Hardware-In-the-Loop Use Cases for Synchrophasor Applications

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***Abstract*— This paper presents use cases for applying Hardware-In-the-Loop (HIL) simulation in the development, testing and validation of PMU devices and synchrophasor-based applications. The use cases include PMU compliance testing, Wide Area Monitoring, Protection and Control (WAMPAC) systems testing, as well as vulnerability studies involving cyber-attacks and GPS spoofing. Real-Time Simulators (RTS) provide powerful system modeling capabilities and versatile interfaces with hardware devices and communication networks. Through the use cases, the RTS has been proven to be a useful tool for testing synchrophasor-based applications. In the paper, typical testing architectures and the advantages of using HIL are discussed.**

***Index Terms*— real-time simulator; Hardware-In-the-Loop; phasor measurement units; closed-loop testing; compliance test; wide area monitoring, protection and control; cybersecurity; model-based testing.**

I. INTRODUCTION

Phasor Measurement Units (PMUs) are the devices which produce synchronized phasor, frequency and rate of change of frequency estimates from voltage and/or current and a time synchronizing signal. The first prototypes of PMUs using Global Positioning System (GPS) were built in the early 1980s; however, it is only during the recent decade that the adoption of synchrophasor technologies has greatly increased in North America, primarily thanks to the Smart Grid Investment Grant Program [1]. PMU applications include state estimation, fault localization, inter-area oscillation monitoring, model parameter tuning and validation, and provide many other wide-area monitoring protection and control (WAMPAC) functions. However, the amount of PMU applications beyond wide-area monitoring that are deployed in the field is still relatively low. A proven approach to the development of such applications is the use of Hardware-In-the-Loop (HIL) simulation. It allows to develop proof of concept for new devices and tools, to evaluate the accuracy and reliability of integrated solutions through testing and to perform certification or pre-commissioning tests.

This paper presents use cases and test setups where HIL simulation has been used to develop new synchrophasor applications, test under different scenarios, and finally validate the performance. Hence, this paper aims:

- To present use cases in the use of HIL for compliance testing of PMUs.
- To present use cases in the use of HIL for application-oriented studies of PMUs.
- To present use cases in the use of HIL for cybersecurity studies of PMUs

The rest of this article is organized as follows. Section II provides a literature review on PMU testing requirements, previous work of using HIL for synchrophasor application studies and the benefits of using HIL. Section III describes different HIL testing architectures, while Section IV presents results of PMU functional testing using HIL to determine compliance to requirements. Section V gives an example of HIL testing of a synchrophasor-based control algorithm. In Section VI HIL cases where impairment of communication network and time synchronization can be studied are described. Finally, Section VII draws conclusions and outlines future work.

II. BACKGROUND

A. *PMU Testing Requirements*

Multiple PMU calibration and testing studies have been conducted over the last decade, prior to the official publishing of the IEEE Standards in 2011, which are briefly summarized next. Paper [2] introduces a study on a power network with 22 installed PMUs with different characteristics. The study focuses on the characterization of synchrophasor measurements, quantification of the error and potential compensation of errors on attributes such as the rise-time, the amplitude, the angle error, etc. In paper [3], a laboratory-developed PMU device is tested and compared with a commercial PMU under various test scenarios, including a steady-state test, a modulation test, and a dynamic test with harmonic injection. In a more formal process, a test program was developed in Brazil in 2012 to perform the certification test on the PMUs from eight different vendors [4]. The project was categorized into three test aspects: steady-state, dynamic, and interoperability.

In response to these and other efforts, new industry standards are developed to provide the guidance and support for validation, testing, installation, and implementation of PMUs. The current test requirements for PMUs performance are specified in the IEEE standard C37.118-2011 with its latest amendments IEEE C37.118.1a-2014. They specify how the phasors should be measured and define the methods for evaluating PMUs in both steady-state and dynamic conditions [5] and [6]. Another IEEE standard C37.242-2013 covers the testing and calibration procedures for PMUs in both laboratory and field environment [7]. In 2015, the second version of IEEE Test Suit Specification (TSS) was published for synchrophasor measurement, which provides organizations that are testing PMU performance with a suite of unambiguous test plans along with the interoperability features [8].

Besides, the International Electrotechnical Commission (IEC) TC57 also published a section IEC 61850-90-5 in 2012 to provide an IEC 61850-compatible way of sending and receiving phasor data between PMUs, Phasor Data Concentrators (PDCs), WAMPAC, and control centers [9]. Furthermore, the North American Electric Reliability Corporation (NERC) has developed a series of standards for Critical Infrastructure Protection (CIP), known as CIP-002 to CIP-014. Applications that use PMU data are contained inside the control system located at either a field location or at a control center, and cybersecurity of those applications is assured by securing the cyber assets that house the data and applications [10].

While these standards help in better PMU functionality, there are new testing aspects and methods that have so far not been considered. An RTS, besides being used to implement all the standard tests, can also help in developing new tests, such as studying the impacts of time synchronization impairment [11], which can be critical in the validation of synchrophasor applications.

B. *RTS Capabilities*

A modern RTS is a digital model-based simulator that can precisely and accurately mimic the response of an actual physical system in hard real-time [12], and it has been proven to be a powerful tool in power system research and studies for several decades. HIL implies the use of an RTS with hardware device or control algorithm in the loop.

The RTS is capable of simulating a wide range of transient frequencies for different applications, as explained in [12] and shown in Figure 1. For synchrophasor studies, a real-time transient stability simulation tool ePHASORsim [13] is available for modeling large-scale power systems in the phasor-domain to perform system contingency studies, testing control devices and SCADA systems. A model predictive controller (MPC) is validated in [14] for a large-scale transmission network with 5000 buses in ePHASORsim using C37.118.2 protocols. Meanwhile, other synchrophasor studies such as Wide-Area Protection [15] might require to model the power grid's behavior with higher granularity than that of transient stability simulation, as illustrated in Figure 1. To that end, the RTS can be used to deploy three-phase, unbalanced, and Electromagnetic Transient (EMT) simulations by using tools such as MATLAB-based eMEGAsim [16] or HYPERSIM [17].

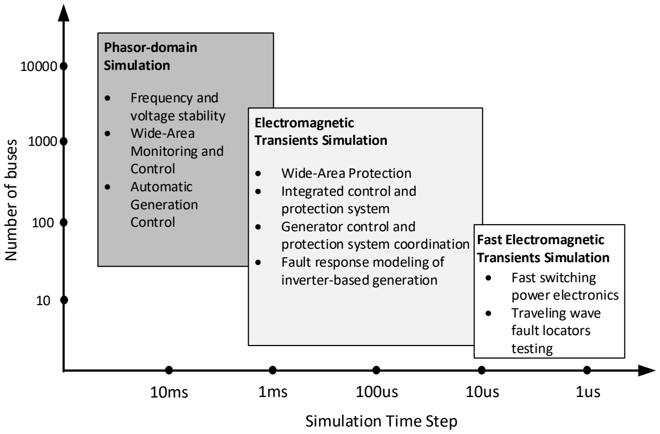

Figure 1 Simulation speed and model complexity by applications

C. *Using RTS for HIL Testing of PMUs and Synchrophasor Applications*

Beyond PMU unit testing, many PMU-based application studies were also performed in the HIL environment. For all the studies discussed below, an RTS is used to simulate various power network conditions to test the performance of algorithms and new applications. In the area of power system monitoring, example study cases of different types of mode estimation algorithms evaluation are presented in [18], [19], [20], and [21]. Also, methods for PMU-based voltage stability monitoring have been proposed in [22] using model-free algorithm based on the data from PMU and in [23] using real-time equivalent Thevenin models. In [24], a new special protection scheme (SPS) for maintaining voltage stability after events resulting in large voltage drop using local and wide-area network PMU measurement was proposed and tested. HIL real-time simulations are performed to first evaluate the PMU accuracy and response and then to prove the reliability, robustness and security of the SPS algorithm. In these case studies, RTS is used either to simulate the power system networks and interface with real PMU devices or to provide phasor data directly.

While the focus of power system monitoring applications has been in those for transmission grids, active distribution networks [25] and microgrids can also exploit synchrophasor technology. [26] presents a novel PMUs placement algorithm based on a Mixed Integer Linear Programming (MILP)-optimization algorithm. The real-time performance of the algorithm was verified on an OPAL-RT simulator. In the active distribution network operation, [27] presents a method to estimate a real-time equivalent model of the grid which was developed using HIL, and later validated using both HIL and an actual distribution feeder. In these emerging areas, the use of HIL is indispensable, as it allows to develop new PMU applications for systems that have not yet been built while considering the different complexities involved in active distribution networks by using detailed models as in [28] and [29].

D. Benefits of Using HIL

The main advantages of using RTS in PMU studies can be summarized in three categories:

1. Model-based design

Modern digital RTS offers the flexibility to model various power system configurations by using the generic or specific, average or detailed models of power system equipment. In addition, in some cases, an RTS may offer open development environment that is available to every user involved in creating a system during different stages.

2. Efficiency, repeatability and better test coverage

Many PMU applications are based on real-time precise phasor measurement in rapid response to any network condition changes. The use of an RTS allows the user to plan various dynamic network operating conditions, to create different testing scenarios and to apply diverse contingencies and perturbations for better test coverage. Since the model can be modified in real-time, users can achieve high efficiency with test automaton. The RTS testing experiments are repeatable because the testing conditions and operating scenarios only depend on the model and are under tightly controlled laboratory conditions when using HIL.

3. Interaction between RTS, PMUs and other devices under test

An RTS has multiple interface modules. It can be connected to external hardware devices through analog and digital channels. It also supports a variety of communication protocols including IEEE C37.118.2. Furthermore, an RTS also provides full data availability feature, which means any model data is accessible during execution, and users can use the real-time data for their specific application purposes.

III. HIL TESTING ARCHITECTURES

As discussed in the previous section, an HIL test bench is a powerful tool for PMU testing and synchrophasor application studies. For general protection and control system testing, 50µs to 100µs is a sufficient time step for simulating most electromagnetic phenomenon, power system dynamics, and "ambient" operating conditions.

In the case of PMU unit testing, the voltage and current measurements from the simulated model are sent out through analog channels as time-domain sinusoidal waveforms to the PMU under test, as shown in Figure 2. The PMU device calculates the phasor and the frequency data and reports the data in the format of IEEE C37.118.2 protocol back to the simulator to compare with the reference. In the case of synchrophasor-based monitoring applications, the C37.118 messages can be collected by a PDC and be further transferred to the control algorithm.

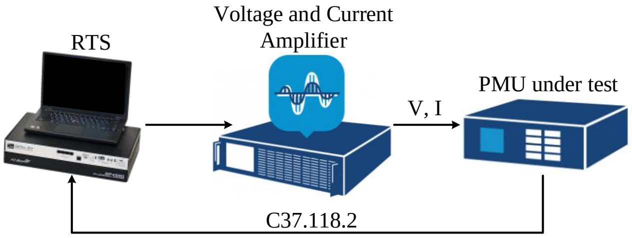

Figure 2 Basic architecture for PMU testing

An RTS also allows exploiting virtual PMU models. This minimizes the effort of hardwiring and/or configuring actual PMU devices, which can be time-consuming, while still providing the same functional value of PMU data streams. In this case, virtual PMUs can be added to the power system network to be simulated in real-time to calculate phasor measurement as a real PMU device with the option of both P and M class. Real-time data streams can be forwarded outside the simulator by using an IEEE C37.118 driver available on the simulator. This driver can be configured to package the data into C37.118 streams with the required reporting rate up to 240 frames per second. In addition, virtual PMUs can be used together with hardware PMU devices to implement validation and testing of WAMPAC schemes, as shown in Figure 3.

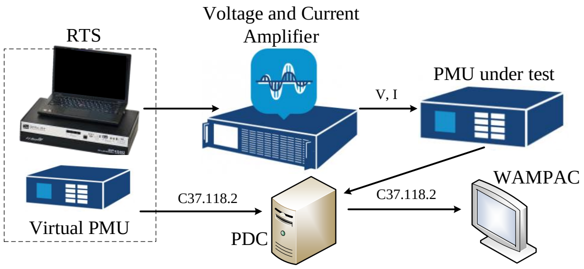

Figure 3 Architecture for PMU study with virtual PMU and PDC

Another common practice with synchrophasor-based applications is to study the electromechanical phenomenon of the power system. Voltage and frequency stability, state estimation and system model validation are among the main key areas for new applications. In this case, a positive-sequence-based phasor-domain model in tools like ePHASORsim [13] allows simulating very large networks. The RTS makes available the outputs at each fixed step iteration, and as these are already computed in phasor, they can be directly mapped to the C37.118 driver on the simulator to transfer as data streams, as illustrated in Figure 4.

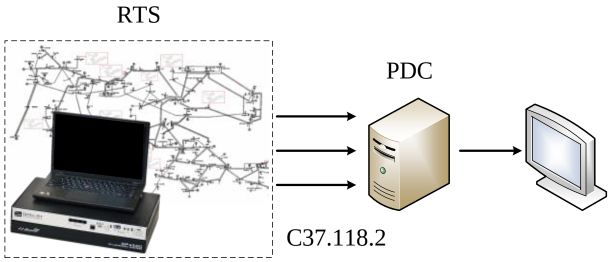

Figure 4 Architecture for PMU study with ePHASORsim

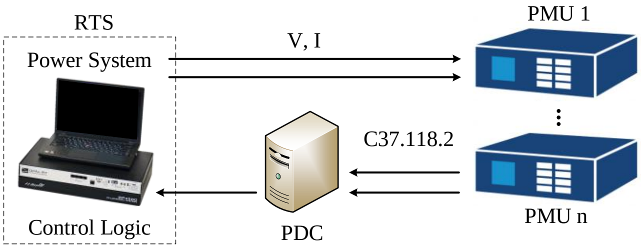

Figure 5 Architecture for PMU study with RCP

Finally, an RTS can be used to perform Rapid Control Prototyping (RCP), as a proof-of-concept for control algorithms, as shown in Figure 5. Because the IEEE C37.118 master driver is available on the simulator, it can be used to receive data from a PDC or multiple real/simulated PMUs to test and validate control algorithms.

Time synchronization is also essential for PMU-based applications and will be discussed in Section VI.

IV. PMU COMPLIANCE TESTING

To ensure the measurement accuracy of PMU devices is crucial for users since the subtle shift in phase angle may corrupt PMU signals and/or trigger a false alarm in a monitoring application. An RTS test suite has been developed in HYPERSIM [30] to automate the tests defined in IEEE C37.118-2011 standard. All test cases are pre-defined in an excel spreadsheet which is read by HYPERSIM TestView to load the test parameters. Comprehensive test report with pass-fail criteria is generated automatically at the end of the tests. The test automation workflow is shown in Figure 6.

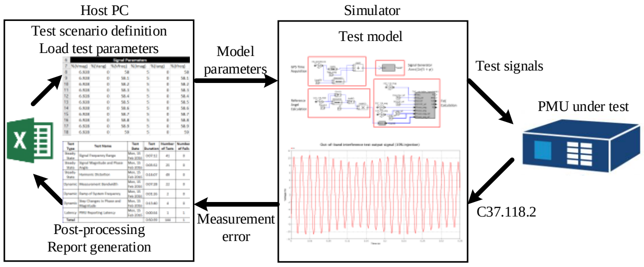

Figure 6 Workflow of test automation in HYPERSIM

Test results with multiple PMU devices from different manufacturers have been obtained using this platform and presented in [31]. Some example results from steady-state tests and step change tests are shown in Figure 7 and Figure 8. In total 5 different PMU algorithms are tested, all M class but with different reporting rates. Figure 7 presents the maximum Total Vector Error (TVE) values of each PMU under test in steady state tests and frequency ramp tests, all PMUs are compliant. Furthermore, the test results also reveal the relationship between the reporting rates and the TVE performance. For a specific PMU algorithm, a higher reporting rate will result in a significant improvement of TVE performance in the frequency ramp test, but a slightly better or very close TVE performance in other types of tests. For example, for the PMU A, the TVE decreases from 0.7% to 0.2% when the reporting rate is changed from 10 frames/s to 240 frames/s.

Figure 8 shows the TVE response during a phase angle step test. All TVE response times are within the limit which is 7/Fs, where Fs is the reporting rate. In addition, it can also be observed from the test results that for different reporting rates, the maximum TVE values are very close; however, regarding the overall TVE performance, a higher reporting rate will produce a shorter TVE response time than that of a lower reporting rate.

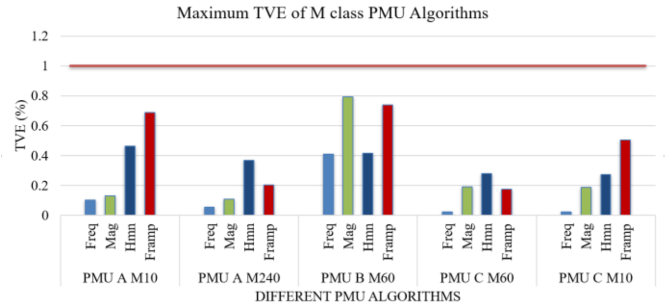

Figure 7 Maximum TVE of M class PMU algorithms under frequency & magnitude, harmonic distortion and frequency ramp tests.

During the step change tests, it is found that for 10 frames/s, the procedure of having 10 test points during 1 second is not sufficient and may introduce false failure result, especially for P class. For example, when testing with 10 test points, the step response time of a P class PMU under test is 34.167 ms, which is higher than the limit; however, the test result becomes 28.667 ms which is compliant, by only increasing the number of test points to 20, as shown in Figure 9.

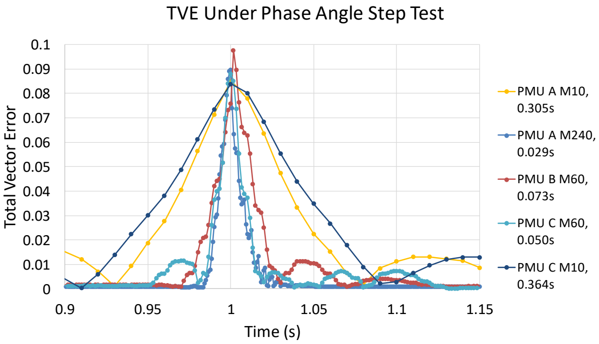

Figure 8 TVE responses under step change tests

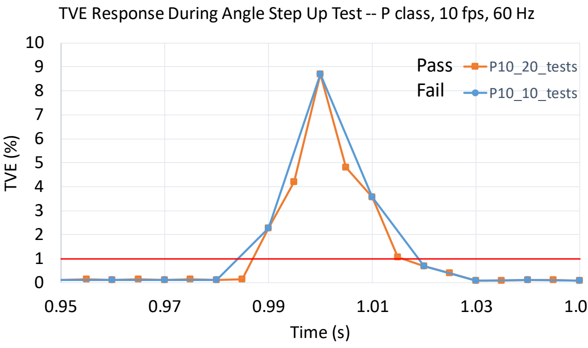

Figure 9 TVE response time results with different number of test points

The previous results were obtained using low power signals, which means the RTS analog outputs are directly connected to the low voltage test interface of the PMU devices. This is not uncommon, as it is an easy and economic testing solution for universities and research labs. However, to be compliant to the standard and evaluate the complete input processing modules of the PMU devices, power amplifiers are required in the loop to drive the low power voltage signals from the simulator to the level of nominal voltage and current inputs of the PMU. In this case, the input/output delay and the bandwidth of the amplifiers are critical values to be assessed. If the amplifier has a long step response time or a narrow bandwidth, the results obtained for the PMU may not be accurate.

Therefore, when working with an RTS with amplifiers in the loop, amplifier performance assessment and calibration is necessary to rule out the uncertainty introduced by the amplifier. This should be taken into consideration in all PMU applications when amplifiers are in use. To illustrate this issue, in Figure 10, the harmonic distortion test results with and without amplifier from the same PMU device are compared. The amplifier uncertainty is well tested and compensated from the simulator outputs. As a result, the TVE obtained from the two tests are similar. Even though the simulator analog outputs are not calibrated for PMU tester level, which is 10 times more precise than the required PMU accuracy, it's still enough to identify design flaws in PMU algorithms, which in most cases results from different filter implementations. The test setup can be used to validate and pre-certify the PMU algorithms, that is to determine if a PMU can potentially pass compliance tests before sending the device for certification, thereby substantially reducing development costs.

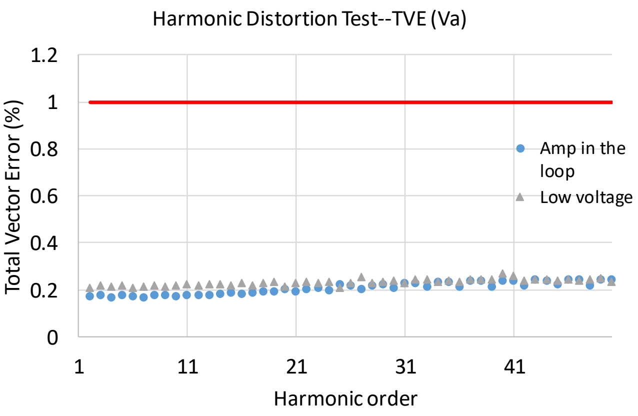

Figure 10 Test results under harmonic distortion tests

V. SYNCHROPHASOR APPLICATION TESTING USING HIL

As introduced in Part I, many synchrophasor applications including state estimation, stability monitoring and wide-area control algorithms can be designed, tested and validated using one of the architectures explained in Section III. Here, the use case in [32] serves to illustrate the use of these architectures.

As shown in Figure 11, a Wide-Area Damping Controller (WADC) prototype, which feeds a damping signal generated from wide-area PMU measurements to a commercial Excitation Control System (ECS) is tested in an HIL environment. Figure 11 illustrates how the RTS is interfaced with PMU hardware devices and how the control signals are processed and brought back to the RTS for closed loop control.

On the RTS, a two-area power system with three generators is simulated in real-time. Voltage and current measurements are sent out through the analog channels to the external devices. Among all the signals, the generator terminal voltage and stator current are amplified to match the nominal input level on the ECS. The excitation control signals from the ECS are fed to the simulator and are connected to one of the generator models. In the model, various perturbations were applied, either local oscillation or inter-area oscillation scenarios are created to test the response of the WADC against the built-in Power System Stabilizer (PSS) in the commercial excitation system. The test results show that the built-in PSS is only tuned for local mode and does not damp in an inter-area oscillatory mode, whereas the synchrophasor-based damping signals from the WADC provide adequate damping in both scenarios [32].

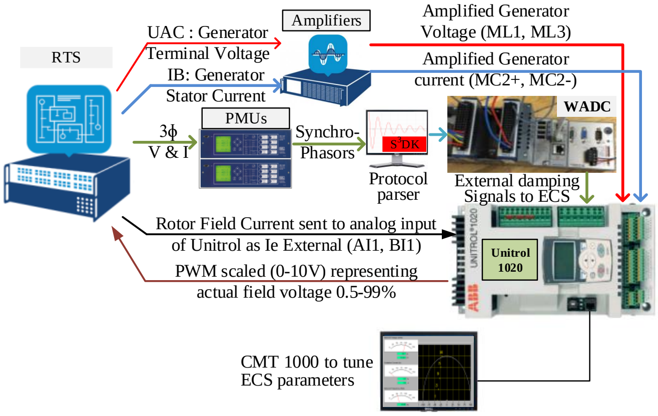

Figure 11 HIL setup for WADC testing **[32]**

This use case underlines the need and advantages of performing HIL testing during validation of synchrophasor applications, especially when real-time wide-area control is considered. First, it's necessary to have the power system model to execute in real-time and to perform the test in a closed-loop fashion. ECS testing is not possible in an open-loop test environment, particularly when considering damping control functions. The system behavior must be adjusted according to the ECS control parameters and at the same time the control parameters will impact the system's measurements, which makes using an RTS the only viable option other than "in-situ" field testing.

Furthermore, compared to a purely off-line software simulation-based validation, the utilization of an HIL setup brings multiple advantages. To start, the communication latency of the wide-area network can be properly represented by connecting the PMU hardware devices with a PDC and configuring the network. A network emulator can be added if required. It is important to address the latency issue since introducing an undetermined time delay to the inputs of a control algorithm can have great impact on the results. In this specific WADC, a communication latency compensation module is implemented to compensate for any potential phase angle offset. To continue, HIL architecture fills the gap between the physical layer, meaning the simulation of power system components, and the communication layer, making it an integrated testbench for a variety of tests. Cybersecurity analysis would be the next natural study to follow for this kind of application, which will be discussed in the next section.

In sum, this use case illustrates how the HIL setup is indispensable for the validation of an actual control hardware prototype. A hardware implementation of a control algorithm helps to optimize the controller's performance when subject to realistic operating conditions within HIL. The implementation process requires to take into consideration the constraints of the computational capability of the existing hardware devices on which the control algorithm will execute, which is discussed in [32]. Other constraints such as sampling rate, number of inputs and outputs, signal characteristics, make the design more practical and easier to be deployed on existing devices available on the market. HIL testing, at the same time, provides the most realistic scenarios to validate the design.

VI. CYBERSECURITY TESTING

Synchrophasor applications rely on wide-area networks, which makes cybersecurity an inevitable topic to address. The architectures presented in Section III can also be applied in use cases regarding cybersecurity. To illustrate this, this section introduces a use case, presented in [33], of evaluating the impact of time synchronization spoofing attacks (TSSA) on synchrophasor-based WAMPAC applications. Several synchrophasor applications are investigated, which include Phase Angle Monitoring (PAM), anti-islanding protection, and Power Oscillation Damping (POD). An HIL test setup is deployed to simulate the power network and initial the real-time TSSA through the IRIG-B timing signals.

A. *The vulnerability of PMUs from TSSA*

PMUs are designed to be capable of receiving time-synchronization signals in a number of ways, with the most common way being Inter-Range Instrumentation Group Code B (IRIG-B) format, but also include other protocols, such as Pulse per Second (PPS) or Precision Time Protocol (PTP). During a TSSA event, the time-synchronization signal receiver of a PMU can be deceived by broadcasting impaired signals or by rebroadcasting the signals captured at another time [34]. As a result, the PMUs under attack will compute false synchrophasors which may be against the specific requirements and limits from IEEE C37.118 and other standards; and eventually it will cause the maloperation of PMU-based WAMPAC applications. It is therefore important to analyze the vulnerability of TSSA on PMU-based applications and understand the potential negative impacts on power system operation and controls.

B. *Cybersecurity HIL Setup*

The detailed test bench for HIL simulation is demonstrated in Figure 12, which includes a 4-core OPAL-RT eMEGAsim RTS to simulate the power network and IRIG-B time code signal generation, two commercial PMUs, and a computer-based PDC. One PMU is considered as the reference by receiving the authentic IRIG-B signals from a GPS-based substation clock, while the other PMU is attacked by TSSA by spoofing the IRIG-B signal through the RTS. The PMUs are coupled to the RTS using a low-level energy interface for safety and in order to eliminate any phasor calculation difference caused by the amplifiers' internal filtering and A/D converters.

The trip commands from the PMUs are generated in IEC 61850-8-1 GOOSE format. The RTS subscribes to the GOOSE messages published by the PMUs and then uses them to open the circuit breakers in the power network model during the simulation. In addition, an external embedded controller is used to receive the synchrophasors from the PMUs, analyzes them with an oscillation damping algorithm, and then sends the damping signals to the RTS, similar to the use case in section V.

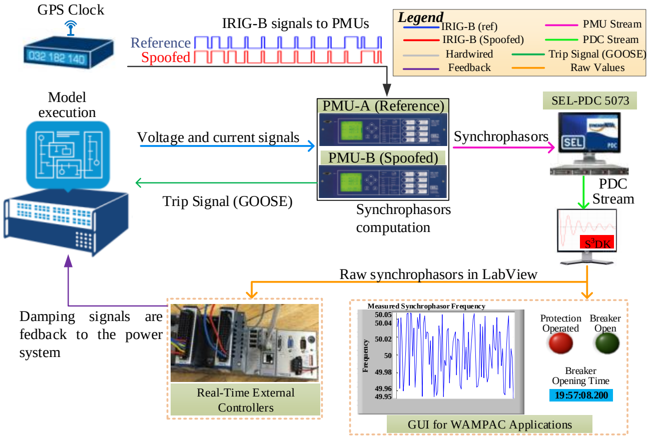

Figure 12 Test setup for TSSA analysis **[33]**

C. *Cybersecurity testing results*

Three WAMPAC applications were tested under TSSA with this test bench. For PAM application, for every 10 μs drifting in the time synchronization signals, the phase angle error introduced is 0.179°; therefore, for a time error beyond 30 μs, the PMU TVE will exceed the maximum allowable limit specified in [5]. During the testing of the PMU-based anti-islanding protection, a false trip is initiated when the time error accumulates beyond a certain level. This is because the anti-islanding detection is based on the phase angle difference between the two PMUs, and the time error causes one of the angles to drift and thus increases the angle difference. In addition, the operation time of the anti-islanding application is also affected with the increasing level of time synchronization errors, thus decreasing the reliability of the protection scheme. Finally, a performance degradation for power oscillation damping is also observed when the spoofing error increases.

Many WAMPAC schemes are sensitive to phase angle error, that's also why the standard requires such a high measurement accuracy. With time synchronization having a strong impact on PMU phase angle computation, it's critical to prevent attacks like time synchronization spoofing. Further studies regarding time synchronization attacks on PMUs applications with a similar test bench are recommended, and meanwhile, HIL simulation is indispensable for this type of study, as mentioned in Section-II.A.

VII. CONCLUSIONS

Advanced and adaptive protection and control applications can be implemented based on the synchropahsor data from local and wide-area networks, to enhance situational awareness and system reliability. To improve the processes of conceptual design and validation of synchrophasor-based applications, different testing architectures using RTS are discussed in this paper. Three specific HIL use cases are analyzed in detail including PMU compliance testing, WAMPAC application validation, and a time synchronization spoofing study. Regarding PMU functional testing, it can be foreseen that when synchrophasor applications evolve, there will be more demanding requirements on harmonic filtering, frequency response or sampling rate, which are not necessarily assessed in the standard PMU functional tests. An application-specific functional test can be easily implemented using an RTS. In WAMPAC application validation, the use cases show that HIL helps to gain confidence in deploying synchrophasor-based applications and accelerating the development and validation process, thanks to its capability of simulating power network dynamics and its versatile interface to hardware devices and communication network. In addition, a validated system model could also be used directly in other studies, which would simplify the modeling tasks and accelerate a study's progress. From the cybersecurity perspective, a secure, fast and reliable synchrophasor data communication network is needed. An RTS can be part of a cyber-physical system simulation setup to provide a closed-loop validation of the communication network reliability. Moreover, for educational purpose, real-time simulation can provide operators, researchers and students with adequate data to learn about the system behavior under different contingencies, with and without the actions of the synchrophasor-based applications. In summary, an RTS can be used in multiple ways in testing PMU devices and developing synchrophasor applications.

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