the state estimation of the system. MATLAB®/Simulink® is used in conjunction with true-time software that is developed by ABB to mimic the process-bus communication of IEC 61850 in this work. Representative results in assessing the impacts of the errors on PMU's performance are presented in the paper.

Keywords

PMU, Process-Bus, IEC 61850, Unscented Kalman Filter, Ethernet network

1. Introduction

In power systems, the purpose of any phasor estimator is to determine the best match to real ones of state of variables such as the magnitudes and the angle at various points in the system [1]. The accuracy of estimation of those states of variables can be deeply affected by the availability of measurements and noise.

Traditionally, measurements have been provided by Supervisory Control and Data Acquisition (SCADA) system. One of the disadvantages of SCADA system is the measurements are not synchronized. This drawback made SCADA measurements not appropriate in applications of protections and control of dynamic power systems. Furthermore, measurements snapshots are typically with time delay of few seconds (two or three seconds) and sequentially, collected measurements are asynchronous with some time delay. These asynchronous and delay in time will cause time skew errors which eventually affect the accuracy of the estimator. Estimating phasors by any conventional static estimation algorithm [1] is not effectual because conventional estimators that were implemented based on traditional algorithms are not able to capture any dynamic changes in state variables of phasors (i.e. magnitude and angle).

The dynamic change in state variables of phasors can be detected and acquired by direct means such as using phasor measurement unit (PMU). Even so, this PMU is implemented based on an algorithm that enables it to track any dynamic changes in the state variables, it has some time skew errors because PMU is synchronized by signal received from Global Positioning System (GPS). Receiving of this signal may affect by space weather or it could be blocked by mountains and tall buildings. Also, to enhance the estimation by adding more PMUs can arise the cost and could be beyond funds of many power utilities. Moreover, adding more PMUs to the existing SCADA systems does not bring any significant enhancements to the estimation of state variables. This was reported by the study supported by ESKOM in 1996 in South Africa [2] as well as by the more recent study done by KEMA in the USA [3].

Enhancing the estimation by using the dedicated PMUs for a could be substituted by of estimators that can be implemented based on the streamed values of IEC61850 process-bus [4]. The estimator can be fed with the streamed measurements from the various merging units (MUs) at process-bus (Figure 1) and the estimation function can be implemented at the central control room (CCR) of power utilities. By this way, more function can be added to the existing substation automation system (SAS).

The novelty of this paper is proposing an alternative approach for estimating of state variable at control room level not at switch yard level as this is the case with the estimation of PMUs. The dynamic estimation function is implemented based on Unscented Kalman Filter algorithm (UKF) fed with the streamed values of IEC61850 process-bus. This new hierarchy can make the estimation more robust and can in some cases replace the static estimation function version or even the PMUs that are typically installed in contemporary power utilities.

The paper is structured as follows: Section II presents conceptual model of IEC61850 process-bus and its streamed measurement. Section II also includes introductory subsection to Unscented Kalman Filter algorithm. Section III presents the hierarchy and simulation setup. This section explains how that True-Time software environment is used in conjunction with MATLAB®/Simulink® in this paper. Section IV presents assessment results of the impacts of BW and time errors on the performance of the estimation. Section V is the conclusions.

2. Overview of IEC 61850 and UKF

2.1 Overview of IEC 61850 Process-Bus

IEC 61850 is EC 61850 is an international standard for the communication within the SAS. In general, the IEC 61850 standard can run over TCP/IP network (station-bus) or substation local area network (LAN) using high speed switched Ethernet network (process-bus). The conceptual architecture of the station-bus and process-bus is depicted in Figure 1.

The applications of process-bus require synchronized sampling processes for the current and voltage measured at high voltage equipment (electronic instrument transformers and the MUs). Typically, MUs are accrue and digitizing the analogue voltage and current waveforms, position and open/close controls and multicast them on the substation LAN. The status of circuit breakers (open or close) is monitored by binary input/output units (IOUs) and is multicast to the intelligent electronics devise (IED) as a Generic Object Oriented Substation Event (GOOSE) messages. The IEDs receive both of streamed values and GOOSE message and use them for monitoring, protecting and controlling.

The exchange of messages for process-bus can be done over serial communication or over Ethernet. The implementation guide of IEC 61850 process-bus [5] defines two kinds of transmission methods: 1) Multi-cast service (MSVC) over Ethernet and 2) a Unicast (point-to-point) service (USVC) over serial links. The implementation guide also defined two sampling rates for streamed measured values: 1) SMV#1 that has 80 S/C and 2) SMV#2 that has 256 S/C.

Any loss of samples that been sent are treated by the receiving functions, e.g. by a protection algorithm. Transmission of samples (messages) can be achieved by using the distributed reservation protocol (DRP). In this protocol, the nodes have reserved slots so it will always have access to the medium or alternatively, they can have prioritized contention access (PCA) that can provide differentiated, distributed contention access to the medium.

The IEC 61850 employs a clock to trigger the event of sending the streamed measured value message (Clock Event). While the clock is used for triggering streamed measured value message, the estimated phasor should be assessed against clock errors. Errors of clock could be offset and drift accuracy which should be corrected.

IEC 61850 standard is using the concept of synchronization. It means that all nodes that perform sampling should be synchronized. This can be accomplished by synchronizing all node clocks to a master clock and thus, it can guarantee that the samples are taken all simultaneously.

It is worth to mention that one of the applications of process-bus is the information transferred is a time critical and has a strong impact on the response time and the accuracy of the estimation function.

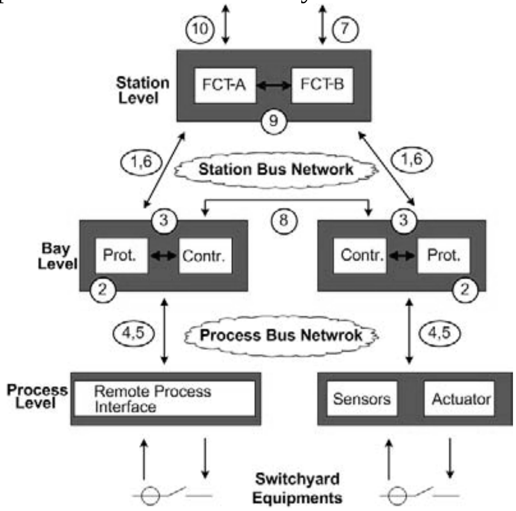

Figure 1. Process Bus and Station Bus in the IEC 61850-based SAS.

2.2 Overview of Unscented Kalman Filter Algorithm

Kalman filtering algorithm (KF) is a mathematical technique widely used in electrical engineering [6-11] to compute the optimal estimates of a dynamic states of power system. The estimates are optimal in the sense that estimation errors are minimized in the least-squared sense. The dynamic system can be described and show how its states change with time by using a set of linear differential equations (both in vector and matrix format) as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{F}\boldsymbol{x} + \boldsymbol{w} \tag{1}$$

where $\boldsymbol{x}$ is the state vector, $\boldsymbol{F}$ is the system matrix, and $\boldsymbol{w}$ is a random driving noise vector. The model defined by equation (1) is also known as the "Process Model".

Assume that a power system has various kinds of sensing nodes for measuring specific quantities (voltages and currents). These measurable quantities and system states can have the following set of linear equations.

$$\boldsymbol{z} = \boldsymbol{H}\boldsymbol{x} + v \tag{2}$$

where, $\boldsymbol{z}$ is the measurement vector (Each variable in this vector represents quantities measurable by sensing nodes), $\boldsymbol{H}$ is the measurement matrix, $\boldsymbol{v}$ is a random vector describing measurement noises.

Model represented by equation (2) is known as the "measurement model". At present, equations (1) and (2) are expressed in continuous-time. To calculate system states at a particular point in time, equations (1) and (2) need to transformed to discrete-time model. It can be shown that the discrete time model of (1) and (2) can be expressed as.

$$\boldsymbol{x}_{\boldsymbol{k}+\boldsymbol{1}} = \emptyset_{\boldsymbol{k}}\, \boldsymbol{x}_{\boldsymbol{k}} + w_k \tag{3}$$

$$\boldsymbol{z}_{\boldsymbol{k}} = \boldsymbol{H}_{\boldsymbol{k}}\, \boldsymbol{x}_{\boldsymbol{x}} + v_k \tag{4}$$

where $\boldsymbol{x}_{\boldsymbol{k}}$ is the system state vector at time t_k, $\emptyset_{\boldsymbol{k}}$ is the state transition matrix and it can be computed from $\emptyset_k = e^{F.\Delta T} \approx I + F\,\Delta T$, where $\Delta T = t_{k+1} - t_k$ is the time-step (*In our simulation, it will be 0.02/80 or 0.02/256*), $\boldsymbol{z}_{\boldsymbol{k}}$ is our measurements vector at time t_k, $\boldsymbol{H}_{\boldsymbol{k}}$ is the measurement matrix at time t_k.

If the driving noise $\boldsymbol{w}_{\boldsymbol{k}}$ and measurement noise $\boldsymbol{v}_{\boldsymbol{k}}$ are defined in stochastic terms, then, KF algorithm requires $\boldsymbol{w}_{\boldsymbol{k}}$ and $\boldsymbol{v}_{\boldsymbol{k}}$ to be random processes with the following characteristics: 1) Zero-mean, 2) Gaussian (Normal) distribution, 3) White (Uncorrelated) and 4) $\boldsymbol{w}_{\boldsymbol{k}}$ and $\boldsymbol{v}_{\boldsymbol{k}}$ have covariance matrix of are $\boldsymbol{Q}_{\boldsymbol{k}}$ and $\boldsymbol{R}_{\boldsymbol{k}}$, respectively.

One basic and important requirement of standard KF algorithm is that both the process and the measurement models are linear as shown in (1) and (2). However, signals in our system are nonlinear (voltage and current sinusoidal signals). In such cases, adaptation to the standard algorithm is required, so it can to be used within our system. A more recent development known as Unscented Kalman Filter algorithm [7, 8] can overcome the weakness of traditional Kalman Filters (Performance deteriorates drastically under highly nonlinear system).

Instead of using linearized equations to approximate the nonlinear model as traditional Extended Kalman Filter (EKF) approach, UKF generates a finite set of points called as sigma points. These sigma points are transformed to a new set of points using the nonlinear model. System states and associated error covariance matrices are determined numerically based on the mean and covariance values of the transformed sigma points. Mathematically, the UKF process can be presented as follows.

The predicted states $x^{-}$is computed by defining $2n$ sigma points $x_{k-1}^{(i)}$from $x_{k-1}^{(i)}$=x_{k-1}^{+}+ $x^{\sim(i)}$, $i = 1, \dots ,2n$ where

$$\boldsymbol{x^{\sim(i)} = \left(\sqrt{n\, P_{k-1}^{+}}\right)_{i}^{T},\ i = 1, \dots . n} \tag{5}$$

$$\boldsymbol{x^{\sim(n+i)} = -\left(\sqrt{n\, P_{k-1}^{+}}\right)_{i}^{T}, i = 1, \dots . n} \tag{6}$$

3. Proposed Hierarchy and Setups

3.1 Proposed Hierarchical Model

To assess the performance, a hierarchical model for dynamic state estimator based on the process-bus of IEC61850 is proposed as depicted in Figure 2. In this hierarchical model, the MUs (sending nodes) can be connected to the process-bus via an Ethernet network.

The inputs of measuring nodes are: analogue voltage and current signals as well as binary status information**.** The measuring nodes can be synchronized to the master substation central computer node clock using any of the following protocols: IEEE1588 Precision Time Protocol (PTP) [12], IRIG or NTP. Possibility of achieving accuracy in sub-nanosecond is only possible with IEEE1588 [13].

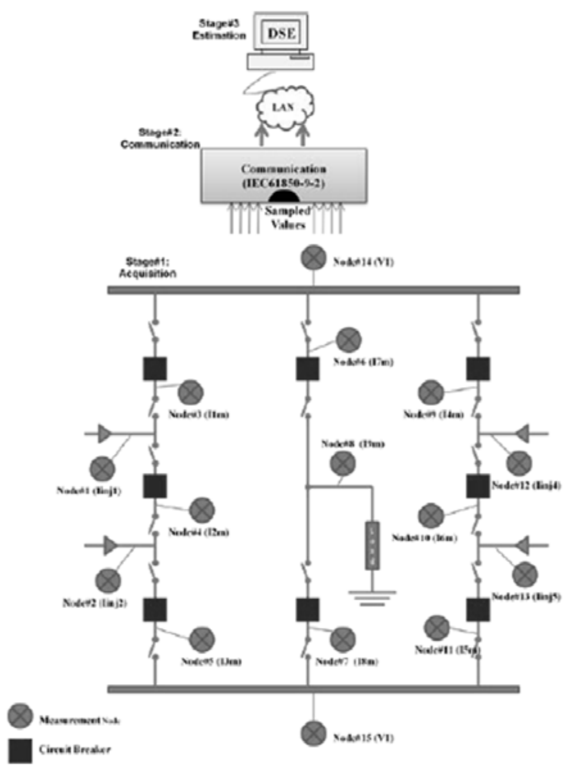

Figure 2. IEC61850 communication and substation-based PMU layout.

The proposed model is a hierarchical of three stages. Stage#1: (Measuring nodes) is consisting of a number of nodes that perform all sampling rate at intervals of 0.25 millisecond (4 kHz) or 78.125 microsecond (12.8 kHz). It is crucial to keep the number of nodes as low as possible to avoid latency in traffic. Stage#2: (Communication network) is a link between the measuring nodes and the CCR (where the PMU function is implemented) according to IEC61850 communication protocol. The role of the communication is to convert first the signals received from the measuring nodes to streamed values message and GOOSE massages and multicast them.

The communication module receives all messages from nodes simultaneously after sampling and time-stamping them. In this hierarchical model, it is assumed that communication module can receive signal from master clock signals and all measuring node clocks are synchronized to it. The main function of measuring nodes in this measurement system is to provide on only the streamed values of process-bus to the substation central control computer where the PMU software module is exist. The PMU function is implemented based on UKF as mentioned before and working according to the IEEE C37.118 standard [14] (Total vector error should be ≤ 1%).

The aim of this work is to find a configuration of a system that can combine the benefits of IEC61850 process-bus, IEEE1588 and UKF to produce dynamic estimator at substation control room with less cost than typical PMU.

3.2 Simulation Environment and Setups

True-Time is library that can be run within a MATLAB®/Simulink® environment. It is developed by ABB corporate research Group in 2008 to emulate the IEC 61850 process-bus. It can facilities simulation of task execution in real-time kernels. The Kernel block is powerful to emulate the behavior of a computer node with a generic real-time kernel, A/D and D/A converters, and network.

Referring to Figure 2, the architecture consists of sixteen nodes that are two sides divided. In one side (switchyard), there are fifteen nodes divided into five groups which each of them include three nodes represents one entity (Bay).

In the other side, there is one node computer that represent the CCR of substation and where the PMU is implemented.

Each entity in the measuring side is able to measure a three phase signal provide by the secondary side of power transformer. Also, each node has its clock offset and drift. All three nodes in one cast its streamed values (messages) to one IEC61850 process-bus network block. The IEC61850 process-bus network block is able to receive the messages from all nodes with the rate of 4 kHz (80 S/C[1]) or with the highest rate (12.8 kHz or 256 S/C) and then convert them to streamed values messages.

MATLAB®/Simulink® model simulating a model of real substation. The model simulates analogue real measurements and provides them to the CCR node via IEC61850 process-bus. The model is converted to a Matlab xPC target model; so it can be possible to run and publish measurements in real time real-time.

This hierarchical model can provide flexible way of testing the impacts of network errors on the performance of the PMU. Since PMU is implemented based UKF algorithm for providing state of the system, it is designed to be in accordance with IEEE C37.118 standards as mentioned in section 3.2.

Ability of UKF to work as a robust filter requires reading each coming messages and update its estimation with execution time interval equals to the sampling time of interval (0.02/80 second) or with more resolution of (0.02/256 second). Increasing the number of nodes and using a resolution of 0.02/256 second has a deep impact on the computational time that UKF needs to compute Phasors of all measuring nodes and this shortage can be avoided by using a high speed computer.

4. Tests and Discussions

In this section, the impact of network error such as insufficient Bandwidth (BW) being assigned or clock errors such as offset or drift on PMU performance have been assessed. To assess the impact of those errors on performance of architecture proposed, several simulations were realized. These tests will show how the percentage error of magnitude and angle provided by PMU will change time.

[1] S/C is Samples per Cycle

4.1 Effects of BW on DSE Performance

The functionality of UKF is depending on that there is no loss of messages that received every update and can update its state before the next message be available. When the operation of UKF depends on the message provided by measuring nodes that using insufficient Bandwidth, this can cause that some of the samples to be lost before they are received by UKF node.

In turn, assigning sufficient BW to nodes that send the messages that are required by UKF will assure best estimation of the signals that are acquired and sampled. Both sampling frequencies that being defined in section II (SMV#1= 80 S/C and SMV#2= 256 S/C) are used in this test. Here, the application of PMU depends on the UKF which in turns depends on the quality of received measured signals.

Working with the higher sampling rate means better quality but more computational effort will be needed to accomplish the task of estimating the phasor (estimation should be accomplished in less than 78 microsecond). The impacts of both BW and sample rate on the PMU performance are shown in Figures 3 and 4.

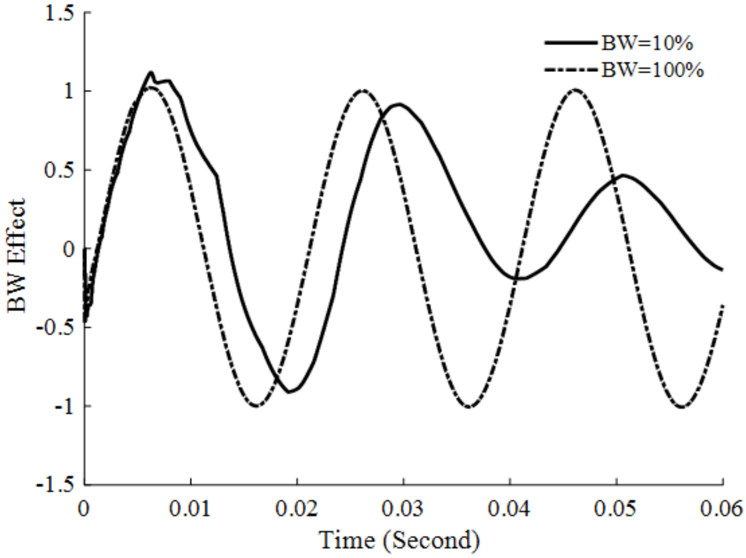

Figure 3. Effect of BW change on estimated signal with SMV#1.

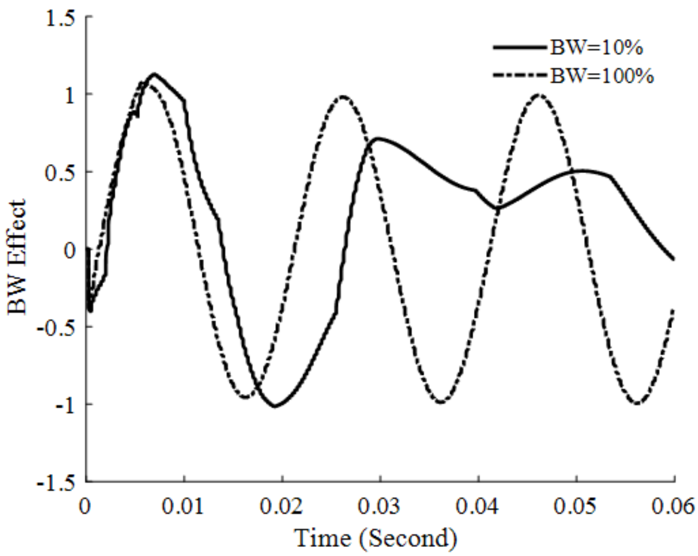

Figure 4. Effect of BW change on estimated signal with SMV#2.

4.2 Effects of Time Errors on DSE Performance

In power flow applications, determining the accurate difference between voltage angles is a crucial for power flow direction determination. Times errors may occur due to a synchronicity between nodes which arise from clocks offset and drift errors must be corrected. As mentioned before, C37.118 Standard forces critical synchronism requirements. To keep the TVE below 1% threshold, highest error allowed for phasor angle is 0.57° on a 50 Hz nominal frequency. It is easy to see that a time error of 10 μs can lead to a phase error of 0.18°.

Functionality of PMU depends on that all clocks of nodes that perform samples are synchronized to one central clock (Master). In our configuration, the clock of the CCR represents the master clock. Error of clocks can deeply affect our PMU functionality and thus, must be handled. To test the impacts of time errors on estimated phasors at CCR node, different values of clock offset and drifts are assigned. These values start with a value of zero to emulate the perfect case whereas the clock of a measuring node is perfectly synchronized to the master clock (CCR node). Figures 5 and 6 show how the % errors in phasors (magnitude and angle) estimations, respectively are increased with increasing the value of clock offset from zero to a maximum value of 1 millisecond.

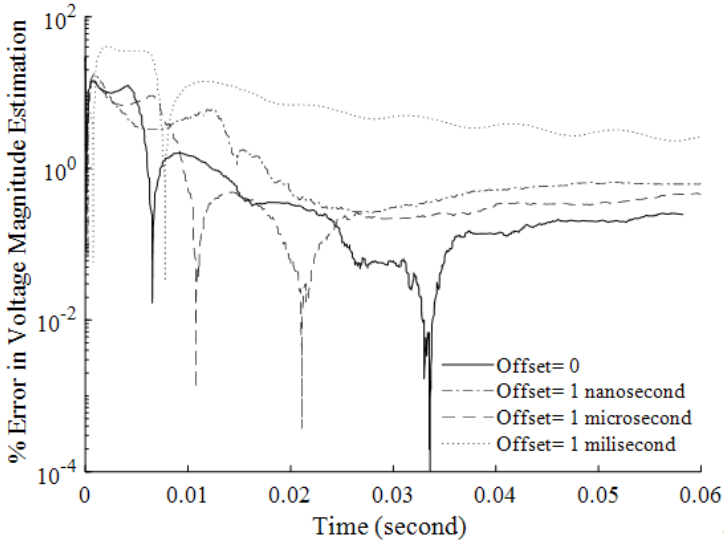

Figure 5. Effect of Clock Offset on % Error in Magnitude Estimation.

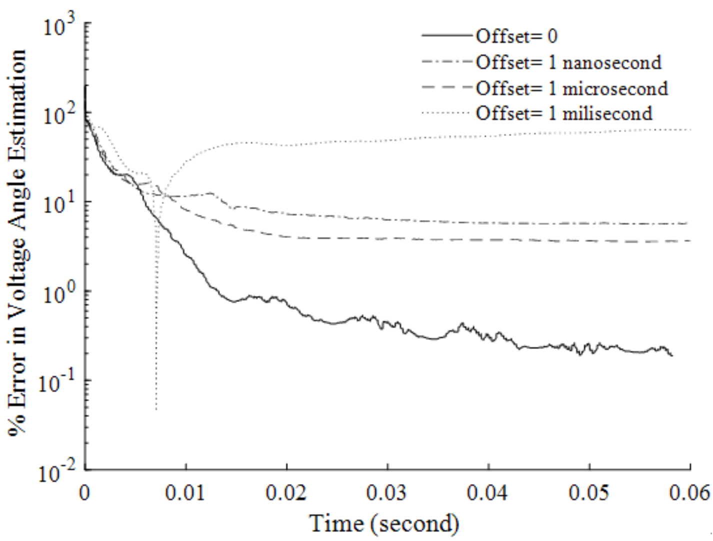

Figure 6. Effect of Clock Offset on % Error in Angle Estimation.

In Figure 6, the % error in voltage angle estimation seems more sensitive to clock offset than % error in voltage magnitude. % error in voltage magnitude estimation starts at about 50% while it starts at about 200% for angle estimation.

The other error that could arise and may affect the performance of PMU is the drift of a node clock. A node with time drift equals 0.01 means that the time of node clock runs 1% faster than the nominal time. Here, the worst case is assumed when the node has a time drift equals 10% faster. One selected node clock has been drifted with values faster than the master (node of nominal time). The effect of drifting this node clock on the estimated phasor is shown in Figures 7 and 8 below.

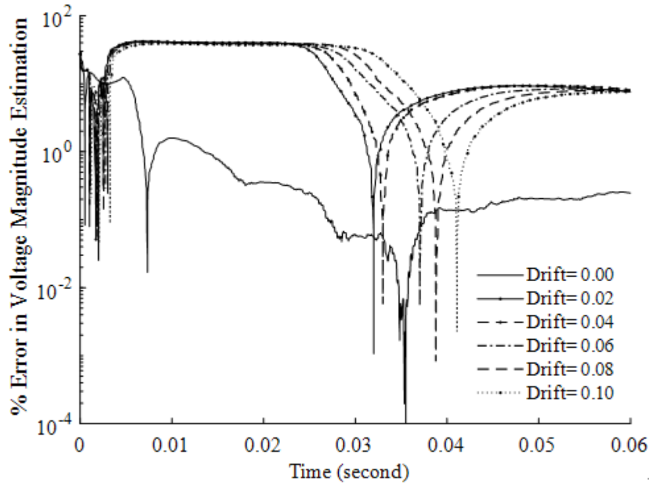

Figure 7. Effect of Drift on % Error in Magnitude Estimation.

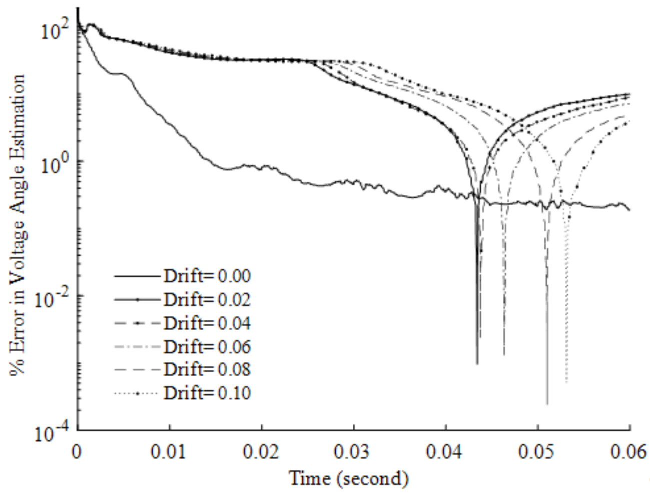

Figure 8. Effect of Drift on % Error in Magnitude Estimation.

These figures show how the drift can affect the % error in Phasors estimation in the node under consideration. The graphs show that % error in phasor estimation is increased with increasing the drift value. It is worthy to be noted that all graphs of % errors decrease rapidly and start to increase again at about 0.04s for magnitude and angle estimation. This value is the drift value that has been assigned in the test.

5. Conclusion

The implementation and performance evaluation of simulator for a Dynamic State Estimator based on IEC 61850-9-2 Sampled Measured Values have been presented in this paper. The computation of synchrophasors in substation by using the sampled measured values provide by substation process bus and to be used by the UKF in the centralized computation has been examined. Evaluating the effects of BW, the offset and the clock drift at each sensor node on the simulated Dynamic State Estimator performance are investigated. IEEE1588 Precision Time Protocol is suggested to handle the problems of synchronization due to the clock offset and drift. Simulations results showed that this proposed dynamic measurement system can be used as a new application and to add new function to the existing Substation Automation System.

References

[1] Abur, A. and A. G. Exposito. (2004). *Power system state estimation: theory and implementation*. 2004: CRC press.

[2] Zivanovic, R. and C. Cairns. (1996). *Implementation of PMU technology in state estimation: an overview*. In *Proceedings of IEEE. AFRICON'96*. 1996. IEEE.

[3] Rice, M. J. and G. T. Heydt. (2006). *Power systems state estimation accuracy enhancement through the use of PMU measurements*. In *Proc. 2006 Transmission and Distribution Conference and Exhibition*. 2006.

[4] Mackiewicz, R. E. (2006). *Overview of IEC 61850 and Benefits*. In *2006 IEEE Power Engineering Society General Meeting*. 2006. IEEE.

[5] Apostolov, A. (2010). *IEC 61850 9-2 process bus applications and benefits*. In *10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*. 2010. IET.

[6] Korba, P., M. Larsson, and C. Rehtanz. (2003). *Detection of oscillations in power systems using Kalman filtering techniques*. in *Proceedings of 2003 IEEE Conference on Control Applications, 2003. CCA 2003.* 2003. IEEE.

[7] Wood, H., N. Johnson, and M. Sachdev. (1985). *Kalman filtering applied to power system measurements relaying.* IEEE Transactions on Power Apparatus and Systems, 1985(12): pp. 3565-3573.

[8] Köse, N., Ö. Salor, and K. Leblebicioglu. (2011). *Kalman filtering based approach for light flicker evaluation of power systems.* IET generation, transmission & distribution, 2011, 5(1): pp. 57-69.

[9] Perez, E. and J. Barros. (2008). *An extended Kalman filtering approach for detection and analysis of voltage dips in power systems.* Electric Power Systems Research, 2008, 78(4): pp. 618-625.

[10] Anagnostou, G. and B. C. Pal. (2017). *Derivative-free Kalman filtering based approaches to dynamic state estimation for power systems with unknown inputs.* IEEE Transactions on Power Systems, 2017, 33(1): pp. 116-130.

[11] Wiltshire, R. A., G. Ledwich, and P. O'Shea. (2007). *A Kalman filtering approach to rapidly detecting modal changes in power systems.* IEEE Transactions on Power Systems, 2007, 22(4): pp. 1698-1706.

[12] Eidson, J. C., M. Fischer, and J. White. (2002). *IEEE-1588™ Standard for a precision clock synchronization protocol for networked measurement and control systems*. In *Proceedings of the 34th Annual Precise Time and Time Interval Systems and Applications Meeting*. 2002.

[13] Giorgi, G. and C. Narduzzi. (2011). *Performance analysis of Kalman-filter-based clock synchronization in IEEE 1588 networks.* IEEE transactions on instrumentation and measurement, 2011, 60(8): pp. 2902-2909.

[14] Martin, K., et al. (2008). *Exploring the IEEE standard C37. 118–2005 synchrophasors for power systems.* IEEE transactions on power delivery, 2008, 23(4): pp. 1805-1811.