A Reconfigurable Synchrophasor Synchronization Gateway & Controller Architecture for DERs

Prottay M. Adhikari, Luigi Vanfretti
Rensselaer Polytechnic Institute
Troy, NY, USA
{prottaymondaladhikari, luigi.vanfretti}@gmail.com

Chetan Mishra, Kevin. D. Jones
Dominion Energy
Richmond, VA, USA
{Chetan.Mishra, Kevin.D.Jones}@dominionenergy.com

***Abstract*—In grid applications featuring various Distributed Energy Resources (DERs), e.g. microgrids, synchrophasor applications would require an extensive infrastructure including substantial instrumentation-hardware, communication network extensions and controller installations, like in WAMPAC systems. Thus, such overall implementation becomes cost-prohibitive. To address this issue, this paper proposes a dedicated centralized synchronization hardware to replace aggregation PDCs, and supplementary control functions into a single piece of hardware. This particular hardware is termed as Synchrophasor Synchronization Gateway & Controller (SSGC). The proposed SSGC hardware utilizes the *Khorjin* library to parse IEEE C37.118 data, concurrently from multiple devices, and in an embedded *hard* real-time (RT) computer system through a synchronization layer. Supplementary control actions, e.g. power flow control, are implemented on top of the synchronization layer. This SSGC based architecture is tested with a RT microgrid model implemented on Typhoon HIL-604 RT simulator. The communication interface between the micrgrid and the SSGC was tampered through external hardware by introducing network delays & data-drops, and its performance SSGC was analyzed.**

***Index Terms*—Synchrophasor, Typhoon HIL-604, IEEE C37.118, TCP/IP, DER, PMU, PMU-based control.**

I. Introduction

A. Motivation

In synchrophasor systems, Phasor Data Concentrators (PDCs) are expected to receive, parse, align, store and publish measurement data. Thus, they must be compatible with synchrophasor data transmission protocols such as IEEE C37.118 and substation automation protocols such as IEC 61850. However, existing PDC hardware architectures are proven to be inadequate to comply with hard **real-time** control requirements. As reported in literature [1]- [3], most existing *real-time compliant* PDC implementations are purely on the software level, and the existing industrial PDC hardware are **not** real-time compliant. This makes the application of PDCs in real-time networked-control of power system a challenging problem. In [4], the authors have proposed a hardware platform for wide area control system (WACS) applications which can function upon a single incoming PMU stream. However, there exists no real-time compliant PDC hardware architecture that can operate on multiple PMU streams, to the best of authors' knowledge.

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This paper reports implementation and utilization of a synchrophasor synchronization gateway capable of processing multiple concurrent incoming PMU/PDC streams that is deployed in a *hard* real-time embedded system, and that can be extended to support real-time control functions. The proposed synchrophasor synchronization gateway and controller (SSGC), concurrently ingests and parses data from multiple streams, and because its on-board GPS signal capabilities, is able to compute and trace end-to-end delays of each stream. Beyond these functionalities, the proposed SSGC hardware is able to support supplementary control functionalities targeted for distributed energy resources (DERs) and 'microgrids'. *'Microgrids'*- as defined by the International Electrotechnical Commission (IEC) in [5] are - *groups of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in either grid-connected or island mode.* Because microgrids are typically supported by DERs, they involve a significant amount of power electronic hardware and the sophisticated control systems associated with those power electronic circuits. This is addressed by the literature in [8] and [9]. The survey in [10] and the the research in [24] demonstrate that the design of a functional control system for microgrids needs to be hierarchical. Within the control hierarchy, synchrophasors can be exploited through the SSG to provide multiple ancillary functions to microgrids.

The central motivation of extending the SSG architecture reported earlier in [13], into the paradigm of control functionalities is to utilize the time synchronized measurements obtained from the PMUs and the on-board GPS timing of the SSG, to seamlessly control the power electronic-based DERs that are used to construct the microgrid. This architecture allows for the proposed hardware to incorporate parts of the microgrid control functionalities to run on the SSG's hardware, while the remaining control actions are implemented locally within the individual DERs. To this end, the design prototype is termed as Synchrophasor Synchronization Gateway & Controller (SSGC). This SSGC was tested with a real-time microgrid implementation on real-time simulator (Typhoon HIL-604). The SSG/SSGC implementation is carried out based on the compact reconfigurable input-output (cRIO) devices. The underlying cRIO hardware is configurable through a graphical interface designed in the LabVIEW environment. This architecture is user friendly in terms of configuration,

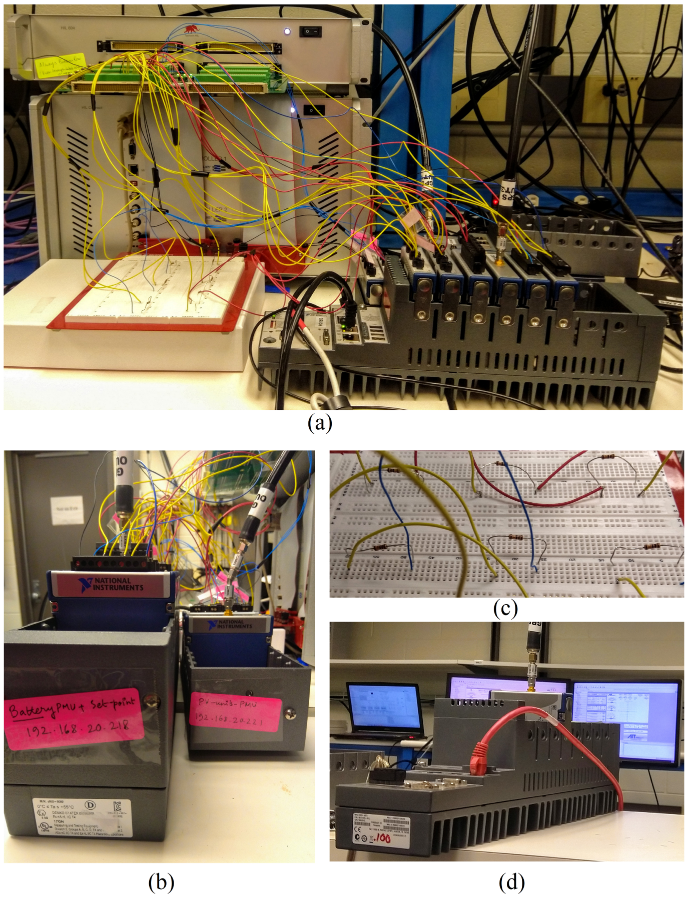

Fig. 1. Hardware Arrangement for RT-HIL Testing the SSGC Hardware: (a) Connection Between the Microgrid & the PMUs, (b) PMUs Receiving Timing Information, (c) Conversion of RT Low-voltage Signals into Current Signals, (d) SSGC Connected Remotely to the Microgrid RT Model

display, and hardware management.

B. Related Works

The authors in [13] reported the architecture for the SSG, and introduced the hardware and software associated with the implementation. On the software level, the SSG uses the C-based *Khorjin* library reported in [15] to parse PMU data streams. The SSG's GUI was designed using LabVIEW and is kept configurable to accommodate additional incoming PMU/PDC streams and modifications in communication network specifications. Because, most of the functionalities provided by the proposed hardware are similar to the functionalities offered by a traditional PDC hardware, it is important to take note of the existing standardization efforts in the domains of PDC hardware implementation. The authors in [2] summarized the standard functional blocks and communication interfaces associated with the PDC architecture. A similar study was reported in the research presented in [6]. This study also explored the communication protocol between the PMUs and PDC in details. In the domain of control system design for microgrids, the authors in [10] surveyed and classified the existing control strategies into three different classes depending on the priorities, time-scales and required speed of the various control actions. To elaborate further, the primary control class consists of the fastest control actions including voltage and current control algorithms for the individual DERs. The secondary control class evaluates the power flows to and from the different existing DERs, and helps the microgrid navigate between the islanded and the grid-tied modes. The secondary control class tackles slower dynamic responses (e.g. power flow) compared to the primary control class. Finally, the tertiary control class consists of supplementary control algorithms sitting on top of both primary and secondary classes of control, and enables the microgrid to operate in an economically-optimized fashion. The research reported in [24] demonstrated significant efforts of standardization across these three classes of control systems in microgrids. The authors in [19] explored the utilization of synchrophasor data to monitor microgrids and to increase the reliability of measurement data. To this end, this research proposed an Advanced Phasor Data Concentrator (APDC) hardware which is capable of operating under a tampered network and estimate missing data points in the synchrophasor streams. However, this hardware was not time synchronized and the reported experiments were performed by a programmable voltage source, instead of RT-simulation models of microgrids. The experiments reported in [20] illustrated a synchrophasor based control architecture for microgrids, where the synchrophasor data is used to formulate reduced order dynamic models for the DERs within the microgrid, and used those models to seamlessly navigate the microgrid between the islanded mode and the grid tied mode. Researchers in [21] demonstrated the utilization of adaptive network management tools within the PDC to compensate the network delays between the PDC and the individual PMUs.

C. Contributions

- Expanding the capabilities of the *Khorjin* library to develop a synchrophasor synchronization gateway & control (SSGC architecture, including a synchronization layer.
- A new PMU-based approach for networked control of the DERs within a real-time microgrid model exploiting the proposed SSGC architecture.
- Review of the SSGC's performance under varying communication network conditions with multiple PMU streams.

II. Architecture and Experimental Setup

A. Controller Architecture

The framework of the SSGC is similar to that introduced by the authors in [13]. However, the research in [13] only demonstrated the data-unwrapping and time synchronization functionalities on the real-time embedded system (host). In the current work the code running on the host side (in an RT operating system) is modified to incorporate key control functionalities targeted to control DERs in a microgrid. This control system comprises of a PI controller that computes its set-point and process-variable by unwrapping the current and voltage phasors it receives in real-time.

In this paper, the proposed SSGC architecture is tuned for regulating the power output from a battery energy storage

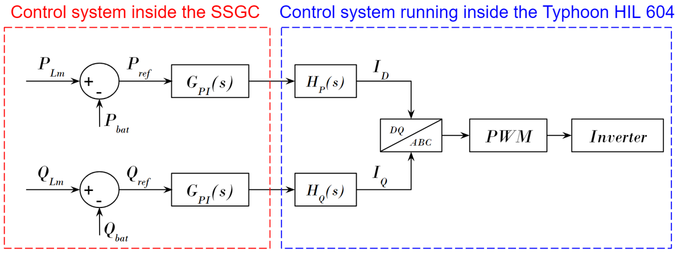

Fig. 2. Microgrid Controller Utilized in the Experimental Setup

system (BESS) based DER. The proportional-integral (PI) controller coded inside the remote SSGC hardware determines the set-point to be utilized in the local controller inside the BESS. The inputs to this control algorithm are the active power P, and reactive power Q, computed from the current and voltage phasors the SSGC receives through the incoming PMU streams in real-time. The controlled output is then fed back to the real-time simulator's input in order to control the Li-ion BESS. This BESS was part of a microgrid model developed and simulated in the Typhoon HIL 604 real-time simulator. Apart from the BESS, the microgrid consists of a diesel generator and a PV system, that together with an external grid, supply a configurable load. The RT model expands on existing component models in the Typhoon HIL's library [16]. The overall model is shown in Fig. 3.

The proposed control architecture is suitable for taking advantage of the hierarchical structure of standard microgrid control infrastructures as those in [10]. The hierarchy of microgrid control, classifies control functionalities into three distinct categories: primary, secondary and tertiary.

B. Experimental Setup

The SSGC hardware reported in this paper is most suitable for incorporating control actions which fall into the secondary class and the tertiary class. For demonstration, a secondary class of control action, i.e. to control the power output of the BESS based DER, is illustrated herein. The set-point for the control action is based on two parameters P_{Lm} which represents the measurement from the load side, and P_{bat}. It is assumed that the P_{PV} (Active power output from PV system), P_{Uti} (Active power dispatch from the utility), and P_{DSG} (Active power output from the diesel generator) are kept constant. In this situation, the parameter P_{ref} will depend only on the total load consumption P_{load}. This can be explained from the block diagram shown in Fig. 2.

Even though the SSGC hardware can be configured to control different DERs, and employ sophisticated control algorithms, such demonstrations are considered to be beyond the scope of the current paper. For experimentation purposes, only the real-time synchrophasor based control of the BESS is presented in this paper. Hence, the primary focus of this paper is the implementation of the SSGC architecture, and its validation in the context of P-Q control of the BESS based DER.

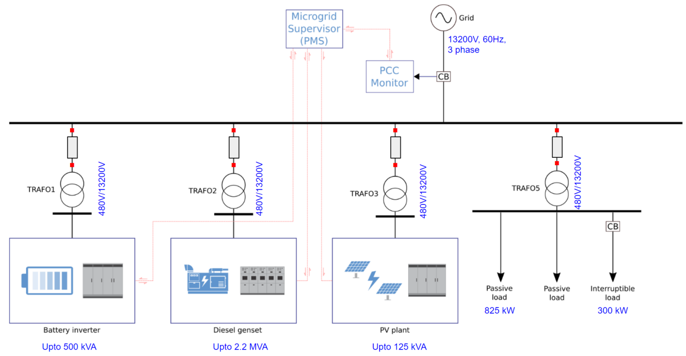

Fig. 3. Simplified Microgrid Model Implemented in Real-time

It has been mentioned that the SSGC receives real-time synchrophasor data. To simplify experiments, some real-time simulators (e.g. Opal-RT), allow to stream synchrophasor data from within the simulator without connecting any physical PMUs to the hardware. However, even though the 2021.2 and 2021.3 releases of the *Typhoon HIL control center* toolkit have dedicated library components for streaming C37.118 data, it was discovered upon experimentation that the current implementations for such blocks are unstable and unreliable for communicating synchrophasor data to external hardware, such as the SSGC. Thus, additional PMUs (as reported in [17] and extended in [18]) were connected to the low voltage analog outputs of the real-time simulator. Importantly, these PMU designs require both voltage and current inputs, whereas the Typhoon HIL 604 is capable of generating only voltage signals proportional to its analog measurements. Thus, it is required to design voltage to current conversion circuits consisting simple resistors as shown in Fig. 1.(c). The connection between the real-time simulator and the PMUs is shown in Fig. 1.(a). Fig. 1.(b) demonstrates how the individual PMUs obtain GPS signals, and Fig. 1.(d) shows the SSGC operating on a remote location, connected to the network in order to receive real-time PMU data.

To test the robustness of the SSGC architecture, the communication network between the SSGC hardware and the PMUs was tampered with. To perform these actions an additional external hardware *CandelaTech CT910* [23] was connected between the SSGC and the rest of the communication network system. This hardware enables the user to introduce custom delays, and data-drops within the network through a GUI or command line.

III. Results

A. SSGC Performance under Ideal Network Conditions

For experimentation, the total load is increased in a step by turning on the *configurable load* as shown in Fig. 3. Initially, a fixed load of 825 kW was supplied by the PV unit (125 kW), Diesel Generator (500 kW), and the utility (100 kW). This makes the initial dispatch for the BESS-inverter to be fixed at 100 kW. With the system running in this 'steady state', a step increase of 300 kW in load was triggered externally. The control system must be designed in

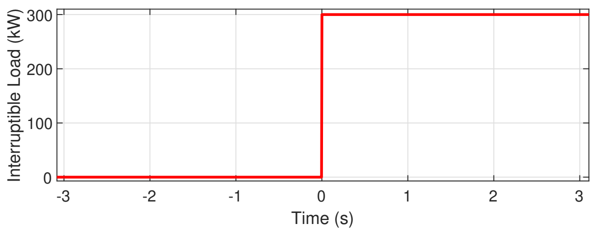

Fig. 4. 300 kW Load Injection by Switching the Interruptible Load

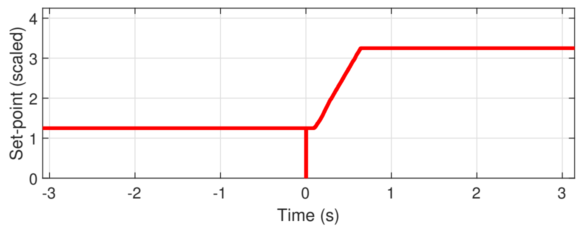

Fig. 5. Response at the Output of the PI-controller Inside SSGC

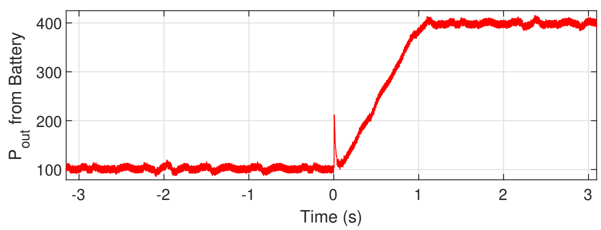

Fig. 6. Active Power Output from the Battery Energy Storage System (BESS)

such a way that, this change in load is reflected in the BESS-inverter, and its dispatch increases from 100 kW to 400 kW. It is important to note that, the portion of the controller (in Fig. 2) within the dashed red-box is the only portion implemented within the SSGC hardware. This portion is capable of utilizing synchrophasor measurement data obtained from the PMUs placed at the load and at the BESS. The PMU data is utilized to compute the active and reactive powers (not demonstrated in this experiment), which are then used for calculating a new set-point (by using the PI controller block G_{PI}) for operating the BESS. This set-point is then utilized by the internal control algorithm (implemented locally inside the BESS) for controlling the individual current and voltage output of the inverter inside the BESS. This portion of the control system must be implemented locally within the BESS model of the real-time simulator, because it requires faster dynamic performance and needs to be capable of generating high-frequency switching sequences for the individual semiconductor switches in the inverters.

Fig. 4 shows the 300 kW manual load-injection in the system. The SSGC incorporates a PI controller onboard. The output of this PI controller - which provides a set-point for the local controller for the BESS to operate - is shown in Fig. 5. This measurement is taken from the SSGC side. There maybe jitters, data-drops or imperfections if this same data is re-measured from the RT-simulator end where the simulator receives the set-point from the SSGC. In Fig. 6, the BESS power output response is shown. It can be observed from this figure, that the power output of the battery increases from 100 kW to 400 kW to cover for the step increase in the load. Figures 4 to 6 demonstrate the SSGC's performance under ideal conditions of the communication network while there are no external communication disturbances. In the sequel, this ideal communication network is corrupted with the introduction of user defined network delays and data drops through the *CT910* network emulator and impairment applicance.

B. SSGC Performance Under Non-ideal Network Conditions

In the following experiments, the *CT910* device is utilized to tamper with the network between the SSGC and the PMUs. For testing the reliability of the control architecture under varying network conditions, the network delay was varied from 0 ms to 500 ms, and the data-drop rate was varied from 0% to 10%. Under these conditions, the same experiment as reported in Section III-A was rerun and the performance of the controller was observed.

Two sets of experiments were performed to investigate the robustness and reliability of the proposed control system.

1) Controller performance under varied communication network conditions: In this test, the quality of controller output data is analyzed for varying network delays and varying data-drop rates. The controller regulating the power output of the inverter inside the BESS, is set to react to a step-increase of 300 kW in the load as demonstrated in Section III-A. However, its performance is expected to deteriorate under stressed network conditions. The results of these tests are summarized in Fig. 7. It can be observed that the analog output of the remote controller loses a lot of resolution under higher network delays and higher data-drop rates. However, as discussed earlier in section III-A, the control-objective of the SSGC does not involve any management of high frequency system dynamics. Thus, in short-term the SSGC-driven control architecture can sustain itself even while operating within a tampered network.

2) Resilience test under varied conditions: For this test, the SSGC is set to operate freely under varying network conditions, and whether or not it can sustain itself for **longer periods** of time, is tested. The network was tampered by introducing network delay and data-drop. Under these conditions, the network was kept running for 10 minutes. After 10 minutes, it was determine if the SSGC was still receiving all the PMU streams successfully, and if the real-time simulator is still receiving the controller's output. This observation is taken 10 times, for each communication network condition. The summary of these results is shown in Table I. It can be seen that the network delay and data-drop can both adversely effect the robustness of the SSGC. In fact, in a situation where the SSGC is subjected to both high network delay coupled with high data-drop rate, the SSGC is almost certain to be unable to sustain itself for a long period of time. However, for lower injected delays and lower data-drop rates, the SSGC is proven to be reliable. (e.g. for 0.5% data-drop and 50 ms delay, 10 out of 10 runs were sustained, while for 5% data-drop and 200 ms delay, only 2 out 10 runs were sustained)

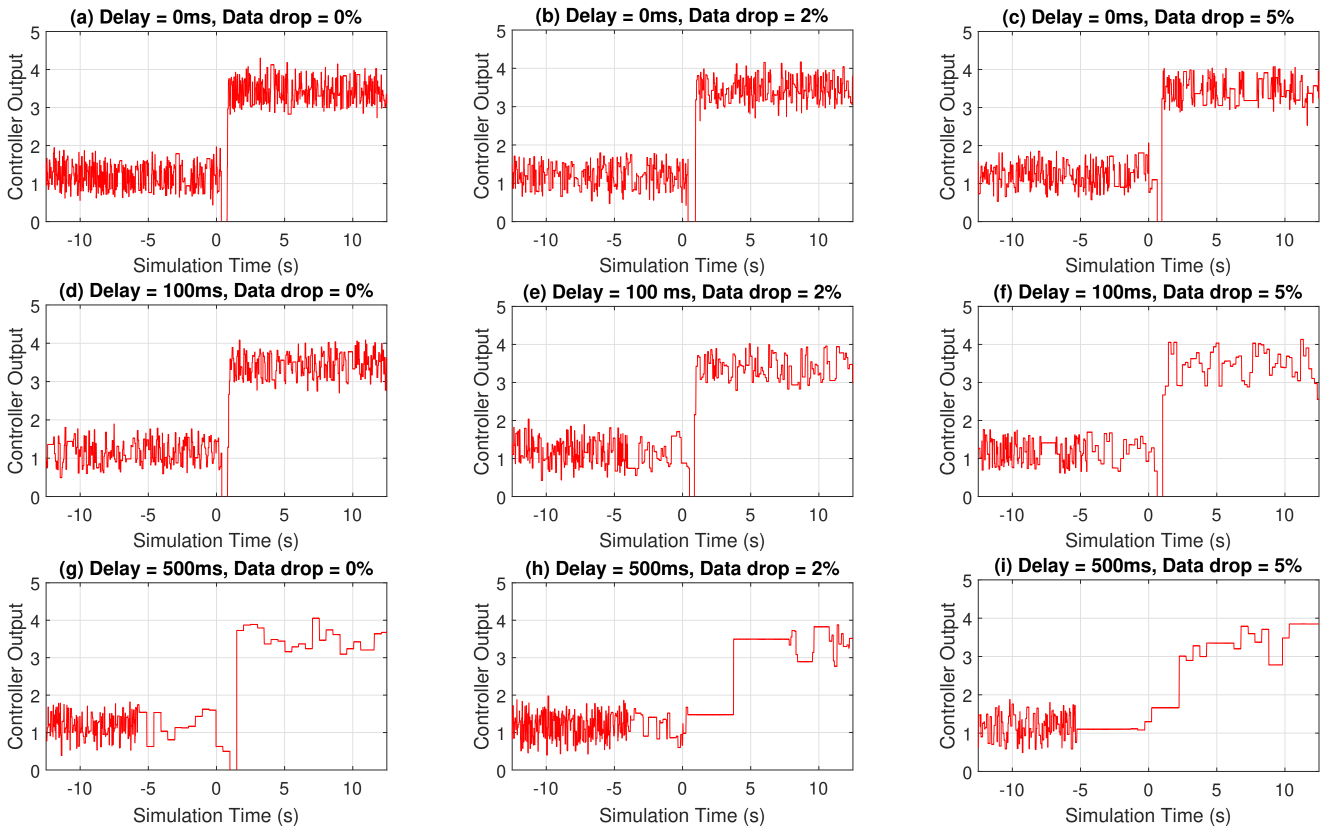

Fig. 7. Control signal received in the Typhoon HIL RTS from the SSGC under varying network delay and data-drop rates

TABLE I
SSGC PERFORMANCE UNDER VARYING COMMUNICATION NETWORK CONDITIONS

Drop Rate (%) / Delay	0%	0.5%	1%	2%	5%	10%
0 ms	10/10	10/10	10/10	10/10	10/10	3/10
50 ms	10/10	10/10	10/10	10/10	9/10	0/10
100 ms	10/10	10/10	10/10	9/10	7/10	0/10
200 ms	10/10	10/10	10/10	6/10	2/10	0/10
500 ms	10/10	10/10	5/10	0/10	0/10	0/10
750 ms	1/10	0/10	0/10	0/10	0/10	0/10

IV. Conclusion and Future Works

The proposed SSGC based architecture has the potential to reduce the complexity and latency of the synchrophasor system and communication network, when compared to traditional WAMS/WAMPAC systems.

It needs to be noted, that only one scenario for controlling the DERs within a microgrid is demonstrated in this paper. In that scenario, the battery is covering for a step increase in the load. While, this experiment is an important 'proof of concept'-study, additional experimentation is crucial before implementing the proposed architecture for controlling real-world DERs.

In real world, the behaviour of a BESS based DER in a power system is complex and the operation of the controllers are restricted by the physics of the battery. In fact, batteries utilized in energy storage systems are limited by their relatively slow response times, both during charging and discharging operations. As reported in [14], the average response time for a battery energy storage system during charging is about 2.2 seconds and that for discharging it is about 0.6 second. Keeping these numbers in mind, the battery cannot be subjected to rapid movements or perturbations in the load. Such high frequency variations, if kept unfiltered, would rapidly increase the switching and would generate excessive heat, thus compromising the health of the batteries. Implementing these precautions within the control system, is well inside the dynamic range of operation for the SSGC hardware. Significant future effort is required in this domain.

Because one of the main objectives for the current research is to minimize the number of PMUs in constructing a functional control system, it is crucial to explore different locations of the PMUs. One such direction of experimentation should be to explore, how the phase angle measured by the PMU placed at the utility end can be used to implement a control system for controlling the active power flow of the DERs. This is a well-studied approach, and the usage of phase angle differences as the control variable for active power management has been known to be utilized for stable, reliable and robust control systems in traditional power systems featuring synchronous machines. It should be an important exercise to export that concept into the paradigm of networked control for DERs in microgrids. Since PMUs readily provide angle measurements,

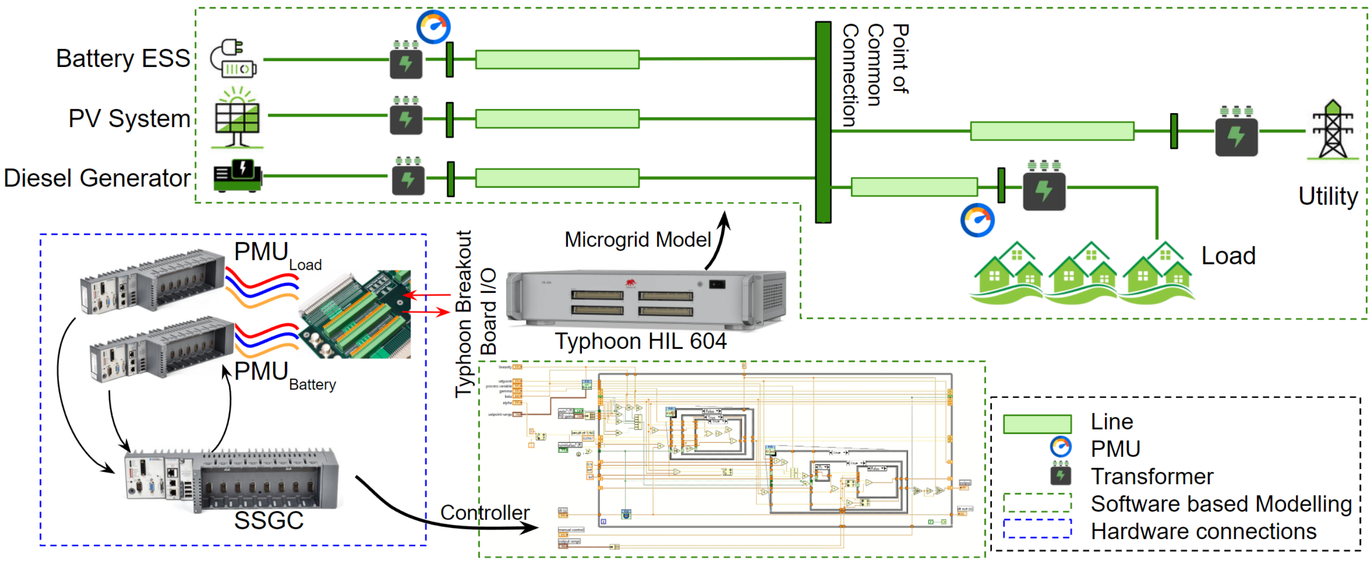

Fig. 8. Proposed Control Infrastructure for Microgrids With Networked PMUs and SSGC

this approach can reduce the design-complexities of the overall control system.

While managing BESSs, the state of charge (SOC) of the battery is a crucial parameter. Depending on SOC, the battery is often put into the charging or the discharging modes. In this paper, the SOC is assumed to be high enough, so that the battery can reliably operate in discharging mode, i.e. it can feed active loads. In real systems, this may not be the case. So, an additional control loop must be designed to determine the SOC state and ensure the safe and reliable operation of the BESS.

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