Impact of Time-Synchronization Signal Loss on PMU-based WAMPAC Applications

M.S. Almas, and L. Vanfretti

***Abstract*—This paper experimentally assesses the impact of loss of time-synchronization signal on synchrophasor-based Wide-Area Monitoring, Protection and Control applications. Phase Angle Monitoring (PAM), anti-islanding protection and power oscillation damping applications are investigated. Power system models are executed using a real-time simulator with commercial PMUs coupled to them as hardware-in-the-loop. The experiments conclude that a phase angle monitoring application shows erroneous power system state whereas the operating time of an anti-islanding protection application increases due to the loss of time-synchronization signal input to PMUs. In addition, the performance of an oscillation damping controller degrades in the absence of time-synchronization input to the PMUs.**

***Index Terms*— Real-Time Hardware-in-the-Loop Simulation, PMU, Wide-area monitoring, protection and control (WAMPAC), Protection Relays, Synchrophasors.**

I. Introduction

PMUs provide synchrophasors for current and line voltages (for each phase and positive sequence) using a high-accuracy time system i.e. Global Positioning System (GPS) [1]. These synchrophasors are streamed out using the IEEE C37.118.2 protocol [2]. A wide range of synchrophasors-based applications are currently being deployed to provide a holistic view and allow for better control of power grids. The reliability of these applications depends on the accuracy of the synchrophasors computed by the PMUs, consequently relying on the precision of input time signals. The IEEE standard for Synchrophasor Measurements for Power Systems (IEEE C37.118.1-2011) [2] specifies a Total Vector Error (TVE) limit of 1%, which corresponds to a phase angle error of 0.573^0 (degrees) or a time synchronization inaccuracy of 31.8 μs at 50 Hz.

Commercial PMUs either receive the GPS signals directly through their GPS antenna installation, or through a GPS substation clock in the form of IRIG-B time-code signals [3]. Some of the PMUs are capable of receiving time synchronization signals through Ethernet using the Precision Time Protocol (PTP) [4].

Recent studies have shown that it is possible to launch a jamming attack targeted on a GPS receiver to block GPS signals [5] [6]. Similarly, time synchronization signal distribution using PTP is vulnerable to Denial of Service (DoS) attacks leading to interruption of the transmission of these signals to the PMU. It is therefore important to analyse the impact of loss of time-synchronization signals on synchrophasor-based applications to ensure the safe power system operation.

Literature has shown the effect of loss of time-synchronization signals on synchrophasor-based offline applications and real-time monitoring applications e.g. voltage stability monitoring and fault location [5] [6]. However, the impact of time-synchronization signal loss on more time-critical applications, such as synchrophasor-based protection and feedback control, is still in its infancy.

This paper investigates the effect of loss of time-synchronization signals on real-time power system monitoring, protection and control applications. Power systems modeled in MATLAB/Simulink are executed in Real-Time using Opal-RT's eMEGAsim Real-Time Simulator (RTS) [7] and real-time hardware-in-the-loop simulation is performed using commercial PMUs [8]. Analysis is performed for three different synchrophasor-based applications, i.e. phase angle monitoring, passive anti-islanding protection and wide-area oscillation damping control. For each of these applications, the case of malfunctioning of the application because of loss of time synchronization signals is analyzed.

The paper is organized as follows: Section II provides detail about Real-Time Hardware-in-the-Loop (RT-HIL) setup deployed for this study. Effect of loss of time-synchronization signal on PMUs' synchrophasor computation is discussed in Section-III. Section IV presents the three different synchrophasor-based applications and their performance assessment when subjected to a loss of time-synchronization signal. Finally, in Section V, conclusions are drawn.

II. RT-HIL Experimental Setup

In order to investigate the impact of loss of GPS time synchronization signals on synchrophasor-based monitoring, protection and control applications, a Real-Time Hardware-in-the-Loop (RT-HIL) simulation was carried out by utilizing two PMUs. Both PMUs were configured with identical settings and their CT and VT modules were bypassed to eliminate any difference in phasor calculation due to internal filtering and A/D converters, instead, PMUs were coupled to the RTS using low-level interface. The overall experimental test-setup is shown in Fig.1.

The power system model was executed in real-time using an Opal-RT RTS. Two identical sets of 3-phase voltage and current signals from selected buses were accessed through analog outputs of the RTS and were fed to each of the PMU using their low-level interface. Both PMUs are configured to receive IRIG-B time synchronization signals from a substation clock (Arbiter 1094-B) using co-axial cables. The substation clock itself was configured to receive GPS signals through a GPS antenna. Both PMUs were configured to stream out a

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similar synchrophasor datasets, i.e. voltage and current three phase phasors and their positive sequences. These PMU streams were concentrated and time-aligned in a Phasor Data Concentrator and were outputted as a concentrated PDC stream to different monitoring, protection and control applications.

The unwrapping of the PMU/PDC stream is done by Statnett's Synchrophasor Software Development Toolkit (S^3DK) [9] which is a real-time data mediator, which unwraps the PMU/PDC stream and provides access to the raw data wrapped inside IEEE C37.118.2 protocol [2]. Once the raw phasors are extracted, they are fed to different monitoring applications executed in workstations or different protection and control applications being executed in National Instruments Compact Reconfigurable I/O Controllers (NI-cRIOs) [10] as external hardware controllers. These controllers take protection/control actions using the synchrophasor measurements and provide trip signals and/or control feedback signals to the power system model in the RTS.

In order to analyze the impact of GPS time synchronization signal loss, the IRIG-B input to PMU 2 was disconnected at a given point in time. This resulted in imprecise synchrophasors computations by PMU 2 as compared to the reference PMU 1, which is continuously receiving IRIG-B signals from the substation clock.

III. Impact of GPS Loss on Synchrophasor Calculation

Figure 2 shows the positive sequence voltage phase angle, voltage phase angle difference and time synchronization error by PMU 2. At t=779.3 sec, the GPS signal to PMU 2 was disconnected. The top plot shows the voltage phase angle in degrees as measured by both the PMUs. The middle plot

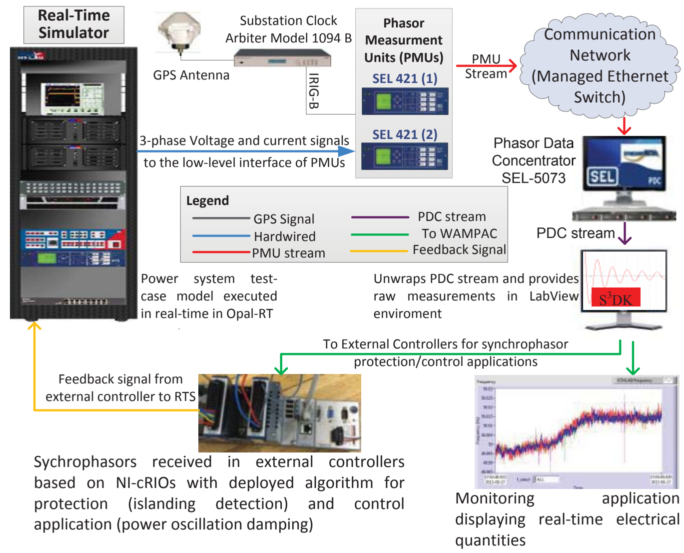

Fig. 1. Experimental setup to analyze the impact GPS signal loss on PMU-based monitoring, protection and control applications.

shows the voltage phase angle difference between PMU 2 and PMU 1. PMU 1 is the reference PMU which is continuously receiving GPS signals. The moment the GPS signal is lost at PMU 2, the voltage phase angle computed by PMU 2 starts deteriorating. The middle plot shows that within 1200 sec from the loss of GPS signal, the error in voltage phase angle calculation by PMU 2 exceeds 15 degrees. The bottom plot shows the time error signals retrieved from PMU 2. The "green" trace shows the moment at which the GPS signal is lost while the "red" trace shows the unlocked time where 1st step corresponds to an unlock time of 10 s, 2nd step refers to unlock time of 100 s while the third step indicates unlocked time of 1000 s.

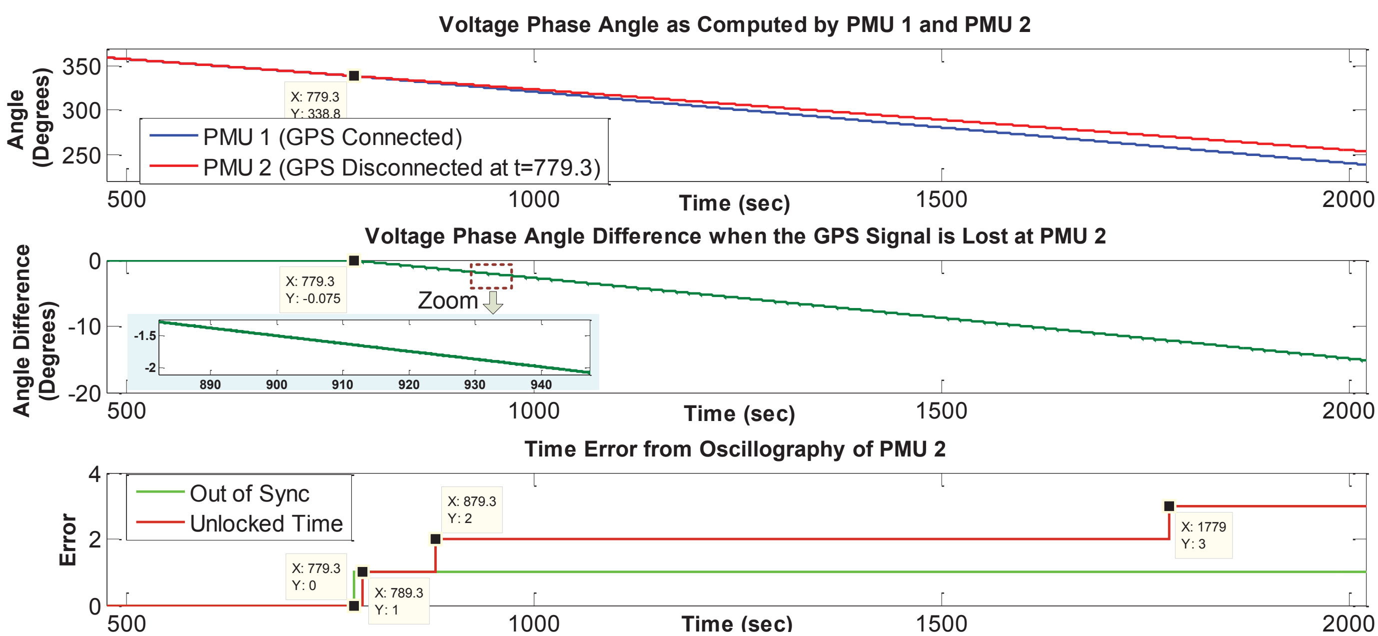

Fig. 2. Synchrophasors obtained from both PMUs under test. As GPS time synchronization signal to PMU 2 is lost, its error in voltage phase angle computation increases. The top plot shows voltage phase angle in degrees as computed by both PMUs, middle plot shows the voltage phase angle difference with respect to reference PMU 1. The bottom plot shows the time synchronization error corresponding to the time at which the GPS signal is lost and the associated unlocked time.

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IV. Impact of GPS Loss on WAMPAC Applications

This section analyses the impact of loss of time-synchronization signal on synchrophasor-based monitoring, protection and control applications.

A. Phase Angle Monitoring (PAM)

An important application of synchrophasor measurements is phase angle monitoring (PAM). The monitoring of phase angle differences between ends of transmission corridors reveals valuable information related to loading, power transfer through the corridor, etc.

The impact of time synchronization signal loss on PAM is analyzed on a variant of the Nordic-32 power system model [11], which is shown in Fig. 3. PMU-1 and PMU-2 are receiving three phase voltages and currents from Bus-38 and Bus-43, respectively which allow monitoring a major corridor between the *North* and the *Central* part of the network. The synchrophasors computed by these PMUs are used to develop a simple real-time PAM application in LabVIEW.

Figure 4 shows the GUI of the synchrophasor-based PAM application developed in SmarTS-Lab. At t=216.48 s, the time synchronization signal is disconnected from PMU-2. This results in an inaccurate phase angle computation by PMU-2 (Bus-43), and consequently leading to wrong computation of power transfer and line loading between the *North* and the *Central* part. As the PAM application shows, the loss in time synchronization signal shows an erroneous increase in line loading from 80% to 92 % and corrupts the power transfer between Bus-38 (*North*) and Bus-43 (*Central*) by showing an increase from 625 MW to 752 MW. All these impact on PAM application occur within a span of 550 s after the disconnection of time synchronization signal from PMU-2.

B. Passive Anti-Islanding Protection

A modified IEEE 3-machine 9-bus system [12] as shown in

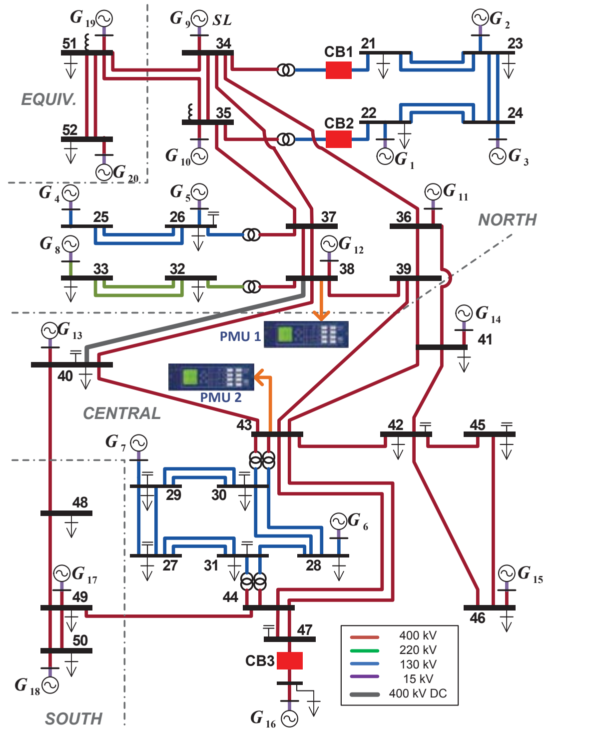

Fig. 3. Real-Time Nordic-32 power system model. PMUs are located at Bus-38 and Bus-43 which are feeding synchrophasors to PAM application.

Fig. 5 is used to study the impact of time synchronization signal loss on synchrophasor-based passive anti-islanding scheme. If CB-1a, CB-1b and CB-2a, CB-2b are opened simultaneously, this results in an islanding condition with G1 supplying electric power to Load A at Bus 5. Once the breakers are opened and the island is formed, this condition needs to be detected and the G1 needs to be disconnected from the isolated network within 2 seconds as specified by IEEE Std. 1547-2008 [13].

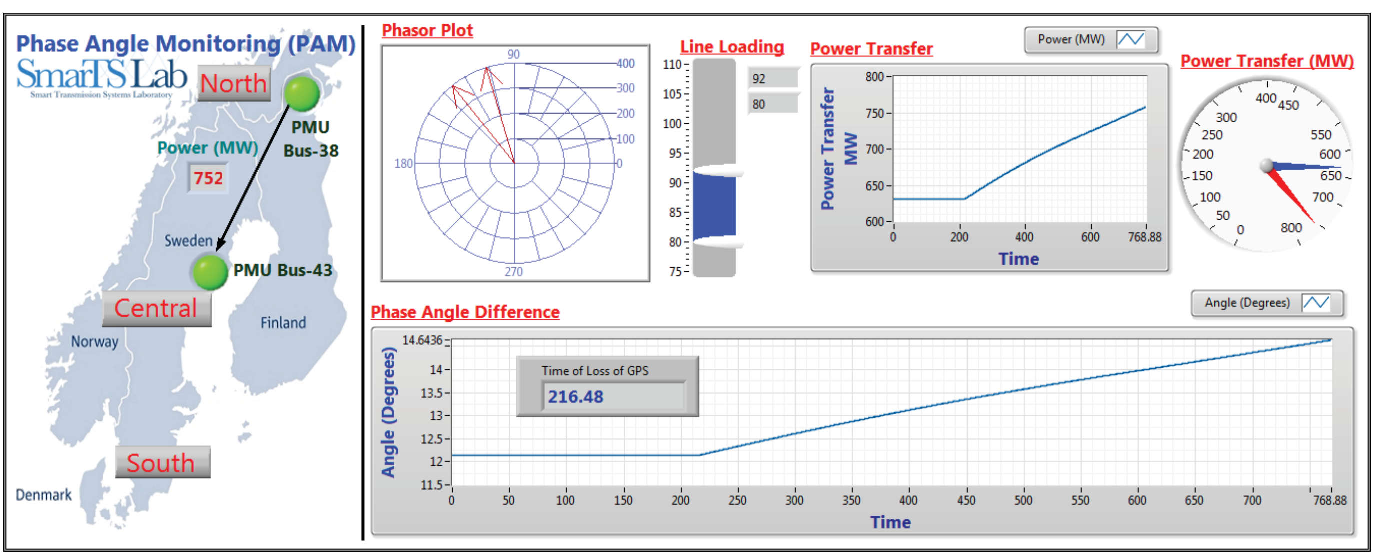

Fig. 4. Phase Angle Monitoring (PAM) application. (Left) shows the map of the Nordic region and the location of the PMUs in the *North* and *Central* region. (Right) shows the phasor plot for positive sequence voltage phasor from bus-38 and bus-43, transmission line loading, power transfer through the transmission line, phase angle difference at the ends of transmission line (38-43) and the time at which GPS signal is disconnected from PMU-2 (Out of Sync bit of PMU-2).

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PMU-2 is considered a local PMU (in the vicinity of G1) being fed with currents and voltages from Bus-4, while PMU-1 is a remote PMU installed at Bus-7 and streaming out synchrophasors at the same rate of 50 frames/s. A frequency-based anti-islanding protection algorithm is deployed using protection logic equations within PMU-2 by configuring it as a client for PMU-1 and using direct relay-to-relay communication between them [14]. Thus, PMU-2 processes the remote synchrophasor data, time aligns them with local data internally and makes them available for the passive islanding scheme.

This anti-islanding scheme detects an islanding condition and opens CB-3 if the difference between synchrophasor frequency computed by local and remote PMUs exceed 1 Hz and this condition persists for 10 cycles. Figure 6 shows the logic diagram of the frequency-based passive islanding detection algorithm and its respective logic equation programmed in PMU-2.

The operating time of the anti-islanding scheme is analyzed for two cases.

Case A: Both PMUs receive reliable time-synchronization signals from the same substation clock and the islanding scenario is initiated at t = 300 s.

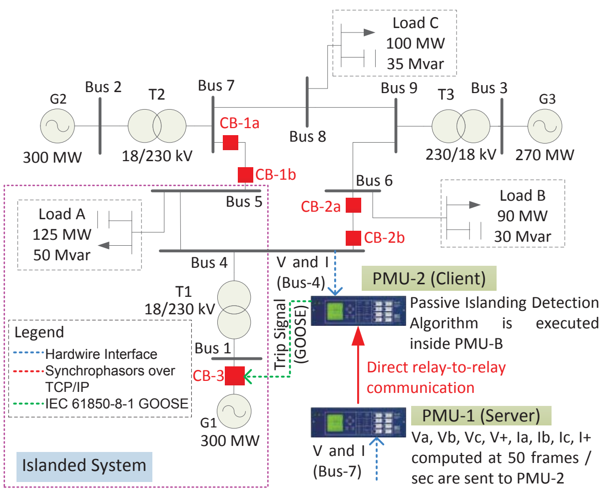
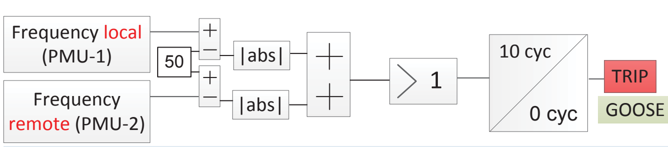


Fig. 5. IEEE 3-machine, 9-bus system. PMU-2 computes synchrophasors of Bus-4 and also receives synchrophasors of Bus-7 through PMU-1. The frequency-based anti-islanding protection scheme is incorporated within PMU-1.



PMV53 := FREQPM % Storing Local measured synchrophasor frequency in user defined analog value
PMV54 := RTCFA % Storing remote measured synchrophasor ROCOF in user defined analog value
PMV55 := 1 % Storing threshold value of 1 in user defined analog value
PSV01 := [Abs(PMV53-50) + Abs(50-PMV54)] > PMV55 % SET if difference between Local and remote synchrophasor frequency exceeds 1 Hz
PCT01IN := PSV01 % Input for conditioning timer. Timer tracks PSV01
PCT01PU := 10.000000 % Pickup is set to 10 cycles i.e. When PSV01 changes state from 0 to 1, the timer will pick it up only if the state of PSV01 stays at 1 for 10 cycles
PCT01Q : Timer output goes to 1 when the total time exceeds 10 cycles after the PSV01 is set

Fig.6. Logic diagram and protection logic equations used to deploy the synchrophasor ROCOF based islanding detection.

Case B: PMU-1 receives a reliable time-synchronization signal while the time-synchronization signal of PMU-2 is disconnected at t = 100 s and the islanding scenario is initiated at t = 300 s.

The operating time of the anti-islanding protection scheme for these cases with different active power mismatch between the G1 and the local load (Load A) is shown in Fig. 7. Due to the loss of the time-synchronization signal input to PMU-2, the protection operation time has increased by 1.022 s for 20 % active power mismatch and 0.62 s for 30 % active power mismatch.

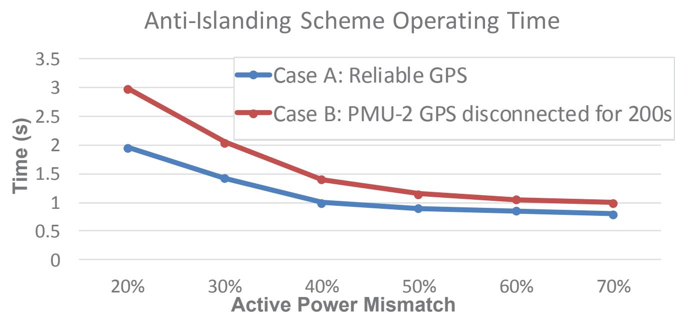


Fig.7. Effect of loss of time-synchronization signals on the operating time of the synchrophasor-based anti-islanding protection scheme.

C. Wide-Area PMU-based Oscillation Damping (WAPOD) Control

To analyze the impact time-synchronization signal loss on synchrophasor-based control applications, the performance of a wide-area PMU-based oscillation damping controller is investigated. The phasor-based oscillation damping algorithm [15] is deployed in National Instrument's Compact Reconfigurable I/O controller (NI-cRIO). This NI-cRIO receives local and/or remote synchrophasors as inputs, it processes them and separates the resulting controller input signal into an average and oscillatory content using recursive least square filter. The oscillatory content of the signal is phase shifted to create the damping signal. This damping signal is provided as a supplementary stabilization signal to the Automatic Voltage Regulator (AVR) of G1 executing in real-time in the RTS to provide damping.

A 2-area 4-machine Klein-Rogers-Kundur power system model as shown in Fig. 8 is used for this analysis. This power system model is inherently unstable due to an un-damped 0.64 Hz mode. This model is executed in real-time using 4-cores of Opal-RT's eMEGAsim RTS. The three phase voltages and currents of Bus-1 and Bus-2 are fed to the low-level interfaces of PMU-1 and PMU-2, respectively. The PMUs compute synchrophasors and stream them out using the IEEE C37.118.2 protocol. These PMU streams are time-aligned and concentrated using a Phasor Data Concentrator (PDC). The PDC stream is unwrapped using Statnetts' Synchrophasor Software Development Kit (S^3DK) which provides raw phasors data to the PMU-based Oscillation Damping (POD) controller. The POD executes damping algorithm using the synchrophasor measurement selected as an input, and provides a damping signal as an output through its analog output module (NI-9264). This damping signal is fed back to the RTS as an additional input to the AVR of G1 to provide damping.

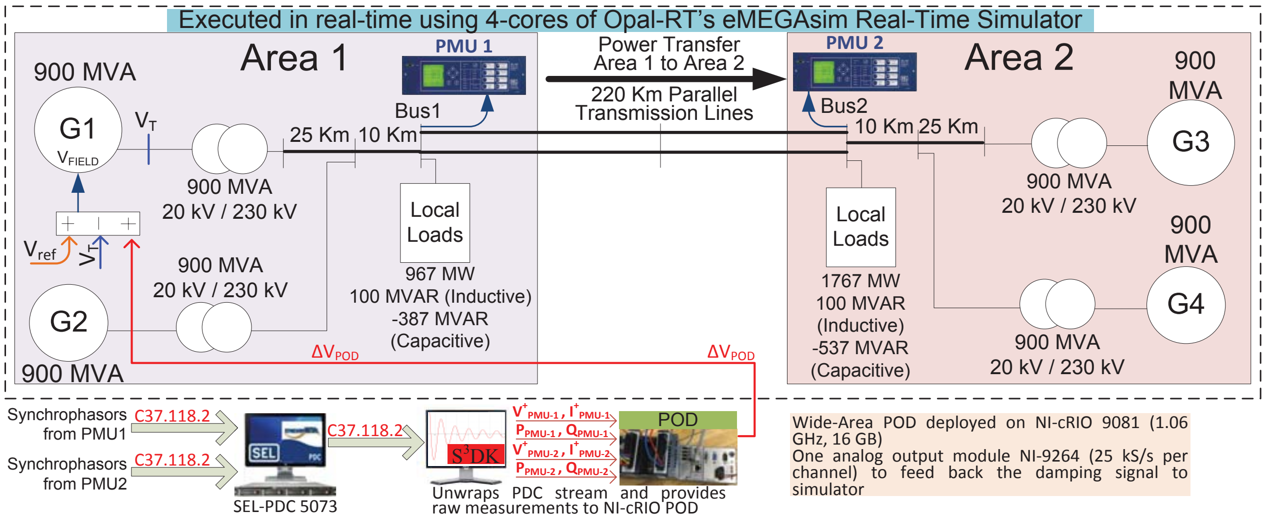


Fig.8. 2-area 4-machine Klein-Rogers-Kundur power system modelled in MATLAB/Simulink. PMU-1 and PMU-2 are hardware PMUs from SEL (model SEL-421) receiving three phase voltage and currents from Bus-1 and Bus-2. These synchrophasors are received in POD controller which provides damping signals to the AVR of G1 in real-time.

In order to analyze the performance of the WAPOD, the voltage phase angle difference (which is computed as a difference in positive sequence voltage phase angle between PMU-1 and PMU-2) is selected. As shown in Fig. 9, with the WAPOD disabled, the 0.64 Hz inter-area oscillation is undamped. With reliable GPS signals to both PMUs, the oscillations are adequately damped. However, the performance of the WAPOD degrades as the GPS disconnection time for PMU-2 increases primarily because of the erroneous phase angle computation by PMU-2 due to loss of time synchronization.

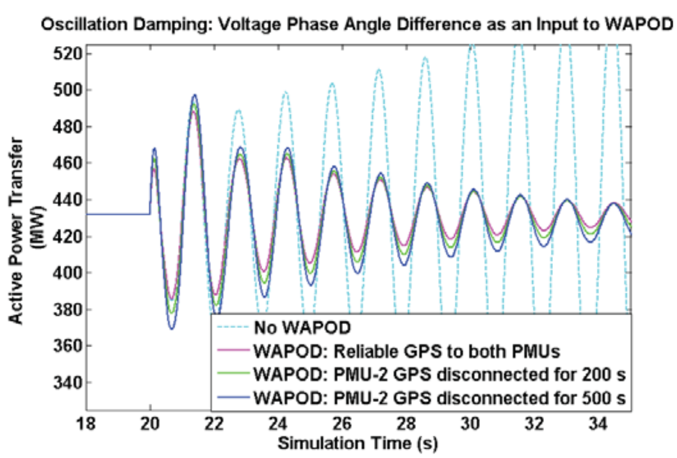


Fig.9. Performance of synchrophasor-based WAPOD controller when subjected to loss of GPS signal.

V. Conclusions

This paper presented the effect of loss of time synchronization signal on synchrophasors-based WAMPAC applications. The GPS system can be interfered both intentionally and/or cosmically. Therefore, it is paramount to investigate the effect of loss of time-synchronization signals on these applications.

When the GPS signal is lost, the PMUs rely on their local oscillator to compute synchrophasors. The local oscillator frequency drifts due to temperature variations and mechanical vibrations, thus providing inaccurate time stamps for synchrophasor computation, which is reflected in the form of erroneous phase angle computation by PMUs.

By performing RT-HIL simulations with commercial PMUs, this paper concludes that loss of time-synchronization signal results in corrupted power system monitoring results, delayed protection activation and degradation of wide-area controller performance.

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