CHIL Validation to Commercialize a Networked Microgrid Controller

Maximiliano Ferrari[1],Guodong Lui[1], Jonathan Lee[2]

[1]Oak Ridge National Laboratory, Oak Ridge, TN, USA. [2] New Sun Road, Richmond, CA, USA

***Abstract*—Networked microgrids provide a way of improving resiliency compared to traditional industry-standard, autonomously operated microgrids. However, real-world demonstrations capable of supporting such networked operation remain scarce. This gap is due in part to the limited availability of cost-effective, commercially mature controllers with the capability to coordinate, control, and optimize networked microgrid systems. This paper presents control hardware-in-the-loop (CHIL) validation of a networked microgrid controller in the process of commercialization by New Sun Road. The controller, implemented on New Sun Road's Stellar Microgrid OS™ cloud software and Stellar Edge™ hardware, employs controls for coordinating multiple microgrid systems. The paper presents the progress achieved to date in enabling this advanced control in a commercial product and provides preliminary CHIL results validating the control functions, with a specific focus on the design of the CHIL testbed and early demonstrations of different configurations for networked microgrid.

Keywords*—*networked microgrids, microgrid orchestrator, energy resiliency, distributed energy resources,

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I. Introduction

With the electrification of transportation and buildings, widespread construction of data centers, and increasing impact of extreme weather events, the power grid is under unprecedented stress to provide sufficient and resilient electricity supply. Microgrids have become a solution to harness local power generation of Distributed Energy Resources (DERs) and reduce electricity cost during grid-connected normal operation. In addition, microgrids have the capability to disconnect from the main grid and operate independently in island mode by leveraging local DERs and energy storage systems (ESSs). This feature enhances the resilience of power supply and ensures continuous powering of critical loads when the main grid is unavailable [1]. Due to these advantages and benefits, microgrids have been widely deployed in the US and globally in recent decades [2].

The current state of the industry, is that microgrids either operate in stand-alone operation (islanded mode) or grid-tied. Networked microgrids increases configuration flexibility by enabling multiple microgrids that are co-located to coordinate their operations and exchange power to meet operation objectives. This coordination maximizes energy resources utilization, improve economic benefit and improves overall system resilience [3,4]. By interconnecting microgrids with heterogeneous load profiles, energy mix, and operating constraints, the aggregated system can dispatch resources more efficiently, improve reliability, and increase islanding capability at reduced cost [5]. In addition, networked microgrids can increase resilience by extending the geographic reach of power to a broader set of customers and enabling modular, incremental expansion of resilient electrical infrastructure [6].

A key challenge in networked microgrids is managing a large and diverse array of assets and the integration of microgrid and equipment controllers from various manufacturers. There has been extensive theoretical research for coordination and control of networked microgrids, most of which are based on centralized or distributed optimization algorithms [7]. The centralized control and optimization structure with a leader-follower control mode, which selects one microgrid as the leader for managing the power exchanges among networked microgrids and take the rest microgrids as followers for executing the power exchanges determined by the leader, has shown significant success in reducing operating costs [8], enhancing resilience and facilitating utility operation [9]. However, the centralized control and optimization structure is subject to heavy communication burden, low tolerance for failures and no privacy protection for individual microgrids. To solve these issues, the distributed control structure, which preserves the autonomy and privacy of individual microgrid controllers and allows certain information sharing among microgrid controllers to improve the performance of overall networked system, has attracted great attention in recent years. One of the most well-known distributed optimization approaches, Alternate Direction Method of Multipliers (ADMM) has been extensively investigated and widely utilized to coordinate the operation of networked microgrids due to its scalability and fast convergence [10]. Under this approach, the networked microgrid controller influences the behavior of independent microgrids without imposing setpoints on assets inside the microgrid, addressing the shortcomings of centralized approaches.

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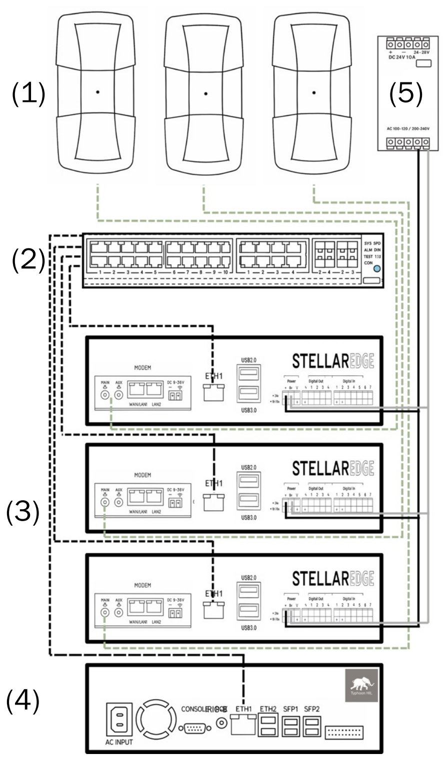
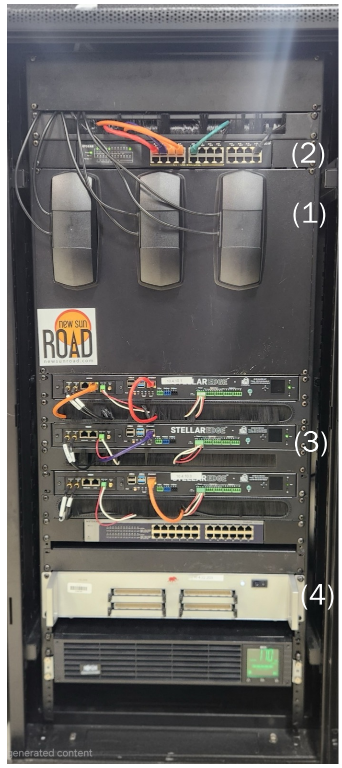


(a)



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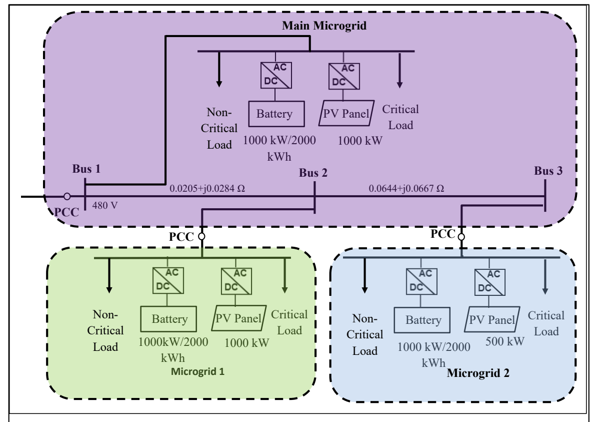

Component	Parameter	Microgrid 1	Microgrid 2	Microgrid 3
Battery Inverter	Power Rating	3000 kW	1000 kW	1000 kW
	Control Modes	VF, PQ	VF, PQ	VF, PQ
	Output Voltage	480 V / 60 Hz	480 V / 60 Hz	480 V / 60 Hz
Battery (ESS)	Technology	Li-Ion	Li-Ion	Li-Ion
	Capacity	2000 Ah	2000 Ah	2000 Ah
	DC Voltage	1000 Vdc	1000 Vdc	1000 Vdc
ESS Transformer	Configuration	Δ (480 V) –Yg(12.47KV)	Δ (480 V) –Yg(12.47KV)	Δ (480 V) –Yg(12.47KV)
	Power Rating	4500 kVA	1500 kVA	1500 kVA
PV Inverter	Power Rating	1000 kW	1000 kW	500 kW
	Control Mode	PQ (MPPT)	PQ (MPPT)	PQ (MPPT)
	Output Voltage	480 V / 60 Hz	480 V / 60 Hz	480 V / 60 Hz
PV Transformer	Configuration	Δ (480 V) –Y(12.47KV)	Δ (480 V) –Y(12.47KV)	Δ (480 V) –Y(12.47KV)
	Power Rating	1250 kVA	1250 kVA	625 kVA
Load	Type	Dynamic resistive	Dynamic resistive	Dynamic resistive
	Critical	66.70%	60%	50%
	Non-Critical	33.30%	40%	50%

(c)

Figure 1: ((a) Simplified single-line diagram of the testbed and the Stellar Edge controller (the actual controller includes additional inputs and ports as described in [1]). (b) Physical testbed consisting of three Stellar Edge controllers, a real-time simulator, networking equipment, and cellular communications. (c) Power system model of the three-microgrid system and associated configuration parameters. (1) 4G Cellular Modem. (2) network switch. (3) 3 Stellar Edge local controllers. (4) Typhoon HIL 606. (5) 24Vdc supply for Microgrid Controllers.

As presented, most of the work on networked MGs has focused on research activities on optimal energy transaction strategies to meet economic objectives. However, there is a lack of commercial controllers that can effectively coordinate large microgrids considering diverse assets with heterogenous controllers. Furthermore, experimental systems for field demonstrations and testing remains limited to few laboratory examples [11], which severely hinders their applicability.

To help address this gap, this paper presents preliminary control hardware-in-the-loop (CHIL) results of a controller that represents the first ADMM-based networked microgrid controller explicitly designed for commercialization. The controller, implemented in New Sun Road's Stellar platform, employs a distributed optimization algorithm to coordinate power flow exchanges among three interconnected microgrids modeled in a real-time simulator. The paper describes the CHIL architecture and provides preliminary results of grid-tied networked microgrid testing using the Stellar Edge^{TM} controller.

II. Control Hardware-in-the-loop Test Setup

Fig. 1 shows the CHIL testbed and the microgrid network modeled on the real-time simulator located at Grid-C facility at Oak Ridge National Laboratory. Figure 1(a) illustrates the testbed consists of (1) cellular communication to broadcast data to NSR's Stellar Microgrid OS^{TM} cloud services. (2) Network Switch. (3) Three local Stellar Edge Controller. (4) Typhoon 606 real-time simulator and (5) 24v Power Supply for bias power.

Three microgrid systems were modeled together in a single Typhoon HIL 606 real-time simulator, including DERs, the grid connection and emulated protective and measurement devices. The test system represents a behind-the-meter campus networked microgrid, which is an important configuration for commercial pilots. The system consists of three microgrids: MG1 and MG2 and MG3. Under normal operation, MG1 microgrid is grid-connected and all three microgrids operate in grid-following mode. Under islanded operation, MG1 microgrid becomes grid-forming and Microgrids 1 and 2 remain grid-following. For this reason, the grid-forming inverter of MG1 must be oversized to accommodate additional capacity. Each microgrid include PV, energy storage and dynamic loads. For the test system, seamless transfer among the three MGs is achieved by a simulated digital-line link between the emulated protective device (SEL 751, modeled according to the manufacturer's Modbus mapping) and the energy storage unit, which emulates a commercial device with appropriately scaled parameters to represent a higher-capacity system. Seamless re-synchronization is accomplished by a synchro-

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check algorithm implemented in the emulated PCC relay (SEL 751).

A. Modbus Mapping

Modbus communication protocol allows interaction between the real-time simulator models and NSR's Stellar Edge^{TM} microgrid controller. Real-world Modbus mappings of commercial equipment were implemented in the simulator. This mapping was simplified and included in the real-time model of the three-microgrid system to make the testbed closely resemble a real microgrid deployment. PV inverter mapping is based on Fronius 24kW Symo Inverter, the energy storage system mapping on Oztek RS40, and the PQ meters and load mappings on SEL 751 and SEL 735. Each microgrid includes two SEL 751 relays, one at the point of connection and another for non-critical loads to enable load shedding when required. Three power quality meters were also included: one at the point of connection near the PCC, one for critical loads, and one for non-critical loads. Figure 2 and Figure 3 shows the Modbus mapping for all these devices, which are a simplified version of the real-device register mapping.

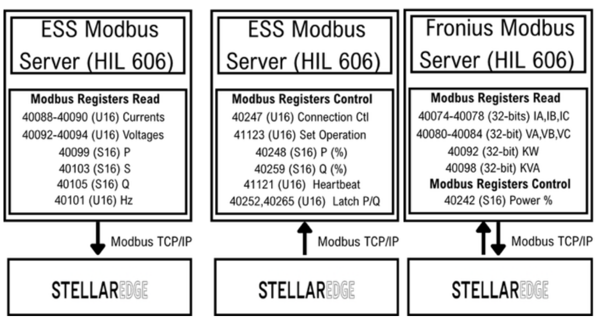

Figure 2: Energy Storage and PV inverters Modbus register mapping

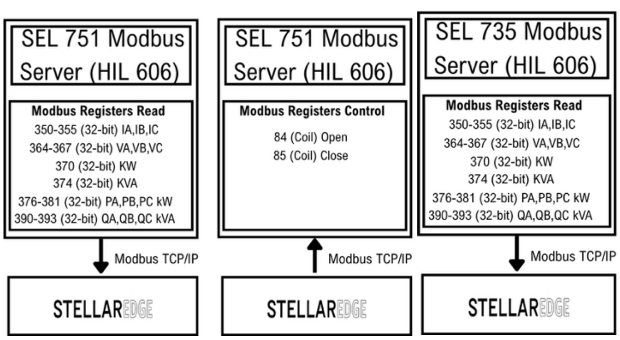

Figure 3: Protective devices and PQ-meter Modbus register mapping.

B. Commerical Platform Implementation

Figure 4 illustrates New Sun Road's microgrid control architecture, using its Stellar Edge^{TM} hardware as a local controller and gateway, and its Stellar Microgrid OS^{TM} for cloud-based optimization and fleet management. NSR, a public-benefit company, operates more than 1,500 microgrids worldwide and provides cost-effective microgrid solutions spanning utility-scale deployments to community-level systems [12]. As shown in Figure 4, the Stellar Edge^{TM} controller is installed locally at the microgrid site. It communicates with field devices using industrial communication protocols and is responsible for the core control functions of the microgrid, including black start, islanding and resynchronization routines, generation control, PV curtailment, and load shedding.

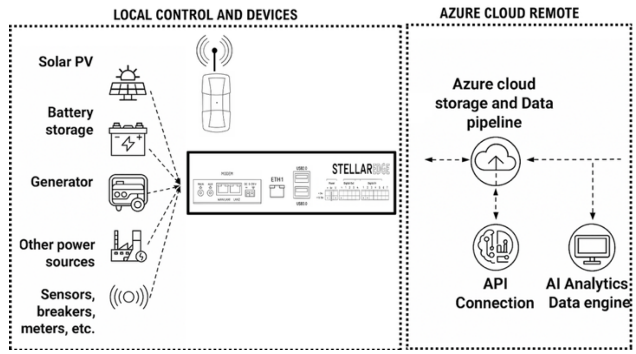

Figure 4. NSR control architecture. The Stellar Edge controller shown includes a simplified port layout for representation purposes compared to the actual commercial product [12].

The Stellar Edge^{TM} controller connects to Microsoft's Azure cloud services via secured MQQT protocol either through a 4G modem, satellite, or a local network connection. In the cloud, NSR provides interfaces for operations centers and microgrid users, performance monitoring, real-time and historical data access, and AI-based analytics, forecasting, and optimization. Computationally demanding tasks such as optimization and forecasting for both individual microgrids and networked microgrids are executed in the cloud. The resulting dispatch schedule is then transmitted back to the Stellar Edge controller, which controls local devices to implement the aggregated dispatch. An ADMM-based networked microgrid optimization was deployed in the Azure cloud and integrated with the optimization engine of the Stellar cloud platform. Each microgrid executes its own local optimization while simultaneously participating in the distributed ADMM coordination process. This enables each microgrid to co-optimize its operation with the global distributed optimizer. The mathematical development of the ADMM optimization can be found [10] and the open-source code in python can be downloaded here [13]. Results of the Stellar platform using the ADMM optimization will be covered in future publications.

C. PV and Load profiles

In the CHIL SCADA environment of the real-time simulator, a Python routine is used to transmit solar generation, critical load, and non-critical load data to the emulator. The data stream is synchronized with the system clock, and new values are sent to the simulator every five minutes. This time alignment is essential, as the dispatch schedule produced by the Stellar Edge optimization engine relies on the same clock reference. Figure 6 presents the flowchart of the timer-based data-handling process.

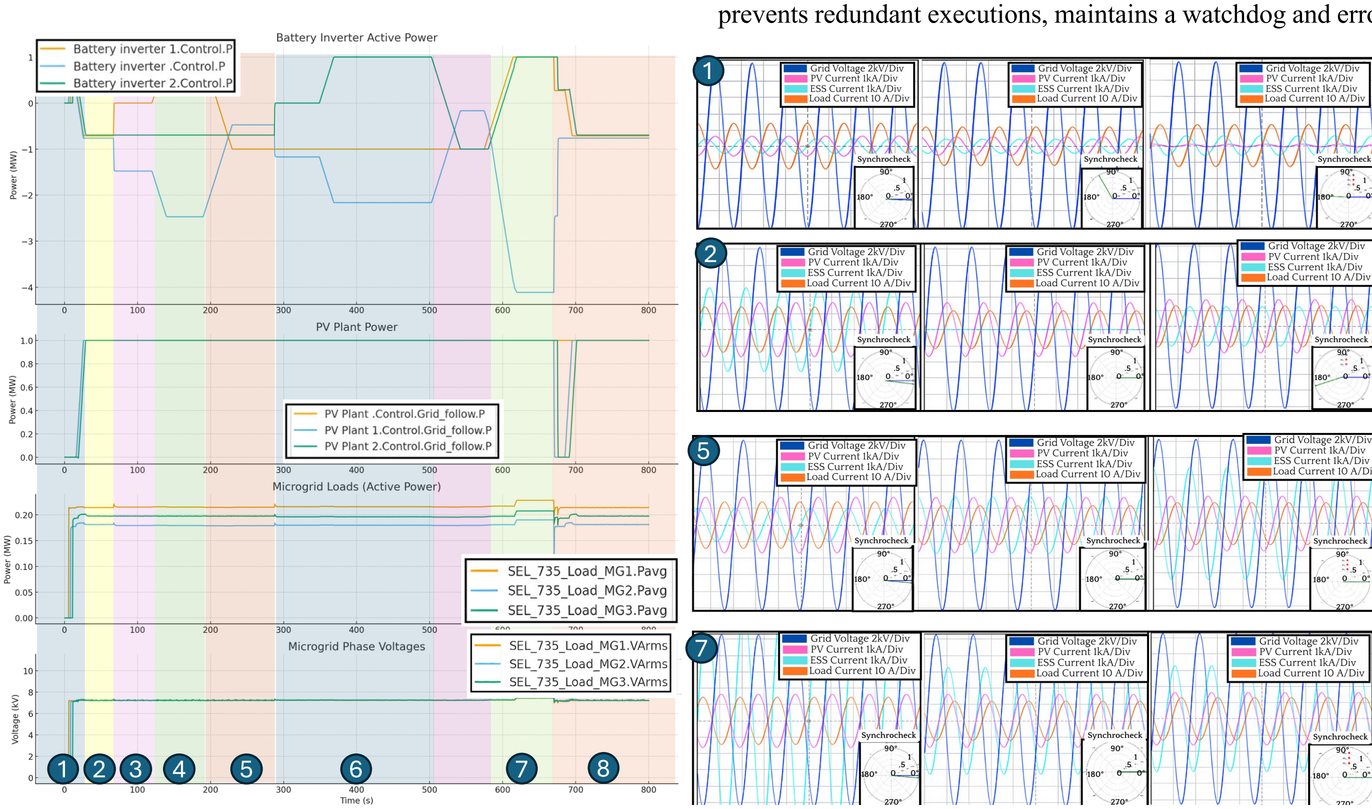

Figure 8. Control-sequence testing of seamless transitions collected from the real-time simulator using SCADA and oscillographic data. (1) Three independent microgrids. (2) MG2 interconnected with MG1. (3) MG1–MG2 networked; ESS2 discharging at 1 MW. (4) MG1–MG2 networked; ESS2 charging at 1 MW. (5) All networked (islanded): MG2 charging 1 MW, MG3 discharging 1 MW. (6) All networked (islanded): MG2 charging 1 MW, MG3 charging 1 MW. (7) All networked (islanded): MG2 discharging 1 MW, MG3 discharging 1 MW. (8) All systems return to islanded operation.

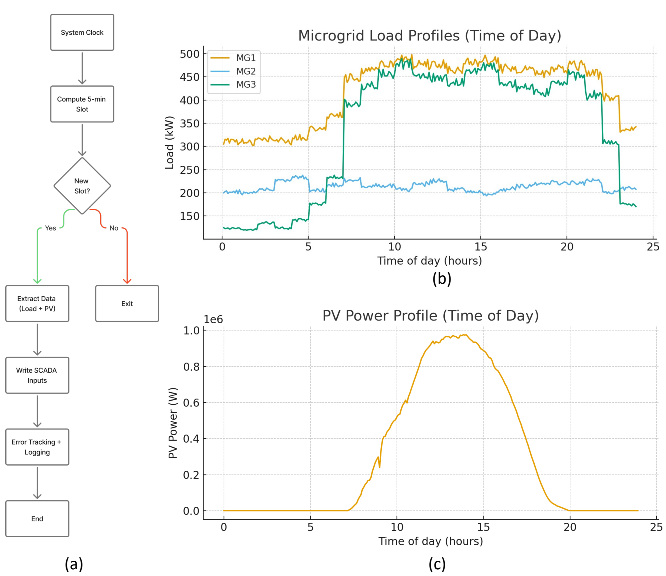

Figure 6: DER Modbus TCP-IP mapping

The timer handler periodically updates SCADA input tags by computing the current 5-minute slot, extracting PV and load values, and writing them to the SCADA interface. It also prevents redundant executions, maintains a watchdog and error counter for robustness, and rate-limits logging to avoid UI slowdowns.

D. Synchrocheck and Protection

Synchro-check is implemented in emulated protective device, which is located at each microgrid's point of connection. This algorithm issues a close command when the microgrid voltage falls within the synchronization window defined in Figure 7. Seamless transfer is achieved via a digital line between the emulated protective device and the energy storage system.

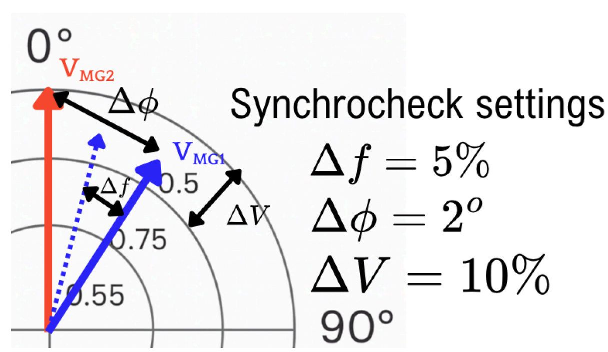

Figure 7: Synchro-check algorithm implemented at each microgrid point of connection (PCC)

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III. CHIL TESTING

A. Basic Control Functions

Figure 6 validates the flexible topologies of the networked microgrids. Using the Stellar Edge, the operator issues manual setpoints to reconfigure the system: (1) *Independent MGs:* Each MG black starts independently via ESS Modbus control; phasor diagrams show different voltage angles. (2) *Synchronize MG2→MG1*: MG2 synchronizes to grid-forming MG1; once connected, MG2 ESS power is set to zero. (3) *MG2 Discharge:* MG2 ESS discharges at 1 MW, confirming stability.(4) *MG2 Charge:* MG2 ESS charges at 1 MW, also stable.(5) *Add MG3:* MG3 synchronizes and connects; MG2 charges at max and MG3 discharges at 1 MW.(6) *Networked – Opposite Flow:* MG2 discharges and MG3 charges at 1 MW.(7) *High-Power Discharge:* MG2 and MG3 both discharge at 1 MW; MG1 maintains stable support. (8) *Return to Independent Island:* System separates seamlessly back into three islanded MGs.

B. Example ADMM distpach

Figure 9 shows screenshots from the Stellar Microgrd OS™ cloud platform illustrating the grid-tied operation of three microgrids between November 14 and November 17. MG1 is the grid-connected microgrid while MG2 and MG3 are downstream; each using a Stellar Edge™ controller that receives an active power dispatch command from the cloud-based ADMM.

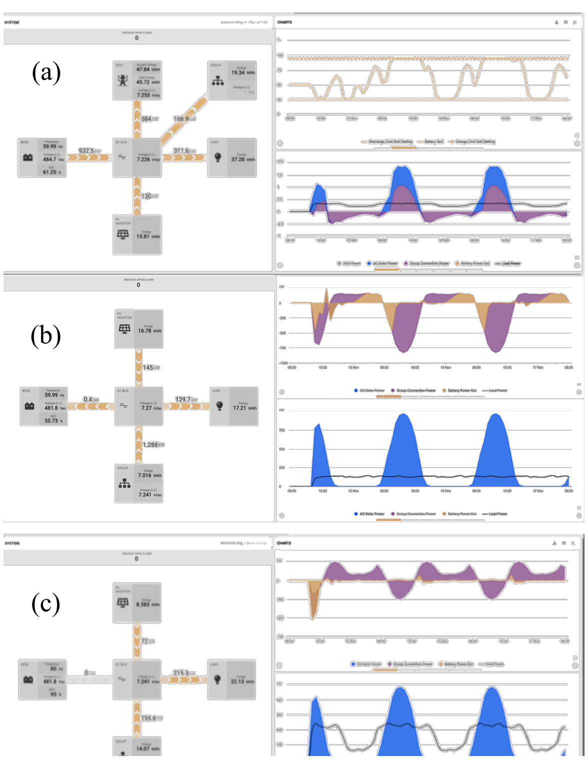

Figure 9: Grid-tied operation of the networked microgrids. (a) MG1 dashboard showing SOC, generation, load, and group power. (b) MG2 dashboard showing group power, battery power, load, and solar generation. (c) MG3 dashboard showing group power, battery power, load, and solar generation.

Figure 9(a) shows the dashboard of MG1. This dashboard was desgined to identify which both the power exported to the grid and the power exchanged within the networked microgrids. Each microgrid dashboard provides a visualization of the power shared among the interconnected systems, for this experiment, the Stellar system dispatches resources to maximize ecconimic benefit via dispatch of the energy storage units.

IV. CONCLUSIONS AND FUTURE WORK

This paper presents preliminary CHIL validation of a controller made by New Sun Road designed for the commercialization of networked microgrids, representing what will be the first ADMM-based controller for networked microgrid operation. The validation using three microgrid systems emulated in CHIL demonstrates flexible topology management and robust operation of networked microgrids under both grid-tied and islanded conditions. Further results of the ADMM-based optimization will be presented in future publications, while this work focuses primarily on the CHIL implementation.

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