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

M. Starke, *Senior Member*, *IEEE,* B. Xiao, *Member*, *IEEE*, P. Bhowmik, *Member*, *IEEE,* S. Campbell, *Member*, *IEEE,* M. Chinthavali, *Senior Member*, *IEEE,* B. Dean, *Member*, *IEEE,* R.S. K. Moorthy, *Member*, *IEEE*, M. Smith, *Member*, *IEEE,* A. Thapa, *Member*, *IEEE*

***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 a set of end-use systems. The agent framework is validated in hardware using controller-hardware-in-the-loop (CHIL) simulation platform.**

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

I. Introduction

The electric grid has seen significant advancements 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 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 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].

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 [6]. Closed loop PES controls for different renewable systems are discussed in [7]. Architectures for the integration options for AC and DC networks and PES are discussed in [8]. Finally, integration of PES into the electric grid and necessary functions are presented in [9]. The work presented in these publications are directed to solve 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 [10].

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 [11]-[12]. 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.

This works proposes to address DER systems integration challenges (considering multiple vendors) through the utilization of a collection of agents that represent a novel approach to systems. The concept of applying agent-based to solve electric power system problems has been widely reported in literature. For example, use of agent systems in distribution networks for improvement of electric grid resiliency, state estimation, and for resource management has been shown [13]-[24]. In microgrids, agents have been used for optimization and general integrated system bidding as means to manage energy [25]-[31]. For DERs, agent systems have also been developed to represent full resource systems such as in the case of ES, RE, and load control [32]-[37]. Agent systems have also been developed for interlinking multiple power electronic converter systems in parallel [38]-[44]. However, integration of DERs with power electronic systems has not been addressed.

The proposed agent framework provides flexibility and opportunities to try new topologies without changing the full system architecture speeding up development and testing of new concepts. 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. The proposed agent system supports full integrated technology capabilities including *integrated safety, plug-and-play capability, unit commissioning and operation, and DER peer-to-peer coordination.*

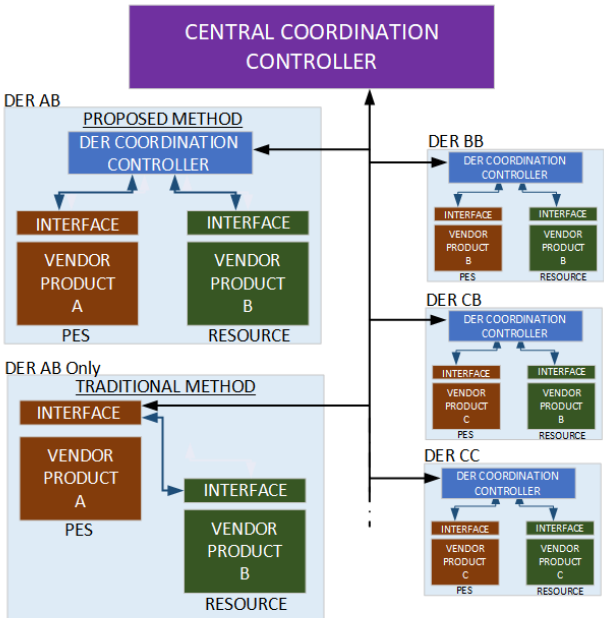


Fig. 1. Depiction of system integration from DER perspective

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 presents the proposed agent integration strategy, Section IV provides a system example of an AC implementation, Section V provides validation of the full system working on a CHIL platform, and Section VI 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 energy resources 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.

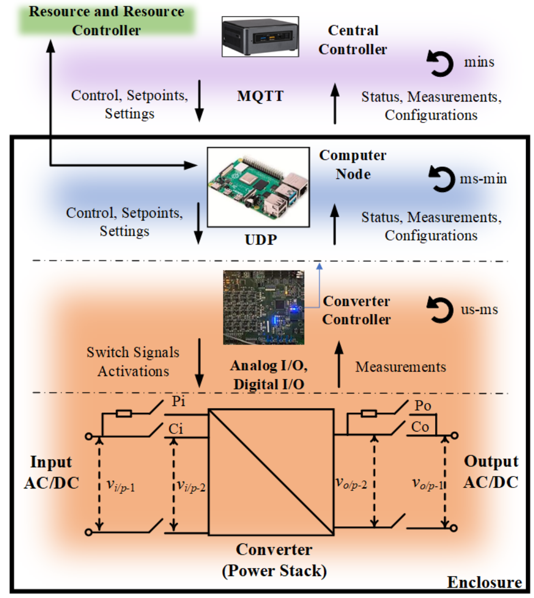


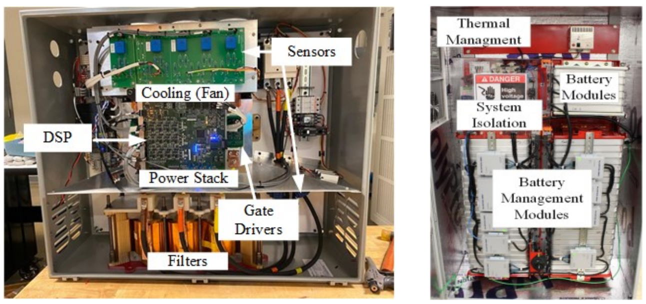
Fig. 2. Data/Signal flow from Converter to Central Controller

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 [45] 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 static and always the same).



(a) (b)

Fig. 3. Depiction of a) power electronic system and b) battery system

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.

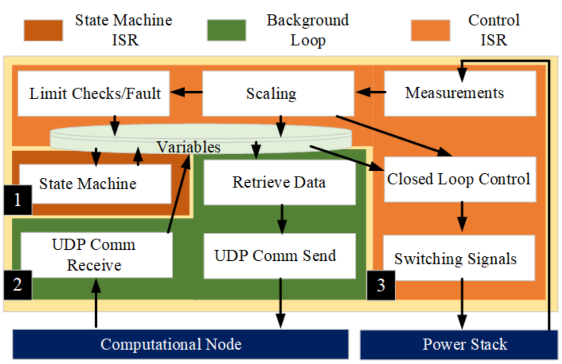


Fig. 4. Converter Controller - DSP loops and functions

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 based on need (such as the case in a fault). 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. 3. 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.

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. 5. 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 [46]. 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 [45]. 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 [47]. MQTT has been evaluated as a communication protocol in [48] and is used heavily in many different applications. This includes wireless sensors communications [49], home automation [50], and microgrids [51] to name a few.

Using MQTT and approaches such as self-discovery [52], 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.

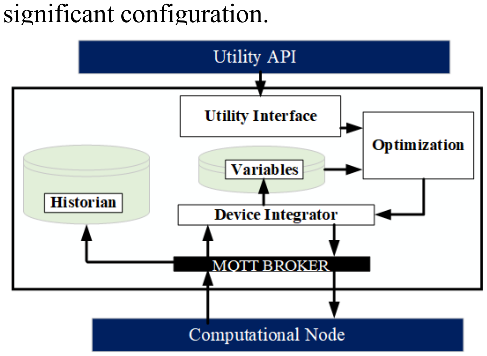


Fig. 5. Central controller workflow.

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 Edge

In this work, agents represent the lynchpin of the systems integration approach. Agents in this work are responsible for *safely 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 [53]:

- 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. 6 and initially presented conceptually in [54]. 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 [53]. 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.

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. 7. 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.

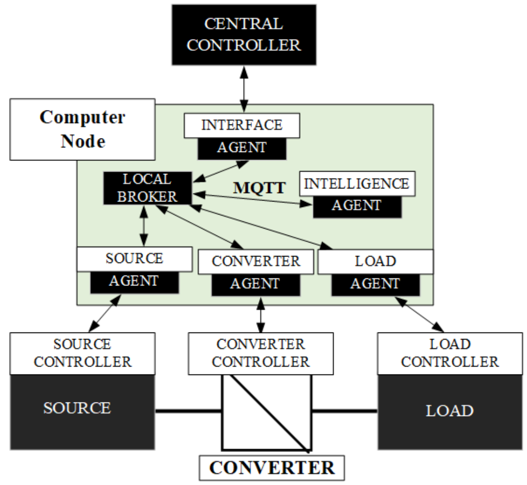


Fig. 6. Agents interactions to systems.

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.

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. 7 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.

As shown in Fig. 8, 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 [52]. Message data types are based on those on Fig. 2. (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.

As an example, to best illustrate the threading functions of the agents (Fig. 8) and communication linkage between the agents and devices (Fig. 2), consider a message being sent from the converter controller to the central controller. The converter agent will receive a UDP message from the converter controller on converter status which is saved into local variable in the converter agent program. Data is retrieved from this variable and used to transmit information through the MQTT protocol (local host) to other agents (including the interface agent). The interface agent subscribes to the message and stores the information into a separate local variable. The message is retrieved and transmitted on the communication network via the MQTT protocol to the central controller.

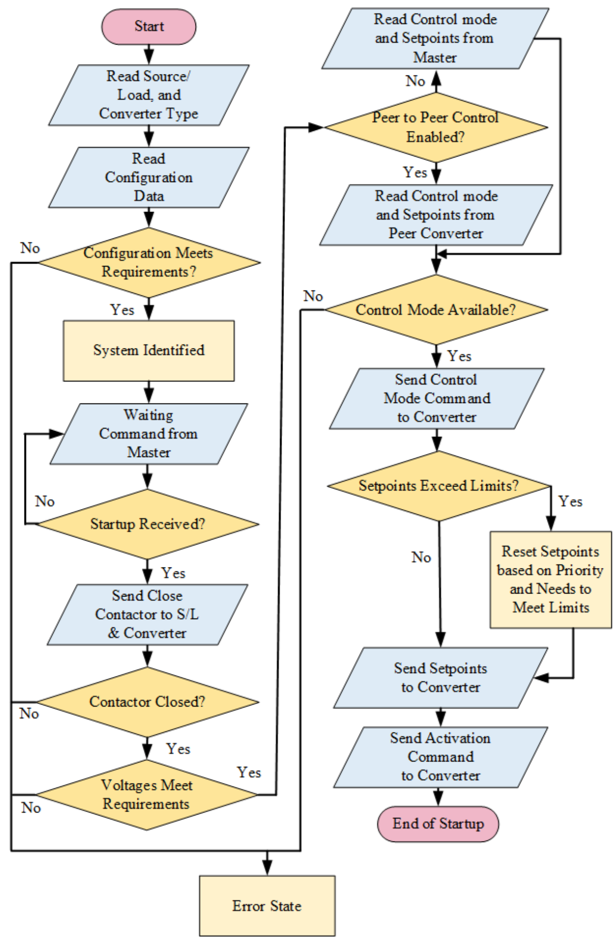


Fig. 7. Intelligence Agent Proposed Decision Making for Commissioning and Startup

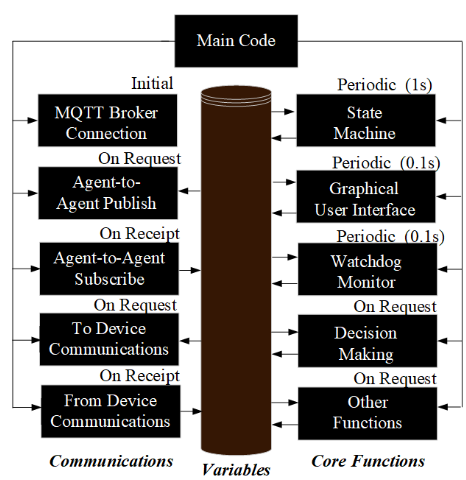


Fig. 8. Single agent threaded functions

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 [45]. 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. In the next several sections, an example of the agent system applied to a single use case is provided.

IV. 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 a single use case (energy storage, PV, and load systems connected by a AC bus). As presented in Fig. 9, 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.*

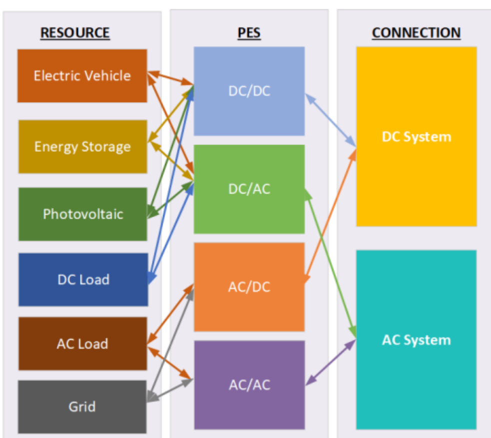


Fig. 9. Agent integration flexibility to support multiple system designs and DER topologies.

For this work, a single use case is discussed with implementation of a agent-based residential networks system. The objective is to demonstrate the ability for this framework to support multiple resources, converter topologies, 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. 10. The single-phase energy storage system presented in this implementation has been fully developed in hardware as presented in [55] and shown to be able to be controlled to support multiple use cases in [56].

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 [56]). These converters systems are comprised of a single-phase H-bridge inverter supporting a nominal 400Vdc link and 240V AC grid connection. The details for the converter system modeled are presented in [56]. 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.

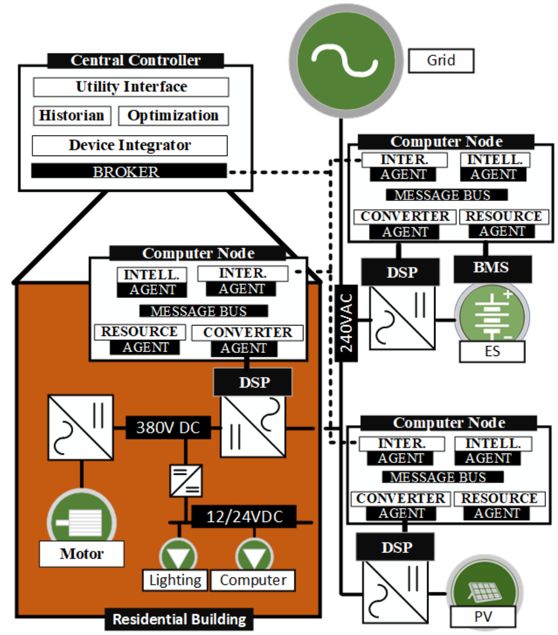


Fig. 10. Agent-based DER System to Support Residential Home

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.

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.

A. Other Examples

The agent framework has also been applied to DC networks as described in [57] and [58]. These include the construction of a multi-chemistry energy storage system composed of multiple batteries and a low voltage hub that integrates resources (load, PV, and ES) for commercial building applications. This demonstrates the flexibility of the agent system to be utilized across multiple platforms.

V. Validation of Agent Systems Via Controller Hardware in the Loop

For demonstration, 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.

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 for communication with the resource agent. Modbus is employed as the resource communication protocol as this has been found to be 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 an onboard ethernet and USB connection (USB to ethernet adapter). 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, and Typhoon HIL system. A HP notebook computer is used as the central controller supporting Linux.

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. 11. 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.

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. 12.

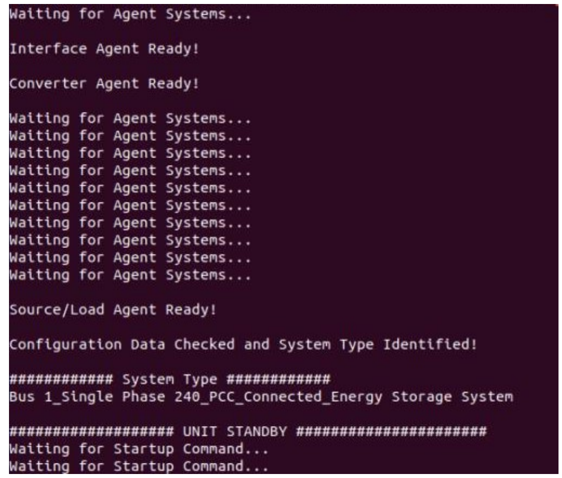


Fig. 11. Depiction of Terminal showing the intelligence agent and DER commissioning process.

Fig. 12. Depiction of Terminal showing the intelligence agent and DER commissioning process.

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. Fig 13 show the data 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 for closing contactors, confirming voltages, and communicating data) before issuing startup command to the next resource. Fig. 14 shows the measured currents of the converters within the residential system measured from the perspective of the Typhoon system.

A utility price signal has been added to the central controller to provide a reference for the optimization and dispatch of the systems [59]. 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.

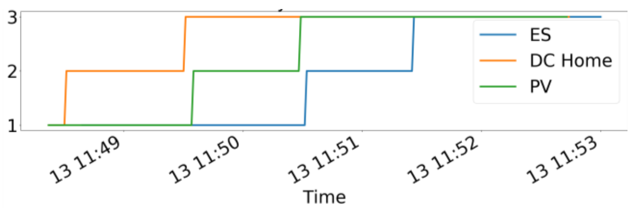


Fig. 13. System startup for residential system (‘Standby State’-1, ‘Startup State’-2, and ‘Normal State’ -3)

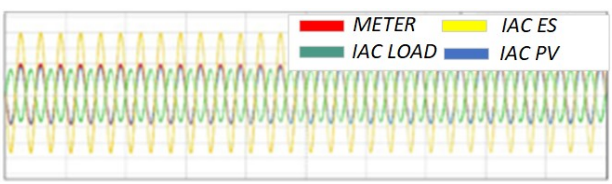


Fig. 14. Screen shot of the observed measurement data in Typhoon HIL

A periodic irradiance and load consumption signal have been applied to the PV and DC load within the Typhoon. As shown in 15, 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 during peak hours. Fig. 16 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.

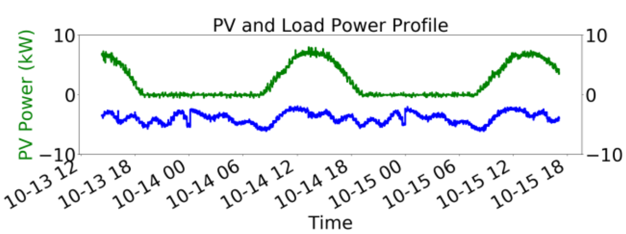


Fig. 15. DC home and PV power profile

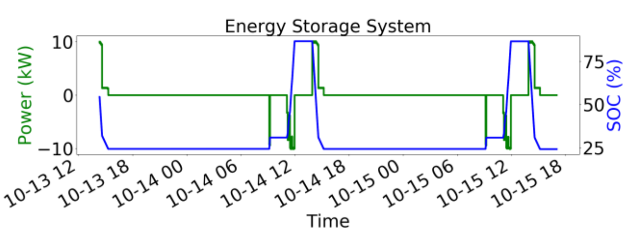


Fig. 16. Energy storage power and state of charge

VI. 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 single converter systems interconnected on a AC system but also presents other work which applies to DC systems.

Work is in progress to demonstrate this agent system as applied to full hardware systems and communication networks and applications. This includes the utilization of a power stack, filters, contactors, and other components modeled within the CHIL platform.

VII. Acknowledgments

This work was funded by the U.S. Department of Energy, Office of Electricity, Energy Storage Program and Office of Energy Efficiency Renewable Energy, Building Technologies Program under contract number DE-AC05-00OR22725.

References

[1] M. Yao and X. Cai, "An Overview of the Photovoltaic Industry Status and Perspective in China," in IEEE Access, vol. 7, pp. 181051-181060, 2019.

[2] W. J. Cole, C. Marcy, V. K. Krishnan and R. Margolis, "Utility-scale lithium-ion storage cost projections for use in capacity expansion models," 2016 North American Power Symposium (NAPS), Denver, CO, 2016.

[3] M. Stecca, L. R. Elizondo, T. B. Soeiro, P. Bauer and P. Palensky, "A Comprehensive Review of the Integration of Battery Energy Storage Systems Into Distribution Networks," in IEEE Open Journal of the Industrial Electronics Society, vol. 1, pp. 46-65, 2020.

[4] E. G. Nilsson, E. K. Nordhagen and G. Oftedal, "Aspects of systems integration," Systems Integration '90. Proceedings of the First International Conference on Systems Integration, 1990, pp. 434-443.

[5] A. C. Silva and G. Loureiro, "System integration issues - Causes, consequences & mitigations," 2011 IEEE International Conference on Industrial Engineering and Engineering Management, 2011, pp. 1338-1342.

[6] M. Gerber and J. A. Ferreira, "A System Integration Philosophy for Demanding Requirements in Power Electronics," 2007 IEEE Industry Applications Annual Meeting, 2007, pp. 1389-1396.

[7] J. M. Carrasco et al., "Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey," in IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1002-1016.

[8] D. Boroyevich, F. Wang, J. D. v. Wyk, F. C. Lee, Q. Liu and R. Burgos, "Systems Integration at CPES," 4th International Conference on Integrated Power Systems, 2006, pp. 1-6.

[9] B. Kroposki, C. Pink, R. DeBlasio, H. Thomas, M. Simões and P. K. Sen, "Benefits of Power Electronic Interfaces for Distributed Energy Systems," in IEEE Transactions on Energy Conversion, vol. 25, no. 3, pp. 901-908, Sept. 2010.

[10] I. Batarseh and K. Alluhaybi, "Emerging Opportunities in Distributed Power Electronics and Battery Integration: Setting the Stage for an Energy Storage Revolution," in IEEE Power Electronics Magazine, vol. 7, no. 2, pp. 22-32, June 2020.

[11] L. Arnedo, R. Burgos, D. Boroyevich and F. Wang, "System-Level Black-Box Dc-to-Dc Converter Models," 2009 Twenty-Fourth Annual

IEEE Applied Power Electronics Conference and Exposition, 2009, pp. 1476-1481.

[12] V. Valdivia, A. Barrado, A. Lazaro, P. Zumel and C. Raga, "Easy Modeling and Identification Procedure for "Black Box" Behavioral Models of Power Electronics Converters with Reduced Order Based on Transient Response Analysis," 2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition, 2009, pp. 318-324.

[13] G. Zhabelova, V. Vyatkin and V. Dubinin, "Decision making for industrial agents in Smart Grid applications," IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 3584-3590.

[14] A. Deshmukh et al., "Multi Agent Systems: an Example of Dynamic Reconfiguration," 2006 IEEE Instrumentation and Measurement Technology Conference Proceedings, Sorrento, 2006, pp. 1172-1177.

[15] K. Eshghi, B. K. Johnson and C. G. Rieger, "Resilient Agent for Power System Operations and Protection," IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, 2018, pp. 780-785.

[16] Y. Liu, Y. Hou, S. Lei, and D. Wang, “A distribution network restoration decision support algorithm based on multi-agent system,” Asia-Pacific Power Energy Eng. Conf. APPEEC, vol. 2016-December, pp. 33–37, 2016.

[17] J. M. Solanki, S. Khushalani and N. N. Schulz, "A Multi-Agent Solution to Distribution Systems Restoration," in IEEE Transactions on Power Systems, vol. 22, no. 3, pp. 1026-1034, Aug. 2007.

[18] T. Nagata, Y. Tao, H. Sasaki and H. Fujita, "A multiagent approach to distribution system restoration," 2003 IEEE Power Engineering Society General Meeting (IEEE Cat. No.03CH37491), Toronto, ON, Canada, 2003, pp. 655-660 Vol. 2.

[19] X. Chen, B. Kong, F. Liu, X. Gong and X. Shen, "System Service Restoration of Distribution Network Based on Multi-agent Technology," 2013 Fourth International Conference on Digital Manufacturing & Automation, Shinan, China, 2013, pp. 1371-1374.

[20] K. Anisha, M. Rathinakumar, N. Veerappan and O. K. Satya Prakash, "Multi agent based distribution system restoration with distributed generation," 2014 IEEE National Conference on Emerging Trends In New & Renewable Energy Sources And Energy Management (NCET NRES EM), Chennai, India, 2014.

[21] P. Prabawa and D. Choi, "Multi-Agent Framework for Service Restoration in Distribution Systems With Distributed Generators and Static/Mobile Energy Storage Systems," in IEEE Access, vol. 8, pp. 51736-51752, 2020.

[22] M. J. Ghorbani, M. A. Choudhry and A. Feliachi, "A Multiagent Design for Power Distribution Systems Automation," in IEEE Transactions on Smart Grid, vol. 7, no. 1, pp. 329-339, Jan. 2016.

[23] S. M. Shafiul Alam, B. Natarajan and A. Pahwa, "Agent based state estimation in smart distribution grid," 2013 IEEE Latin-America Conference on Communications, Santiago, Chile, 2013, pp. 1-7.

[24] I. Ahmad, P. Palensky and W. Gawlik, "Multi-Agent System based voltage support by distributed generation in smart distribution network," 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), Vienna, Austria, 2015, pp. 329-334.

[25] F. I. Hernandez, C. A. Canesin, R. Zamora and A. K. Srivastava, "Active power management in multiple microgrids using a multi-agent system with JADE," 2014 11th IEEE/IAS International Conference on Industry Applications, Juiz de Fora, 2014, pp. 1-8.

[26] H. S. V. S. K. Nunna and D. Srinivasan, "An agent based energy market model for microgrids with Distributed Energy Storage Systems," 2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Trivandrum, 2016, pp. 1-5.

[27] H. S. V. S. K. Nunna, A. Sesetti, A. K. Rathore, and S. Doolla, “Multiagent-Based Energy Trading Platform for Energy Storage Systems in Distribution Systems with Interconnected Microgrids,” IEEE Trans. Ind. Appl., vol. 56, no. 3, pp. 3207–3217, 2020.

[28] F. Y. S. Eddy and H. B. Gooi, "Multi-agent system for optimization of microgrids," 8th International Conference on Power Electronics - ECCE Asia, Jeju, 2011, pp. 2374-2381.

[29] K. Nunna and D. Srinivasan, “A Multi-Agent System for Energy Management in Smart Microgrids with Distributed Energy Storage and Demand Response,” IEEE Int. Conf. Power Electron. Drives Energy Syst. PEDES 2016, vol. 2016-January, pp. 1–5, 2017.

[30] M. Meiqin, D. Wei and L. Chang, "Multi-agent based simulation for Microgrid energy management," 8th International Conference on Power Electronics - ECCE Asia, Jeju, 2011, pp. 1219-1223.

[31] Z. Jiang, "Agent-Based Control Framework for Distributed Energy Resources Microgrids," 2006 IEEE/WIC/ACM International Conference on Intelligent Agent Technology, Hong Kong, China, 2006, pp. 646-652.

[32] M. Starke et al., "Agent-Based System for Transactive Control of Smart Residential Neighborhoods," 2019 IEEE Power & Energy Society General Meeting (PESGM), 2019, pp. 1-5.

[33] M. Starke et al., "Real-Time MPC for Residential Building Water Heater Systems to Support the Electric Grid," 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2020, pp. 1-5.

[34] T. Logenthiran, D. Srinivasan and T. Z. Shun, "Multi-Agent System for Demand Side Management in smart grid," 2011 IEEE Ninth International Conference on Power Electronics and Drive Systems, Singapore, 2011, pp. 424-429.

[35] H. Guo, J. Wu, L. Kong and X. Qiu, "Distributed hybrid wind-PV power system based on multi-agent," 2009 3rd International Conference on Power Electronics Systems and Applications (PESA), Hong Kong, 2009, pp. 1-3.

[36] Sangsoo Park, Y. Miura, and T. Ise, “A maximum power control scheme based on multi-agent system for distributed flexible network photovoltaic system,” in 2012 International Conference on Renewable Energy Research and Applications (ICRERA), Nov. 2012, pp. 1–6.

[37] X. Li and D. Zhang, “Coordinated control and energy management strategies for hundred megawatt-level battery energy storage stations based on multi-agent theory,” Int. Conf. Adv. Mechatron. Syst. ICAMechS, vol. 2018-Augus, pp. 152–156, 2018.

[38] J. Hamar, "Decentralized, agent-based control of low and moderate power DC-DC converters," 2009 Brazilian Power Electronics Conference, Bonito-Mato Grosso do Sul, 2009, pp. 410-416.

[39] P. Bartal, J. Hamar and I. Nagy, "Parallel DC/DC converters with multi-agent based multi-objective optimization for consumer electronics," 2011 IEEE International Conference on Consumer Electronics -Berlin (ICCE-Berlin), Berlin, 2011, pp. 276-280.

[40] E. Krüger, J. Liu, F. Ponci, and A. Monti, “Optimization of task sharing towards multi-agent control of PEBB based power systems,” 2012 IEEE PES Innov. Smart Grid Technol. ISGT 2012, pp. 1–7, 2012.

[41] A. Benigni, H. L. Ginn, A. Lowen, F. Ponci and A. Monti, "An embedded solution for multi-agent control of PEBB based power electronic systems," 2014 IEEE International Workshop on Intelligent Energy Systems (IWIES), San Diego, CA, 2014, pp. 12-17.

[42] H. L. Ginn, F. Ponci, and A. Monti, “Multi-agent control of PEBB based power electronic systems,” 2011 IEEE PES Trondheim PowerTech Power Technol. a Sustain. Soc. POWERTECH 2011, pp. 1–6, 2011.

[43] A. Monti and F. Ponci, “PEBB standardization as key enabler for power control flexibility,” IEEE Int. Symp. Ind. Electron., pp. 3695–3699, 2010.

[44] A. Monti, R. Liu, A. Deshmukh, F. Ponci and R. Dougal, "Towards a new fully-flexible control approach for distributed Power Electronics Building Block systems," 2008 34th Annual Conference of IEEE Industrial Electronics, Orlando, FL, 2008, pp. 2955-2961.

[45] M. Starke et al., "A Plug-and-Play Design Suite of Converters for the Electric Grid," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020, pp. 2314-2321.

[46] G. Liu, M. Starke, Xiaohu Zhang and K. Tomsovic, "A MILP-based distribution optimal power flow model for microgrid operation," 2016 IEEE Power and Energy Society General Meeting, 2016, pp. 1-5.

[47] N. Naik, "Choice of effective messaging protocols for IoT systems: MQTT, CoAP, AMQP and HTTP," 2017 IEEE International Systems Engineering Symposium (ISSE), Vienna, Austria, 2017, pp. 1-7.

[48] M. Houimli, L. Kahloul and S. Benaoun, "Formal specification, verification and evaluation of the MQTT protocol in the Internet of

Things," 2017 International Conference on Mathematics and Information Technology (ICMIT), Adrar, Algeria, 2017, pp. 214-221.

[49] U. Hunkeler, H. L. Truong and A. Stanford-Clark, "MQTT-S — A publish/subscribe protocol for Wireless Sensor Networks," 2008 3rd International Conference on Communication Systems Software and Middleware and Workshops (COMSWARE '08), Bangalore, India, 2008.

[50] Y. Upadhyay, A. Borole and D. Dileepan, "MQTT based secured home automation system," 2016 Symposium on Colossal Data Analysis and Networking (CDAN), Indore, India, 2016, pp. 1-4.

[51] A. Vukojevic, S. Laval and J. Handley, "An integrated utility microgrid test site ecosystem optimized by an open interoperable distributed intelligence platform," 2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2015, pp. 1-5.

[52] Starke, Michael; King, Dan; Herron, Drew, "Implementation of a DDS protocol in Microgrid Islanding and Resynchronization with Self-Discovery", IEEE Transactions on Smart Grid, September 2017.

[53] A. Dorri, S. S. Kanhere and R. Jurdak, "Multi-Agent Systems: A Survey," in IEEE Access, vol. 6, pp. 28573-28593, 2018

[54] M. Starke et al., "Agent-Based Framework for Supporting Behind the Meter Transactive Power Electronic Systems," 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2020, pp. 1-5.

[55] M. Starke et al., "Residential (Secondary-Use) Energy Storage System with Modular Software and Hardware Power Electronic Interfaces," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 2445-2451.

[56] M. Starke et al., "Control and Management of Multiple Converters in a Residential Smart Grid," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 668-674.

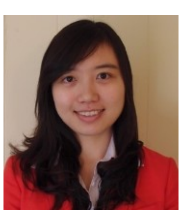
[57] M. Starke et al., "Secondary Use-Plug-and-Play Energy Storage System Composed of Multiple Energy Storage Technologies," 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2021.

[58] M. Starke, B. Xiao and M. Chinthavali, "A Low Voltage DC Power Electronic Hub to Support Buildings," 2021 IEEE Fourth International Conference on DC Microgrids (ICDCM), 2021, pp. 1-8.

[59] Georgia Power, Electric Service Tarriff, Time of Use – General Service Demand Schedule (TOU-GSD-10) https://www.georgiapower.com/content/dam/georgia-power/pdfs/business-pdfs/rates-schedules/small-business/TOU-GSD-10.pdf

BIBLIOGRAPHY

Michael Starke is a Electrical Engineering System Integrator at the Oak Ridge National Laboratory. He has been at ORNL for over 10 years performing research in different areas of optimization, control, and communications in power systems. He received his B.S, M.S. and Ph.D. in electrical and computer engineering at The University of Tennessee in 2004, 2006, and 2009 respectively. His research interest lie in systems integration, optimization, controls, and communications.



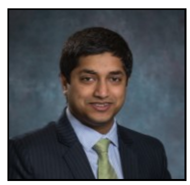
Bailu Xiao (S'09-M'14) received the B.S. and M.S. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2006 and 2008, respectively, and the Ph.D. degree in electrical engineering from the University of Tennessee, Knoxville, TN, USA, in 2014. She is currently a R&D staff at Oak Ridge National Laboratory (ORNL). Her current areas of interest include power electronics system integration, multilevel converters, and microgrid modeling and control.

Radha Sree Krishna Moorthy received the B. E in electrical and electronics engineering and Ph.D. in electrical and computer engineering from Anna University, Chennai, India in 2012 and National University of Singapore (NUS), Singapore in 2016 respectively. Currently she is a R&D Associate Staff Member in Oak Ridge National Laboratory (ORNL) in Knoxville, Tennessee with research interests include wide band gap devices-based power electronics and advanced power electronic interfaces for grid and vehicular applications.

Benjamin R. Dean (S 2018) received the B.S. in electrical engineering from the University of Tennessee, Knoxville, Tennessee. He presently is an M.S. student in electrical engineering at The University of Tennessee. His research interests include power electronic system communication and energy storage systems.

Anup Thapa received his M.S. and B.S. in Electrical Engineering from Clemson University in 2016 and Tribhuvan University, Nepal in 2011, respectively. He is currently with the group as an R&D Assistant Staff. His research interests are power electronics for power systems, motor drives, and embedded systems programming.

Mitchell Smith received his Bachelor of Science in Physics from Ursinus College in 2012 and PhD in electrical engineering at the University of Tennessee in 2019. He is presently a post-doctoral research associate at Oak Ridge National Laboratory. Research interests include systems design and integration, utility scale energy storage, and modular power electronics systems.



Pankaj Kumar Bhowmik (S'15-M'19) received the B.Tech. degree in Electrical Engineering from National Institute of Technology, Silchar, India, in 2012, M.S. and Ph.D. degree in Electrical and Computer Engineering from University of North Carolina, Charlotte, USA, in 2015 and 2019 respectively. He is a Post-Doctoral Research Associate at Oak Ridge National Laboratory (ORNL). His research interests are utility applications of power electronics and power quality issues.

Madhu Chinthavali received his M.S. and Ph.D. degrees in electrical engineering from the University of Tennessee, Knoxville, TN, USA, in 2003 and 2015, respectively. He is presently a group leader for the power electronics systems integration group and also director of Grid Research Integration and Deployment Center GRID-C at Oak Ridge National Laboratory. Dr. Chinthavali's research includes developing power electronics systems with advance semiconductor devices and developing device and system level models.

Steven L. Campbell (M'18) received the A.A.S. degree in electrical engineering technology from Pellissippi State Community College, Knoxville, TN, USA in 2007 and the B.S. degree in electrical engineering from The University of Tennessee, Knoxville, TN, USA in 2018. Steven is a Technician at Oak Ridge National Laboratory. His research interest includes the development of power electronics for vehicle, grid, and wireless applications from packaging at the device level to designing full systems.