Agent-Based Distributed Energy Resources for Supporting Intelligence at the Grid Edge

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***Abstract*— This paper proposes a novel multi-agent framework that can link various forms of resources and power electronic systems into distributed energy resources (DER). The proposed multi-agent architecture can also integrate DERs to a central controller for optimization and control to support the grid. To demonstrate the flexibility of this novel framework, the developed agent system is applied to two different end-use systems. The agent framework is validated in hardware using controller-hardware-in-the-loop (CHIL) simulation platform.**

***Index Terms*-- agents, power electronics, distributed energy resources, energy storage, renewables**

I. Introduction

The electric grid has seen significant advancements. This has been driven by an evolution in available low-cost computational horsepower and intelligent systems that are pushing technological development to the grid edge. One area where distributed intelligence is having a significant impact is in distributed energy resources (DERs).

In recent years, renewable energy (RE) and energy storage (ES) costs have seen significant reductions as the technologies continue to mature and reach market acceptance [1]-[3]. This has led to growing deployments and a shift in generation from centralized systems to DERs. This is a key challenge as large generators that previously have provided our system energy needs and stability are being replaced with large volumes of small hierarchal systems. In the past, these small systems have only represented a small percentage of the overall system capacity and could be adopted into electric grid without significant oversight. However, as these numbers grow, advanced controls and low-cost integration and implementation techniques are becoming vital [1]-[3].

Many RE and ES system technologies utilize power electronic systems (PES) for energy conversion and grid integration. The integration of the resource with a PES often requires significant engineering and development even as communication standards become available. As presented in [4], the integration of systems is challenging and must be conducted by considering the integrating technology, the architecture, semantics, and user. Systems that have not been integrated efficiently lead to configurations of the system that underutilize the capabilities, poor testing results of the prototype (adequate and long-term testing requirements due to problems or failures), and potential early system failure [5]. Early system or mid-life failures, as represented in the failure rate bathtub curve [6]-[7], represent a significant portion of the causes in poor product reliability.

While systems integration is discussed in various publications with varying focus on PES, discussion of PES integration with a generation or load resource system in a general architecture has been limited. PES design with electrical, thermal, and mechanical considerations and how these considerations are interconnected are discussed in [8]. Closed loop PES controls for different renewable systems are discussed in [9]. Architectures for the integration options for AC and DC networks and PES are discussed in [10]. Finally, integration of PES into the electric grid and necessary functions are presented in [11]. The work presented in these publications focusses on key single layers of systems integration, however, a holistic view of the broader implementation challenges (integration of multiple vendor systems into a common framework efficiently) is not presented. Integration across multiple technologies and vendors is presented as a key challenge for this decade in [14].

As shown in Fig. 1, the integration of PES and resources to construct a DER can be performed through a multiple vendor 'black-box' integration effort [12]-[13]. The 'black-box' designation signifies that only the interface information is disclosed. The traditional approach is for a vendor to develop all the integrated solution for the technology for a single product concept with the focus on a specific PES topology (as presented as DER AB in Fig. 1). This work proposes a more flexible solution by maintaining the separate PES and resource systems and using an integration layer (coordination controller) composed of agents to perform the system integration. As shown, utilizing the developed controller, the DERs can be coupled based on different vendor technologies. This flexibility provides opportunities to try new topologies without changing the full system architecture speeding up development and testing of new concepts.

This works proposes to address technology DER systems integration challenges through the utilization of a collection of agents that represent a novel approach to systems integration solution for PES and energy resources (RE and ES) and a DER coordination controller for rapid prototyping and testing.

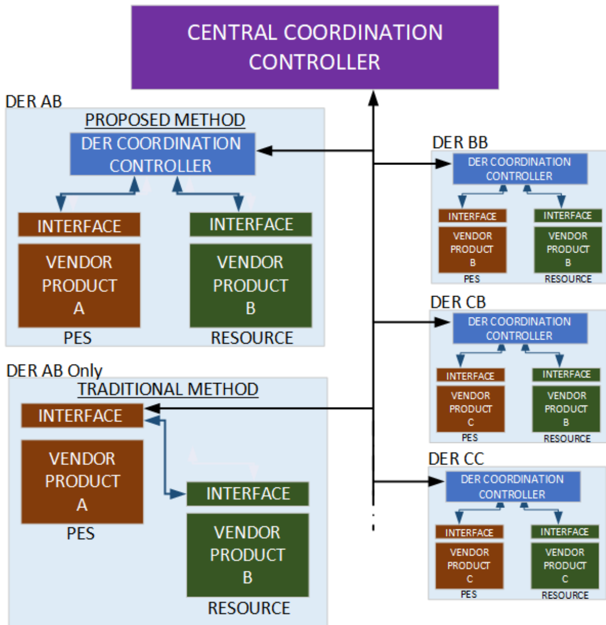


Fig. 1. Depiction of system integration from DER perspective

Utilizing the general architecture as presented in Fig. 1, layers of systems can be integrated from energy storage, renewables, and loads seamlessly into full systems such as microgrids or distribution management systems. This agent system supports full integrated technology capabilities including *integrated safety, plug-and-play capability, unit commissioning and operation, and DER peer-to-peer coordination*.

This paper is organized as follows: Section II provides a general background on the proposed hierarchal architecture for the various systems that construct a DER, Section III performs a review on literature regarding agents as applied to power electronics and the electrical grid. Section IV presents the proposed agent integration strategy, Section V provides system examples both in AC and DC implementation, Section VI provides demonstration of the full system working on a CHIL platform, and Section VII ends the paper with the Conclusion.

II. Proposed Distributed Energy Resource Architecture Applied in this Work

A DER is a system of systems that links a energy resource to the electric grid. This integration is usually conducted through a power electronic interface that converts and controls the output of the DER. Changing function requirements, nomenclature, state machine operations, and safety mechanisms represent only a few of the challenges with integrating technologies to construct and control a DER.

A depiction of a proposed architecture considering the hardware and systems integration of a PES, resource, and central controller is presented in Fig. 2. In this design, six distinct layers are presented: 1) central controller, 2) computational node (integration layer via agents), 3) resource controller (e.g., a battery management system, solar forecaster), 4) resource (e.g., batteries, photovoltaic array), 5) converter controller, and 6) converter (hardware stack) layer. These layers each support different purposes and operate in different timing regimes. The converter and converter controller collect data and perform closed loop control in spans of microseconds to milliseconds while at the central controller, resource optimization is on the order of minutes. Details on these subsystems that pertain to the agent system are described in the next subsections.

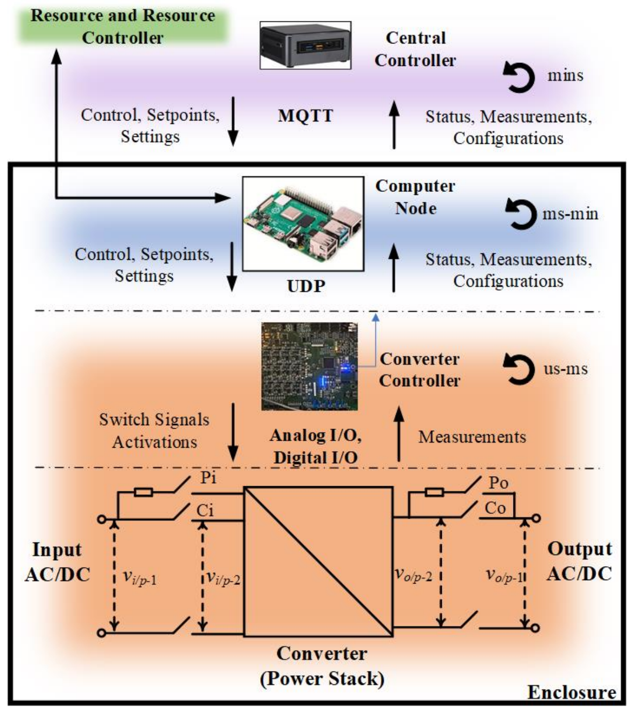


Fig. 2. Data/Signal flow from Converter to Central Controller

A. *Converter and Converter Controller*

A power electronic system (PES) is a self-contained, collection of hardware and software that converts current and voltage from one form to another (AC or DC). A conventional PES includes the following hardware systems: a power stack - power electronic switching modules/devices and associated gate drive circuitry; filter - power conditioning and electromagnetic interference (EMI) systems that reduce electrical noise; protection devices – provide automatic isolation of system components; sensors – used for collecting measurement data; and controllers - embedded software on digital signal processors (DSPs) or field programmable gate arrays (FPGAs) (Converter Controller). These systems as integrated into a PES are shown in Fig. 3.

In this work, the converter controller supports three core processes to perform the needed functions and communicate with the agent system: 1) a state machine (~5ms), 2) background loop for communications with the computational node (~10ms), and 3) closed loop control (~100us), as shown in Fig. 4. The converter controller state machine determines allowed operational modes of the converter and limits activation of specific functions based on the state. The state machine is also responsible for the coordination of the protection devices.

The background loop receives and sends data to the computer node (agent system) through a datagram protocol (UDP). A plug-and-play solution developed and described in [53] has been adopted to integrate the converter system automatically. The UDP communication systems developed is based on 4 byte messages. The first byte represents the data type (01- Configuration Control, 02-Status, 03-Measurements, 04-Setting, 05-Control, 06-Setpoints), the second byte the designation of the information contained such as Mode, and the third and fourth bytes the actual data (which could be a number representation for the example of Mode). Two communication ports are established on both ends for sending and receiving of data between computer node (in this case a Raspberry Pi) and converter controller. This is all performed over ethernet with a dedicated Internet Protocol address (ipaddress) on both the computer node and converter controller. The computer node and converter controller have a dedicated communication connection to provide high bandwidth communications, limit vulnerabilities, and ensure plug-and-play capability (ipaddress for setup is always the same).

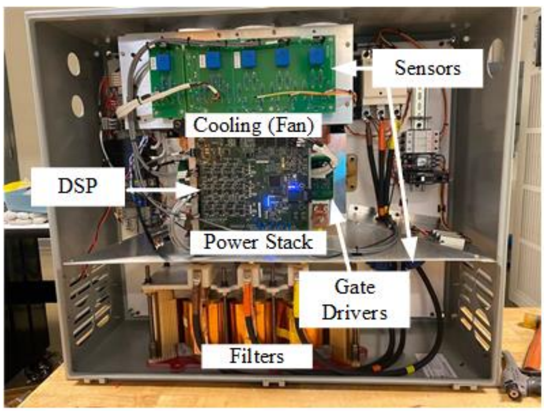


Fig. 3. Power electronic system depiction with components.

Through the UDP communications. the converter controller provides unique configuration information regarding the converter including converter type (AC/DC, AC/AC, DC/AC, or DC/DC), available control modes, and system ratings. While this provides a demonstration of one communication approach, others such as Modbus or IEC 61850 can be used.

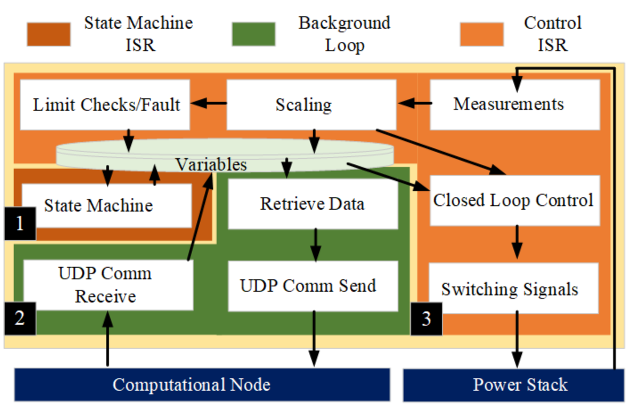


Fig. 4. Converter Controller - Digital Signal Processor (DSP) loops and functions

The closed loop control is based on the different modes programmed for supporting DER integration. Modes are chosen by the integration layer (agent system) based on availability as provided by the converter controller, however under anormal conditions the modes are overwritten by the converter controller. Details on implemented control can be found in [54]. A control interrupt service routine (ISR) collects measurements, scales the measurements, and confirms no faults or limits have been exceeded while also performing closed loop control.

B. Resource and Resource Controller

In many DER systems, the energy resources (energy storage, wind, solar, or variable load) utilize separate controllers and system managers for thermal management, data collection, and system monitoring and protection. In this work, these are recognized as the resource and resource controllers. These systems must be coordinated with the PES to create a fully integrated system.

An example of an energy storage system is shown in Fig. 5. In the presented example, the energy storage system utilizes a battery management system (BMS) that controls the various subsystems and represents the main communication interface. The BMS controls the isolation contactors, measures the cell voltages, and currents, enacts cell balancing, and determines the operations of the thermal management system. For an energy storage system, the BMS represents the resource controller and the energy storage medium (in this case the batteries) the resource.

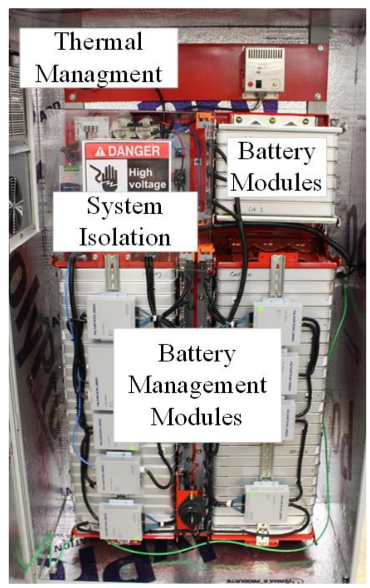


Fig. 5. Energy storage as a set of systems.

C. Central Controller

At the other end of the proposed hierarchy, a central controller has been developed that is able to coordinate, optimize, and graphically represent device performance through a data historian. A depiction of the central controller architecture is presented in Fig. 6. Since the system has been designed to support various integrations of DER systems and be plug-and-play, the central controller optimization was formulated to consider both AC and DC systems and to identify the coupling of the various integrated systems. A state machine has also been programmed as part of the central controller to orchestrate start-up and shutdowns of the devices within the system as needed. Optimization formulations considered in this work include utility economic signals, voltage limitations, energy storage capacity limitations, and device limits to name a few and are performed in each central controller state. These formulations are represented in previous work in [52]. Linear programming optimization methods are used within the central controller to perform the functions of energy management.

A message queuing telemetry transport (MQTT) protocol has been employed between the agent system (computer node) and central controller to create flexibility and plug-and-play type capabilities [53]. MQTT is a lightweight publish/subscribe protocol that uses TCP as a transport protocol and TLS/SSL for security and supports Quality of Service (QoS) for delivery of messages [54]. MQTT has been evaluated as a communication protocol in [55] and is used heavily in many different applications. This includes wireless sensors communications [56], home automation [57], and microgrids [58] to name a few.

Using MQTT and approaches such as self-discovery [59], each DER can self-identify and register with the central controller. This plug-and-play capability enables the integration of different single resource assets into a common framework without significant configuration.

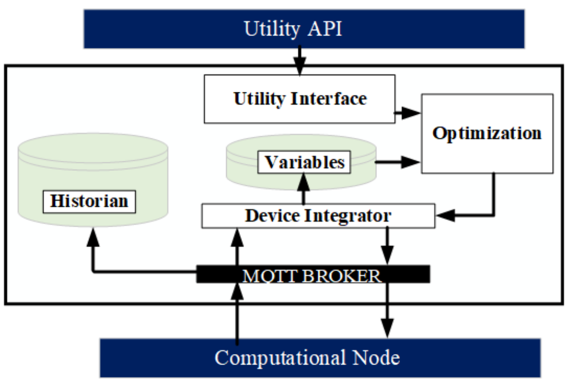


Fig. 6. Central Controller workflow.

For historical data capture, all the communication messages observed by the MQTT broker are recorded in Structured Query Language (SQL). A utility application programming interface (API) is used to pull optimization objectives and reference signals.

III. Agents as Applied to Grid Research

A depiction of the proposed electric grid hierarchy of systems considering PES and energy resources as DERs is provided in Fig. 7. In literature, different types of agent systems have been applied to each area.

For example, agent systems have been developed to support control of power in transmission systems [15]-[18]. An agent system has been developed in [15] to coordinate control of line reactor systems to adjust the network impedance and manage power flow. Agent decisions are guided by shared information from the system. In [16], agents systems have been applied to high voltage direct current (HVDC) systems. In this work, power electronic converters at the end of each line provide bus voltage control through direction from agent systems based on a shared control strategy. Agent systems have also been applied to improve transient stability in [17] by evaluating small signal stability at each node. A hiearchal system of agents linking transmission and distribution systems has been developed in [18]. In this work, transmission power flow is managed through agents at the distribution system interconnections. A centralized optimization scheme guides voltage targets.

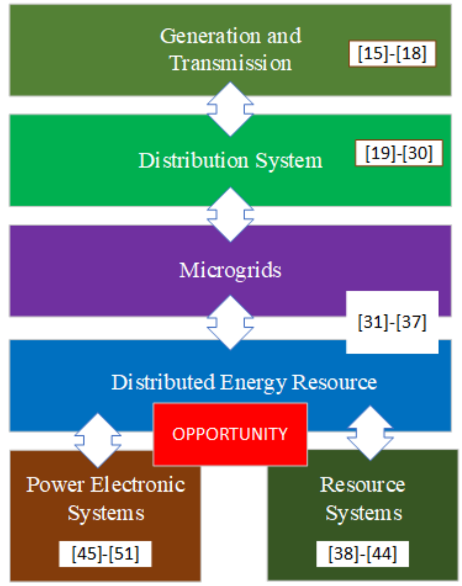


Fig. 7. Depiction of Hierarchy in the electric grid and existing

Within distribution networks, agents have been examined for targeting the improvement of electric grid resiliency, state estimation, and for resource management [19]-[30]. For grid resiliency, agent systems have been presented with decision making to support fault location, isolation, and self-restoration (FLISR) and system reconfiguration. In [19]-[27], the focus is on system restoration using chains in communication between protection systems or agents and a set of actionable sequences. These chains have been designed to detect and communicate to neighboring systems the outage and determine the outage limits and restoration in collaborative fashion. This includes the utilization and consideration of DERS in [26]-[28]. In [29], state estimation of the electrical distribution network has been developed with agents to increase the intelligence of the virtual system representation. Here, sensors at each node represent the agents and are coordinated through information sharing and a convergence on the estimation of voltage. In [30], DERs have been included and managed as part of the effort.

Microgrids have also seen agent systems proposed [31]-[37]. For microgrids, agents have been used to perform optimization and general integrated system bidding as means to manage energy. Sub-market development has been a key development in [32]-[33]. In [36]-[37], a set of agents were used to represent DERS as integrated systems within microgrids. In [36], a generalized control agent and resource type agent have been developed to produce bids.

For DERs, agent systems have also been developed and applied to support ES, RE, and load control [38]-[44]. In [38]-[40], real-world deployments of agent systems have been applied to learn, optimize, and control residential building water heaters and heating, ventilation, and air conditioning systems. A generic load management for shifting and curtailment was developed and simulated in [41]. Bidding systems for DERS as agent systems were created in [42]. Control over large numbers of PV [43] and ES [44] have also been demonstrated with agents.

Agent systems have also been developed for interlinking multiple converter systems in parallel [45]-[51]. In [45]-[46], agent systems have been employed to support parallelizing of DC/DC power electronic converters. The agent systems are used to provide a negotiation capability between converters for sharing power. This was conducted first in simulation [45] followed by demonstration in hardware [46]. Beyond power sharing, task sharing has been demonstrated through agents [47]. Agents have also been applied to power electronic building blocks (PEBBs) [48]-[51]. In [48], a small computing platform is connected to a DSP for control and demonstration on a controller hardware-in-the loop (CHIL) platform. In [49], hardware is developed, and a power quality improvement target is implemented.

In the reviewed works on agent systems, the development of a DER through the utilization of agents to integrate a resource and PES is not presented. Instead, the discussions have focused on either an existing integrated system connected with the electrical network for optimization and control or on the individual parts of the systems (such as in the case of PEBBs or renewables). This work proposes the utilization of agents within a local DER coordination controller which can seamlessly integrates various PES and resources to fill the missing gap as shown in Fig. 7. The proposed agent system is presented in the next section.

IV. Proposed Agent System For Systems Integration of Distributed Energy Systems

In this work, agents represent the lynchpin of the systems integration approach. Agents in this work are responsible for *safety in integrating multiple systems, commissioning and operation of a DER, addressing plug-and-play capabilities, and providing DER peer-to-peer coordination*. Agents represent the primary decision-making interfaces to the subsystems integrating the PES and resources into a common framework for DER coordination through a central controller. Features of agents that inherently benefit DER integration include [61]:

- Agents are social – agents share knowledge as requested information to improve performance on reaching a goal.
- Agents have autonomy - agents can act independently and execute based on information received
- Agents are proactive – agents use historical information and data to predict future actions.

In the following sections, the agents as applied to PES and resource integration is described in detail along with the features.

A. Core Agent Architecture

The developed agent framework centers around four core agents: 1) a resource agent (represented by a source or load), 2) converter agent, 3) interface agent, and 4) intelligence agent as shown in Fig. 8 and initially presented conceptually in [60]. These set of agents create a standardized configuration to best represent the respective integrated technologies needed to construct a DER and the use of a facilitator as described in [61]. In this framework, only a single agent of each type is needed for the computer node.

The resource agent interfaces with the integrated DER resource controller and is either in the form of a load or a source. The resource agents that have been developed and readily available today include: energy storage, photovoltaic (PV), AC and DC load, electric vehicle, and grid to name a few. These agents collect and provide information to be used by the central controller in terms of forecasts, system configuration, ratings, and measurements. These agents and the corresponding communication and control capabilities are described in Table I.

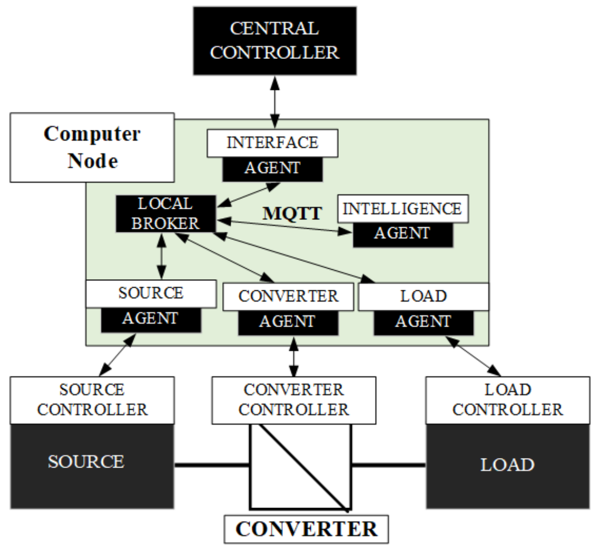


Fig. 8. Agents interactions to systems.

TABLE I. Resource Agent Descriptions

Agent	Purpose
PV	Communicates and obtains data regarding PV forecasts and measured data and issues electrical isolation control requests
ES	Communicates with the battery management system and obtains data regarding cell voltage, cell temperature, pack current, and pack state of charge.
EV	Communicates with the EV battery management system and obtains data regarding cell voltage, cell temperature, pack current, and pack state of charge and charging profile
AC Load, DC Load	Communicates and obtains data regarding load forecasts and measured data and issues electrical isolation control requests
Grid	Communicates and obtains grid configuration and measurement data.

The converter agent interacts with the converter controller (or DSP) and is able configure according to the data communicated by the converter. This information includes the converter configuration, ratings, available modes (both on the input and output sides of the converter), and any available precharge circuity. The facilitator (intelligence agent) is the agent that ties the systems into a single representable DER. The intelligence agent is responsible for ensuring the core agents are present, establishing the type of DER represented by the agents and subsystems, ensuring capability between the systems, ensuring modes and control options are available, and orchestrating system commands into targeted requests to the various DER subcomponents. Communication through the core agent system is represented in Fig. 9. As shown, the central controller obtains the various measurement, configuration, and status data and uses this information to determine the optimal trajectory for the set of resources based on user specifications and utility economic signal. In the next section, details regarding the agent system features developed are presented. These features support the rapid deployment and integration of DER technologies.

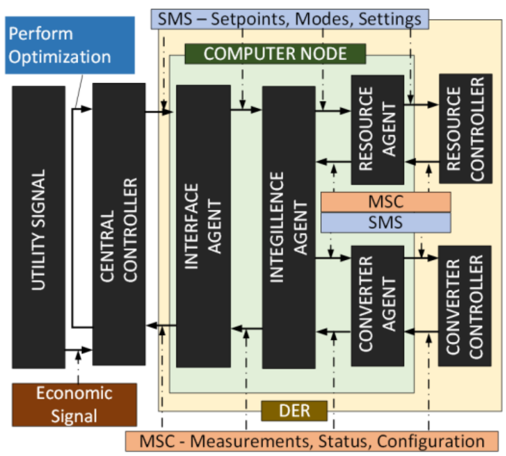


Fig. 9. Agent system interactions.

B. *Core Features offered by DER agent system*

A set of core agent system features have been developed to support the integration of PES and resources to construct a DER and include *integrated safety, unit commissioning and operation, plug-and-play capability, and DER peer to peer coordination*. These are critical to rapid expansion of DER systems.

While the agents represented by DER subcomponents (resource, converter, and interface) act primarily as communication interfaces to the various interconnected technologies, the agents also contain independent state machines, system monitoring, and decision making (or autonomy and proactive capabilities). Hence, these systems can monitor the integrated device data sets and act as another layer of verification and safety. The intelligence agent is used to combine the resources and verify device compatibility ensuring the systems are configured correctly and *integrated safely*. The intelligence agent is also responsible for hosting the DER system state machine.

The states represented for the individual agents and DER system include commissioning, standby, startup, normal, shutdown, faulted, error, and lockout. These states create a common framework for the agents independent of the interconnected resource. This ensures a consistent nomenclature is used within the agent framework to integrate systems independent of vendor-based protocols. Any faulted or errored state within an agent immediately results in messaging to the other agents to error and enact safety measures in the independent systems.

Each agent is launched in the *commissioning* state and upon completion of communication initiation and basic system parameter collection can transition to a standby state. In this state, the agent waits for further instructions from the intelligence agent. Fig. 10 shows a flow diagram of the intelligence agent decision-making process for DER system startup. As shown, the intelligence agent examines the resource types, converter type, the overall system type, configuration data including AC and DC interconnection, nominal voltage, and power ratings, enacts and verifies contactor closings, mode and setpoint collection as well as converter activation.

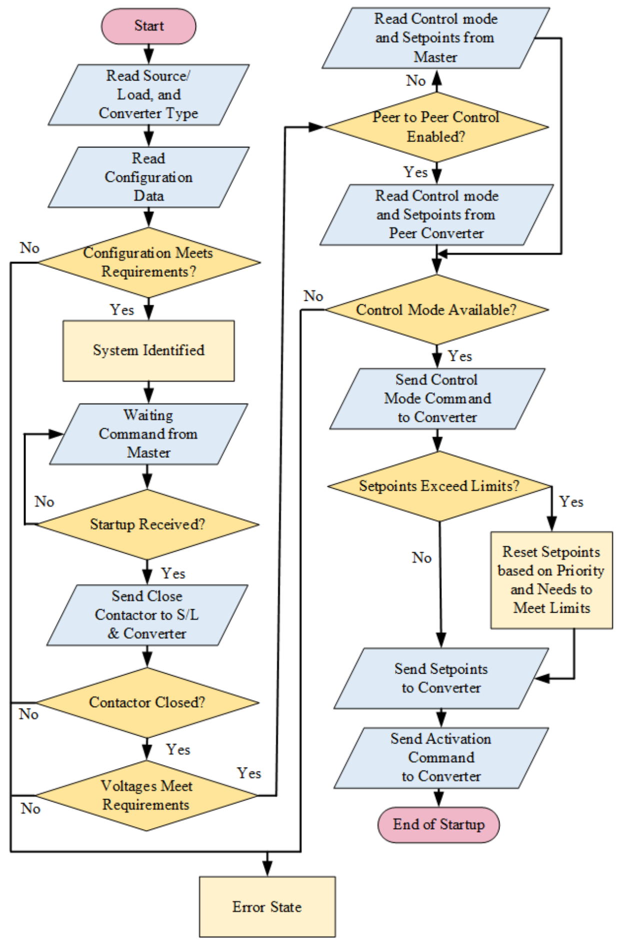


Fig. 10. Intelligence Agent Proposed Decision Making for Commissioning and Startup

As shown in Fig. 11, each agent has a core set of capabilities that are run in separate threads within a main program. These capabilities represent the social, autonomy, and proactive nature of the agent. These are run asynchronously and are constantly exchanging information with stored variables in local memory as global variables. Depending on the need, the various functions are either called at different intervals, upon receipt of data, or upon request from another function. Hence, each agent operates independently, reviewing data from the resource, and awaiting instructions from other agents. Since these systems are operated as independent entities, watchdogs have been added to each agent to ensure intercommunication between agents.

For agent-to-agent communications, the MQTT protocol has been chosen. On commissioning, the resource agent, converter agent, and interface agent all compile data and publish messages on the localhost to the intelligence agent to *self-identify* and to provide information regarding the integrated technology. Since, the four core agents are part of the standardized framework, the intelligence agent automatically begins to orchestrate system processes providing for plug-and-play configurability. The message topic in the MQTT schema is based on the recipient of the message and the type of information being shared [54]. Message data types are based on those presented in Fig. 9 (Configuration, Status, Measurements, Settings, Control, Setpoints). Javascript object notation (JSON) is used to contain the message payload allowing for simplified messaging structure and expansion of the architecture to support a growing evolution of system needs.

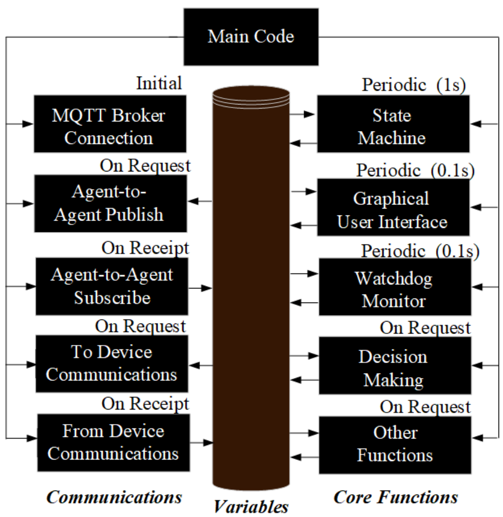


Fig. 11. Single agent threaded functions

Device coordination has also been enacted in the central controller and intelligence agent. A separate set of messages have been created to allow one DER system to follow another DER systems messages as shown in Fig. 12. This provides device coordination functions such as PV smoothing and load following. The intelligence agent enacts a proportional-integral calculation to perform the closed loop coordination control with the other DER resource.

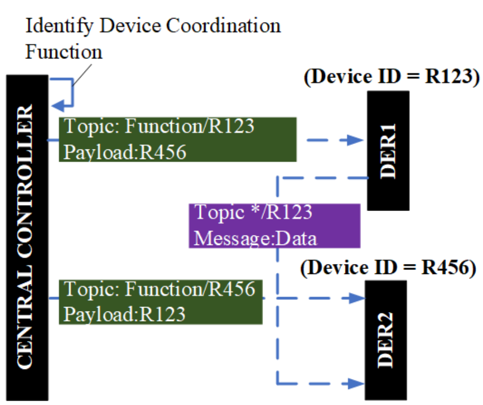


Fig. 12. Example messaging to enact peer-to-peer communications

In the next several sections, examples of the agent system applied to different system types are provided. The systems are discussed in terms of applications with resources and demonstrated to work in a controller hardware in the loop (CHIL) platform.

V. Example Use Cases for Proposed Agent Systems as Applied to Distributed Energy Systems

In this section, the integration of systems is discussed and presented through a detailed examination of multiple use cases (residential AC use case and energy storage system DC use case). As presented in Fig. 13, the integration of the resource, PES, and the electrical interconnection to create a DER can be coupled in many ways. The proposed agent system can intercouple these different configurations without any modifications in architecture because of the agent design. *This capability is not present in existing work.*

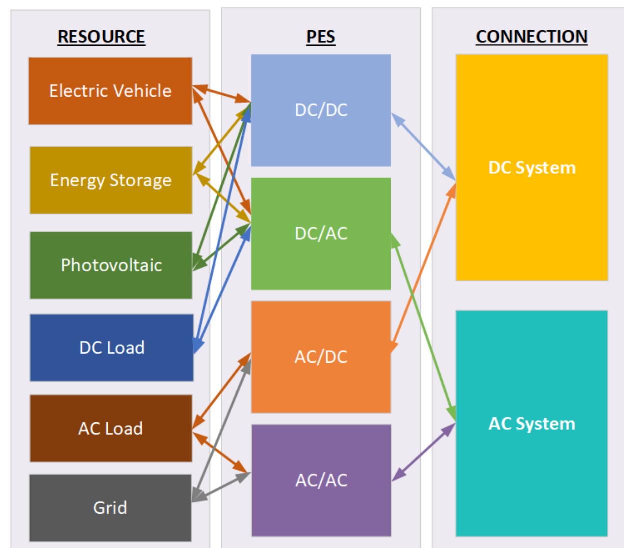


Fig. 13. Agent integration flexibility to support multiple system designs and DER topologies.

For this work, two sets of use cases are discussed with implementation of the agent-based distributed energy resource system. The objective is to demonstrate the ability for this framework to support multiple resources, converter topologies, and both AC and DC connections and how this system could be applied to real hardware implementations.

A. *Individual Coupled AC Systems (Residential System)*

An example depiction of a grid connected DC home with integrated PV and energy storage technologies is presented in Fig. 14. The single-phase energy storage system presented in this implementation has been fully developed in hardware as presented in [62]-[64] and shown to be able to be controlled to support multiple use cases. In these demonstrations simple control approaches have been applied with without the auto configurability and flexibility offered with the current agent systems.

As shown, in this configuration 380VDC has been identified as the DC high bus voltage for a home while a separate 12/24 VDC system is available for low power devices. The proposed agent system has been incorporated into each of the DERs (all single-phase AC/DC systems interconnected to a AC system but with different integrated resources and control mode needs as presented in Table II). These converters systems are comprised of a single-phase Hbridge inverter supporting a nominal 400Vdc link and 240V AC grid connection. The details for the converter system modeled are shown in Fig. 15. In this configuration, the dc side has been defined by the converter controller as the input and the ac grid interconnection as the output. Input signals to the system include contactor signals for input and output precharge circuits and pulse-width modulation (PWM) signals for controlling the semi-conductor switching that come from the converter controller (and other supporting circuits not discussed). DC and AC voltage and AC current measurements are used as the primary measurements for closed loop control.

These systems include grid-connected energy storage system, grid-connected PV system, and grid-connected DC home converter. The DC home and PV system resource agents support forecasting of expected consumption or production of the interconnected systems (24-hour at 5- minute resolution.) The energy storage resource agent communicates with the energy storage resource controller or battery management system (BMS) to extract SOC, status, and other information regarding the energy storage system.

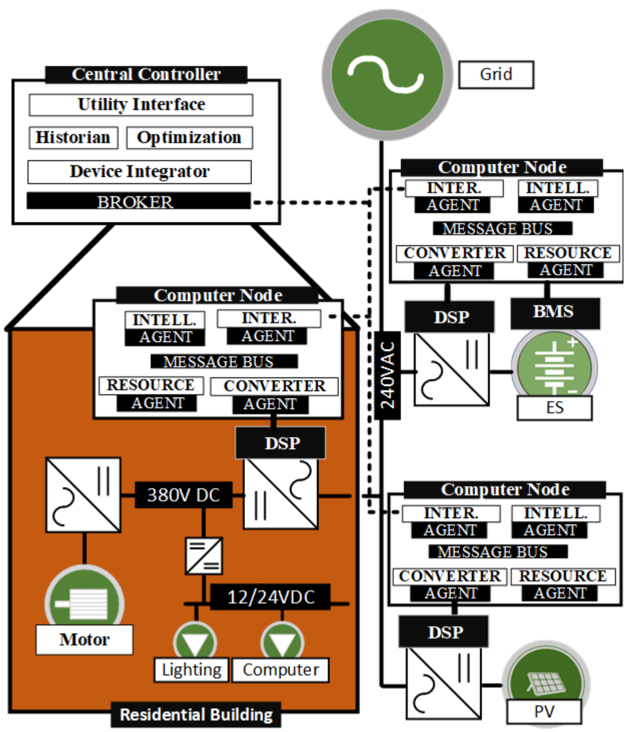


Fig. 14. Agent-based DER System to Support Residential Home DER integration.

TABLE II: AC SYSTEM CONTROL MODES PROGRAMMED

System Configuration	DSP Control Option		Resource Agent
	Input (400VDC)	Output (240VAC)	
PV System	MPPT		Forecast
ES System		P	BMS
DC Load	Vdcreg		Forecast

The control modes offered by the programmed converter controllers for the different resources include: maximum power point tracking (MPPT) for maximizing PV output; Vdcreg for regulating the DC voltage at the load side; and constant P for dispatching real power to charge and discharge the energy storage system. These modes are automatically adopted through the intelligence agent upon commissioning and startup of the system. The modes are also provided to the central controller where optimization is performed considering the available modes. In this use case, the optimization is focused on minimizing home-owner cost as driven by a price signal by the utility. In the next section, a DC coupled system is discussed followed by discussion of the CHIL testbed and results of simulation.

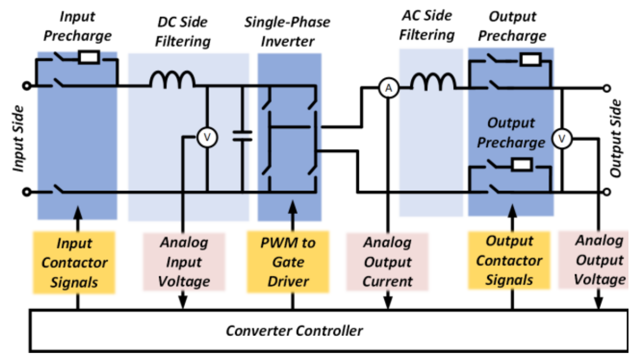


Fig. 15. Simplified circuit schematic of single-phase converter.

B. *Individual Coupled DC Systems (energy storage system)*

Grid connected energy storage systems come in a variety of power (kW) and energy ratings (kWh). For large systems, this usually includes multiple energy storage blocks integrated through power electronics. In this example, AC/DC and DC/DC converters are utilized to link various battery technologies into a single DC link for grid integration as shown in Fig. 16. The DC/DC conversion stages provide flexibility in adopting different energy storage systems with potentially differing system voltages and chemistries. The AC/DC conversion stage ties the DC link (nominal voltage of 1000Vdc) to the grid (3-phase, 480V) which can be integrated with other resources or be used as a stand-alone system with a transformer.

The details of each converter system modeled are shown in Figs. 17-18. The AC/DC converter is a conventional bi-directional three leg full-bridge converter with a 1000VDC bus and 480V three phase AC connection. DC/DC converter is a bi-directional buck-boost converter converting 400VDC battery voltage to the 1000VDC DC link voltage. In all these cases, the converter controller and supplementary circuits supply the contactor control for precharge circuits and PWM and receives voltage and current measurements for closed loop control.

In this configuration, the converter controller has been programmed to offer the modes presented in Table III. Similar to the DC home converter, the AC/DC converter controller is programmed to regulate the DC bus. The DC/DC converter controllers are programmed for constant power control with the objective to absorb and inject real power to the DC bus from the energy storage modules. The objective for the optimization in this case is to maximize the economic system value for the energy storage system considering a price signal while ensuring the DC bus voltage remains stable. In the next section, validation of the agent framework as applied as in a DER development is presented followed by simulation results.

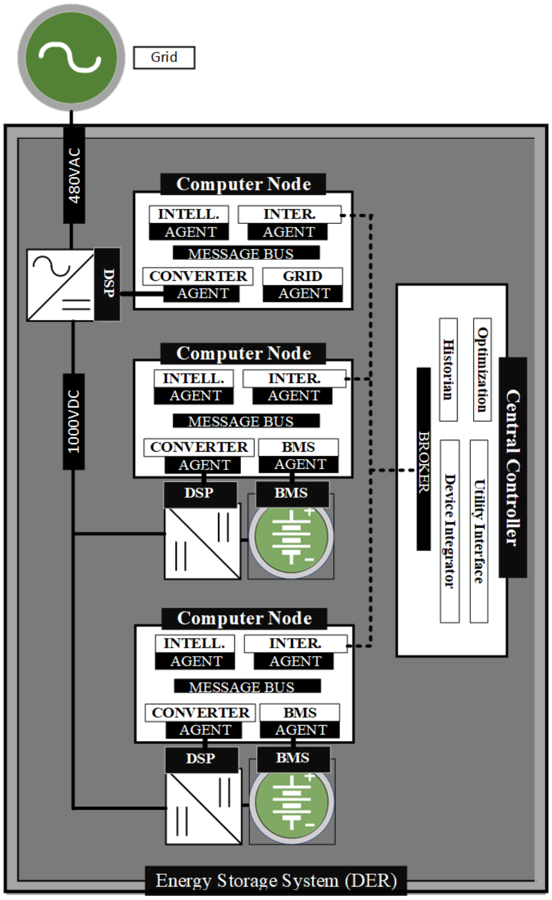


Fig. 16. Agent-based DER System to support the integration of multiple energy storage technologies to the grid.

TABLE III: DC SYSTEM CONTROL MODES PROGRAMMED

System Configuration	DSP Control Option		Resource Agent
	Input	Output	
ES System		P	BMS
Grid Converter	Vdcreg		Grid

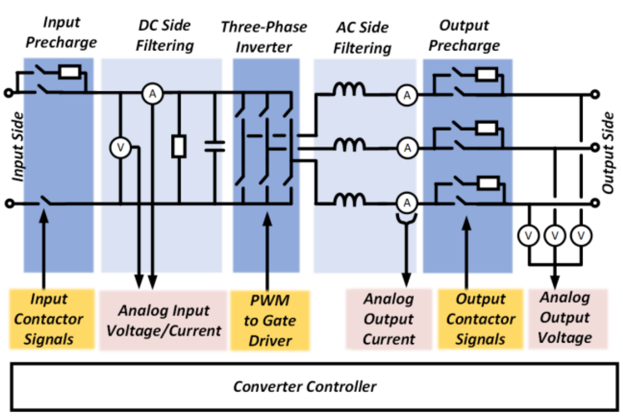


Fig. 17. Simplified circuit schematic of 100 kW three-phase grid connected converter

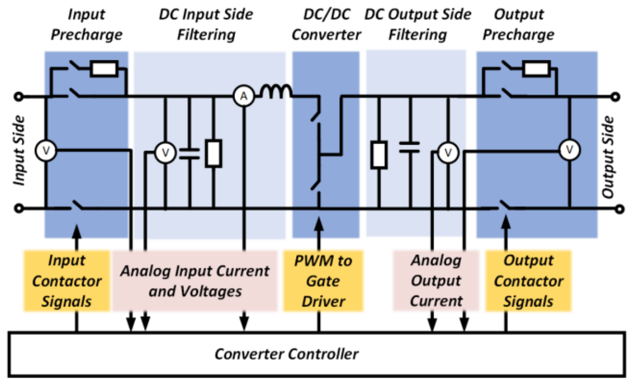


Fig. 18. Simplified circuit schematic of 50 kW DC-DC converter

I. VALIDATION OF AGENT SYSTEMS VIA CONTROLLER HARDWARE IN THE LOOP

The simplified block schematic for the CHIL implementation is presented in Fig. 19. A Typhoon HIL platform has been applied to the model the resources, resource controllers, and the converter stacks. The converter controllers are implemented in a digital signal processor (DSP) and programmed to perform the closed loop control modes described for the various use cases. The modelled power electronic systems include power electronic switch models, filtering, pre-charge and contactor circuitry, and system measurements. To provide closed loop control capabilities, the measurements from the circuit model are fed to the converter controller from analog I/O ports on the Typhoon. Digital control signals (switching and contactor control) from the converter controller are provided to separate digital I/O ports on the Typhoon to interact with the model. These interactions are represented previously in the power electronic topology schematics with the converter controller.

Resource models already existing in the Typhoon system (including energy storage, PV, and load) have been leveraged as part of this work. Load profiles for the electrical consumption of the loads and solar irradiance have been integrated through a Python extension on the Typhoon platform. Resource controllers have been modeled in the Typhoon system and employ a Modbus communication interface as shown in Fig. 19. for communication with the resource agent. Modbus is employed as the resource communication as this the most readily available communication capability constructed within the Typhoon HIL platform.

The agent systems have been deployed on Raspberry Pi 3.0 B+ as computational nodes with UDP and MQTT/Modbus communications performed through onboard ethernet connection and USB to ethernet adapter as shown in Fig. 19. Agents have been developed in Python 3.0.

Network switches are used to tie the communication between the resource, converter controller, computer node, and central controller. A HP notebook computer is used as the central controller supporting Linux.

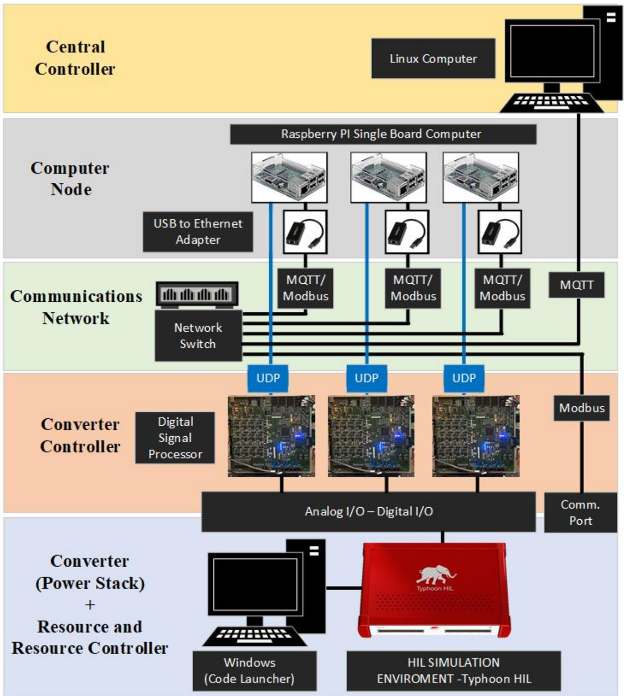


Fig. 19. Depiction of Typhoon CHIL implementation.

Commissioning of the systems begins with the agent systems that lie within the computer node. The agents are launched consecutively with a batch file and begin communicating with the interconnected converter controllers and resource controllers (in this case the Typhoon HIL simulator) and self-identify with the intelligence agent. This is shown in Fig. 20 (example of single-phase energy storage for the residential use case). The intelligence agent confirms the existence of the interface agent, resource (source/load) agent, and converter agent. Once the configuration data is obtained by the intelligence agent from the other agents, the intelligence agent validated configurability and creates a system type. At this stage, the system is commissioned and awaiting a 'startup' request from the central controller. A depiction of intelligence agent graphical user interface is shown in Fig. 21.

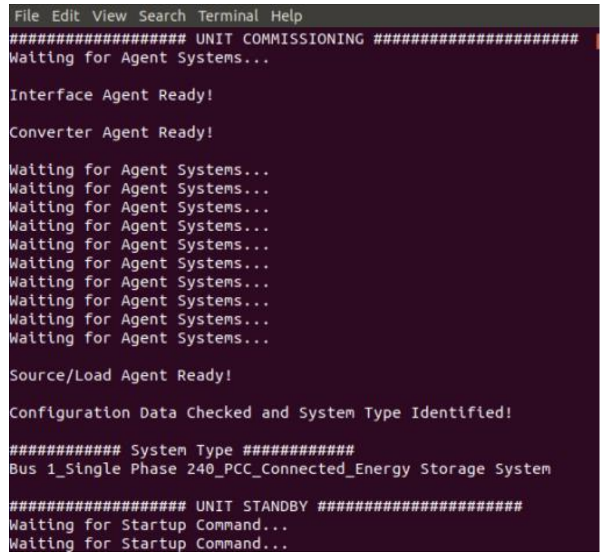


Fig. 21. Depiction of Terminal showing the intelligence agent and DER commissioning process (residential single phase energy storage example.)

Upon startup request from the central controller to start the DER (received and sent via the interface agent), the intelligence agent reviews the selected control mode and enacts a startup sequence. The intelligence agent communicates both with the energy storage system (modeled in the HIL system) through the resource agent and converter controller via the converter agent to coordinate the sequence of precharge and contactor settings as shown in Fig. 22.

As part of the startup sequence for the systems, the central controller identifies the available resources (via the intelligence agent designation) and optimizes the startup sequence. The optimization has been formulated based on two system types: 1) isolated systems and 2) systems connected to the grid. For isolated systems, the resources able to inject power into the bus are activated first followed by load assets. Systems that are grid connected are assumed to have sufficient supply and load is activated first. Figs 23-24 show the data

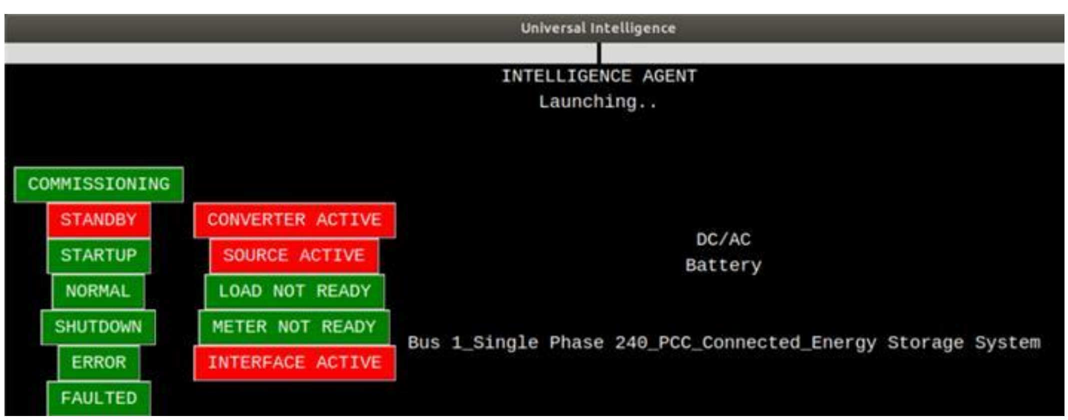


Fig. 20. Depiction of GUI showing the integration (residential single phase energy storage example.)

collected for startup from the central controller for the energy storage system and residential building. In each case, the central controller waits for full startup of each resource (which could take about 1min) before issuing startup command to the next resource. Fig. 25 shows the measured voltage at the AC bus and the currents of the converters within the residential system measured from the perspective of the Typhoon system.

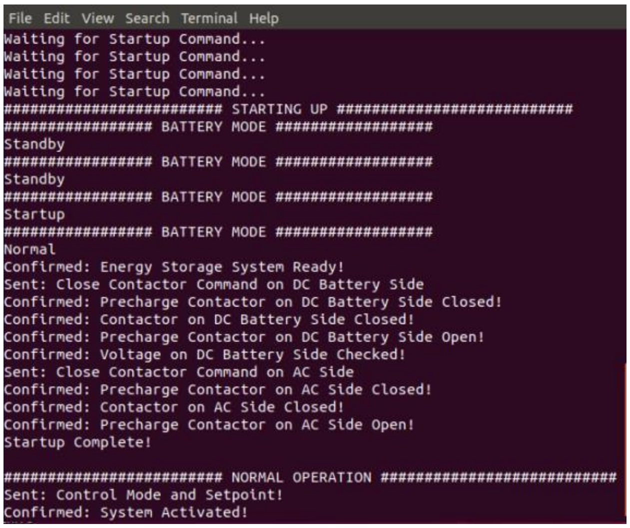


Fig. 22. Depiction of Terminal showing the intelligence agent and DER commissioning process (residential single phase energy storage example.)

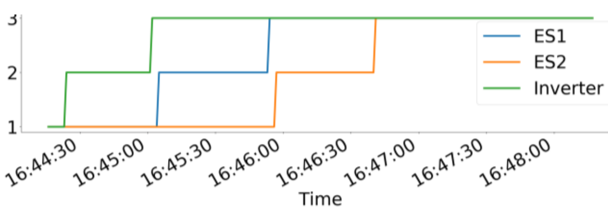


Fig. 23. System startup for energy storage system (‘Standby State’-1, ‘Startup State’-2, and ‘Normal State’ -3)

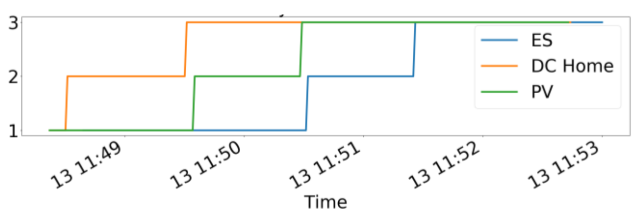
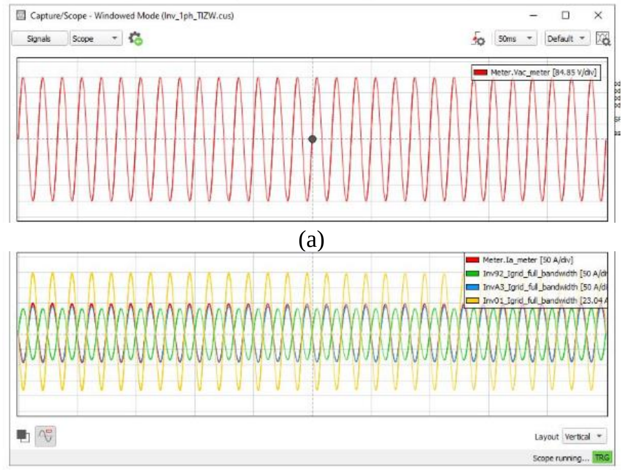


Fig. 24. System startup for residential system (‘Standby State’-1, ‘Startup State’-2, and ‘Normal State’ -3)

A utility price signal has been added to the central controller to provide a reference for the optimization and dispatch of the systems. The price signal is presented in Fig. 26. Long-term runs (exceeding 24 hours) have been conducted and are presented here to demonstrate the stability of the proposed hierarchy, agent system, central controller, computer node, and converter controller. In a 24-hour run, the agent systems will have communicated, processed, and responded to thousands of messages from the various interfaces. This provides a layer of confidence as the agent technology transfers to hardware implementation.



(a)

(b)

Fig. 25. Screen shot of the observed measurement data in the Typhoon HIL system based on converter controls and resource models in the residential system (a) measured voltage in HIL platform at PCC and (b) measured currents at the meter and DER systems: energy storage system, PV system, and load system.

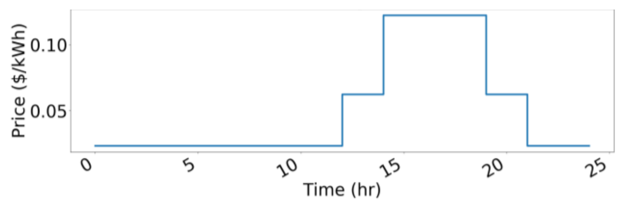


Fig. 26. Price signal applied in central controller [65]

For the residential AC use case, a periodic irradiance and load consumption signal have been applied to the PV and DC load within the Typhoon. As shown in Fig. 27, the PV system tracked the maximum power point successfully and produced maximum available power. The DC home also consumed power (showed as a negative value) as anticipated based on a constantly changing load. The periodic price signal incentivized the utilization of the energy storage system. Fig. 28 presents the real power and state of charge (SOC) of the energy storage system as dispatched by the central controller. As shown, the energy storage system was dispatched to charge (negative power) before the 12pm time frame and discharge (positive power) at the highest price period at 3pm. This demonstrates that the agent systems have 1) integrated multiple types of resources (PV, DC load, and energy storage) and PES (single phase inverter) into DERs effectively for optimization by a central controller, 2) provided AC system DER integration, and 3) operated the DER systems reliably.

For the energy storage system DC use case, the grid-connected inverter regulates the dc bus voltage for the frame of the experiment as shown in Fig. 29. The inverter provides 100kW of power to the grid when both energy storage systems inject power to the DC bus and absorbs 100kW to the DC bus when both energy storage systems are charging based on the optimal dispatch associated with the economic price signal. The power and SOC for the two energy storage systems presented in the use case are presented in Figs. 30-31. This demonstrates that the agent systems have 1) integrated multiple types of resources (grid and energy storage) and PES (DC/DC and AC/DC converters) into subsystem DERs effectively for optimization by a central controller for the energy storage system 2) provided DC DER sub-system integration, and 3) operated the DER sub-systems reliably.

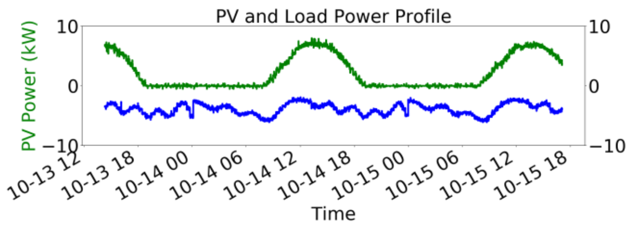


Fig. 27. DC home and PV power profile

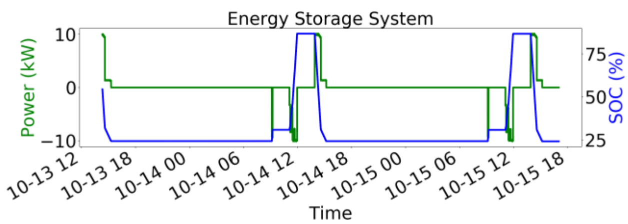


Fig. 28. Energy storage power and state of charge

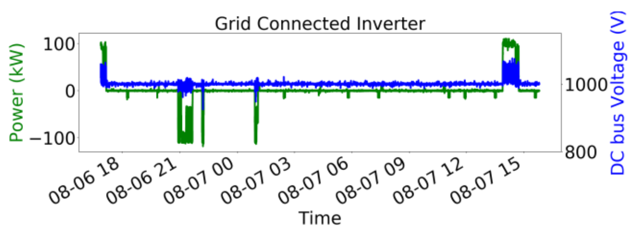


Fig. 29. Grid Connected Inverter Power and DC bus Voltage

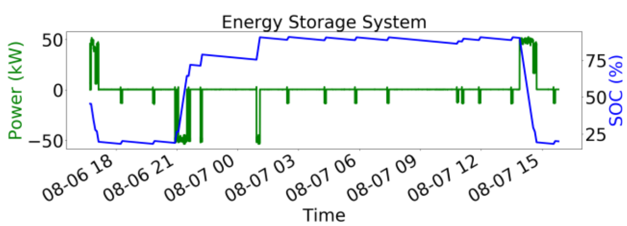


Fig. 30. Unit 1: Energy storage power and state of charge

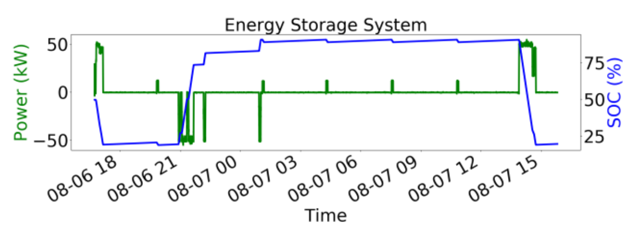


Fig. 31. Unit 2: Energy storage power and state of charge

II. Conclusion and Future Work

In this work, an agent system is proposed that can integrate different power electronic systems and resources into a distributed energy resource (DERs). This system of agents is focused on four different core agents that provide the basic premise of the agent system: interface agent, intelligence agent, converter agent, and resource agent. This paper demonstrates that the developed agent works for multiple use cases including single converter systems interconnected on a AC system and multiple converters connected to a DC system.

Future work will focus on the deployment of the agent architecture and system onto full DER systems. This includes the utilization of a power stack, filters, contactors, and other components modeled within the CHIL platform.

III. Acknowledgments

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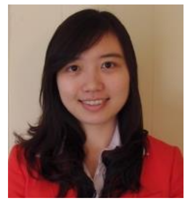

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