Control of Grid-Connected Multiport MV Power Electronics Energy Hub

Preprint

Akanksha Singh,[1] Emma Raszmann,[1]
Kumaraguru Prabakar,[1] and Madhu Sudhan Chinthavali[2]

1 National Renewable Energy Laboratory
2 Oak Ridge National Laboratory

Presented at the 2022 IEEE International Symposium on Industrial Electronics
Anchorage, Alaska
June 1–3, 2022

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-82438
August 2022

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Suggested Citation
Singh, Akanksha, Emma Raszmann, Kumaraguru Prabakar, and Madhu Sudhan Chinthavali. 2022. *Control of Grid-Connected Multiport MV Power Electronics Energy Hub: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-82438. https://www.nrel.gov/docs/fy22osti/82438.pdf.

Conference Paper
NREL/CP-5D00-82438
August 2022

National Renewable Energy Laboratory
15013 Denver West Parkway
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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Grid Modernization Initiative and the Office of Electricity. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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Akanksha Singh, Emma Raszmann, Kumaraguru Prabakar
National Renewable Energy Laboratory
Golden (CO), USA
{akanksha.singh; emma.raszmann; kumaraguru.prabakar}@nrel.gov

Madhu Sudhan Chinthavali
Oak Ridge National Laboratory
Oak Ridge (TN), USA
chinthavalim@ornl.gov

Abstract—**In this paper a new concept of multiport, modular, medium-voltage, power electronics hub (M3PE-HUB) is introduced for the future power grid. The goal for this project is to design, develop, and demonstrate foundational technologies and capabilities for multiport power electronics energy hubs that can serve as intelligent devices to coordinate and control several different sources and loads. This paper presents the architecture of the controller, the central controls, and their verification.**

Keywords—multiport power converter, controls, grid-support functions

I. INTRODUCTION

Presently, the number of power electronic (PE) converters connected to the power grid is increasing rapidly due to higher integration levels of distributed energy resources (DER). This increase can be observed at the distribution levels as well as in sub-distribution systems. One emerging issue faced by the distribution system is the evolution of PE converter-interfaced loads, such as electric vehicle (EV) charging (especially EV fast charging), and computational facilities such as server farms and data centers. These changes are compelling utilities to adapt at a rapid pace. A major challenge for utilities is the requirement to control and coordinate these PE interfaces with the wide-area distribution management systems (DMS). It is essential to control and coordinate them in this manner to effectively use them as resources and to manage loads. These issues mandate a change in the design and architecture of PE interfaces and the optimization and control of the managing systems. Although significant investments are being made to overcome some of these issues, there are several key technical challenges and gaps that need to be addressed. The presence of multiple power converters on the grid poses challenges in communications, control, coordination, and compliance with grid standards (e.g., IEEE 1547). Furthermore, the lack of standards especially for software and communication interfaces has led to unique designs and proprietary interfaces from multiple vendors, high balance-of-system costs for grid-tied systems, and challenges with interoperability. These converters require centralized controls for each system and lack autonomous operating capabilities, thereby stressing the requirement for communications. Finally, there is a lack of medium-voltage converter technologies, and most applications that have resolved these issues have been limited to 480V AC grid connections.

This work is focused on the design, development, and demonstration of controls for multiport PE energy hubs (a.k.a. HUBs) that can serve as intelligent devices to coordinate and control several different sources and loads to address these challenges. The HUB includes new features, including standardized interfaces, the local decision-making capability of individual grid-tied PE converters, and the de-centralized control of distribution feeder sections. In this paper, the grid-support controls, the controller architecture, and its implementation are discussed. This paper is focused on the development of control algorithms and coordination strategies for integrating the medium-voltage HUB model into the bulk grid models. The medium-voltage power converter models are developed in a real-time platform, such as OPAL-RT. These models in the real-time platform are interfaced with a controller interface that acts as a central multiport, modular, medium-voltage, power electronics (M3PE)-HUB controller and has the communications interface hardware to complete the controller-hardware-in-the-loop (CHIL). The bulk grid services that the medium-voltage HUB can provide are demonstrated in this paper. Section II describes the concept and architecture of the HUB. Section III describes the architecture and implementation of the central controller. Section IV includes the evaluation of the developed controls and details of the next steps in the work. Section V concludes the paper.

II. MEDIUM-VOLTAGE HUB CONCEPT AND ARCHITECTURE

In order to illustrate the value of the HUB concept, this work designs and develops a multiport, direct grid-tied medium-voltage AC architecture as shown in Fig. 1. The M3PE-HUB has a low-voltage section for 480 V to 1 kV DC conversion and an medium-voltage section for 1 kV to medium-voltage (up to 13.8 kV) conversion. The functionality of the M3PE-HUB will be demonstrated using a CHIL model. The individual converter models of the low-voltage and medium-voltage sections are developed using average models and switching models in a real-time platform. The controls developed for each converter are hosted in controller hardware and interfaced with the real-time platform models.

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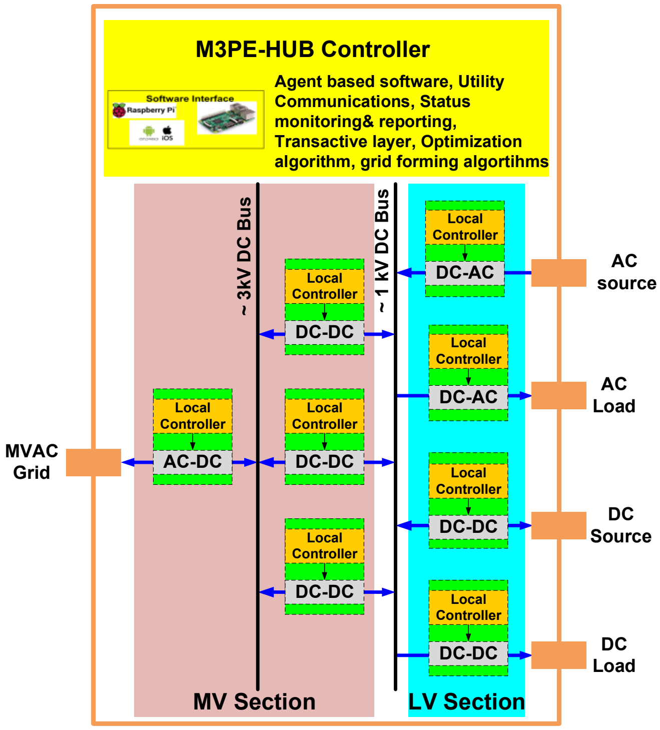


Fig. 1. Multiport Modular Medium-Voltage (M3) PE HUB and control architecture.

The hardware development stages of this M3PE-HUB include the low-voltage section (1 kV DC and 480 V AC with 1.7 kV devices) and the medium-voltage section (3.3 kV devices and 10 kV devices). Power electronics hardware and prototypes will be integrated with open-source software interfaces and evaluated in one or more use cases; however, the medium-voltage power stages will not be integrated with the low-voltage section because of differences in the power ratings. For the low-voltage section, multiple power stages that are commercially available will be used to connect various AC, DC sources and loads. For the medium-voltage section, medium-voltage power stages with H-bridge configuration is being developed. Additional component innovations include the semiconductor packaging, advanced isolated gate drivers with protection, and high-voltage magnetics for filtering.

III. CENTRAL CONTROLLER ARCHITECTURE AND DEVELOPMENT

This section discusses the overall architecture of the central controller. The implementation of the central controls is also presented in this section.

A. Central Controller Architecture

The control layer architecture for the central controller of the M3PE-HUB is shown in Fig. 2. The system-level control architecture is shown here. This layer implements the communications with the DMS, receives feedback from the DC and AC sensors in the system, and also receives inputs from the lower-level agent-based controls. The communications from the DMS include receiving status commands, scheduling, and dispatch information. The change in the operation modes, such as grid-connected to islanded operation, is also communicated to the DMS through the central controller. The local sensing inputs include the grid- and converter-side voltages, grid frequency, and current being injected or absorbed by the converter. These measured values from the sensors enable the local autonomous operation of the HUB, which is described in the next section. The inputs from the lower-level, agent-based controls include the availability of power from the photovoltaic system, the state-of-charge of the battery system, the value of the local load, etc. These are determined by the lower controls depending on the sources and loads connected to the low-voltage section of the HUB (see Fig. 1).

The operation mode of the HUB is determined by the communications with the DMS and the status of the local grid conditions as determined through the sensed feedback. If all conditions of normal operations are met, the system follows the normal operation mode, as shown in Fig. 2. Then the HUB controller in coordination with the DMS, determines the operation mode, such as PQ control mode and active grid-

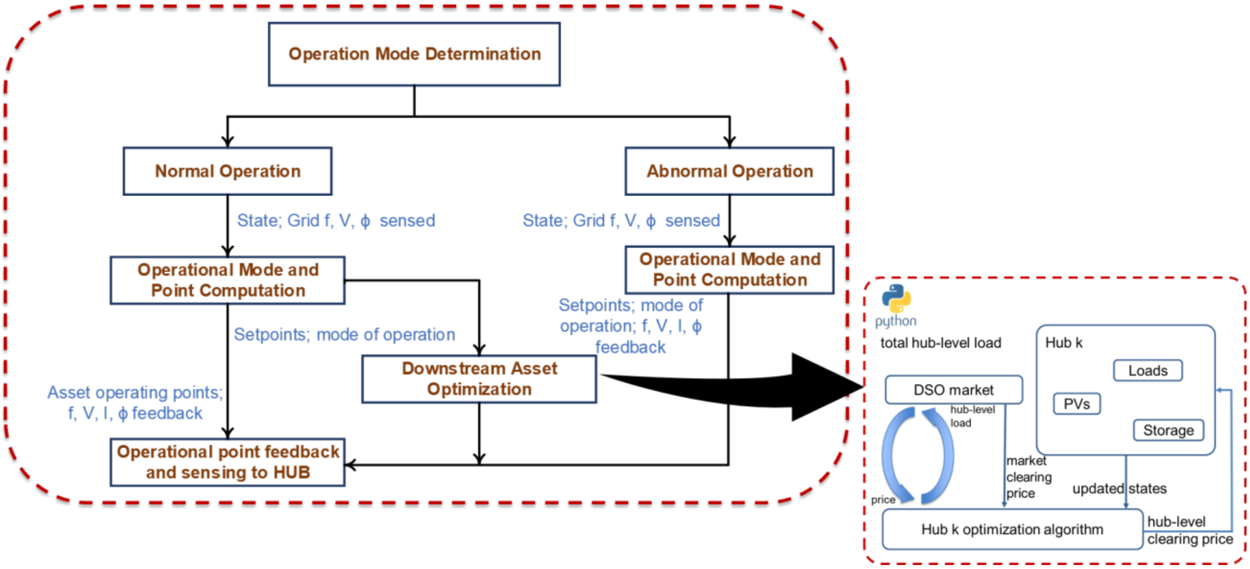
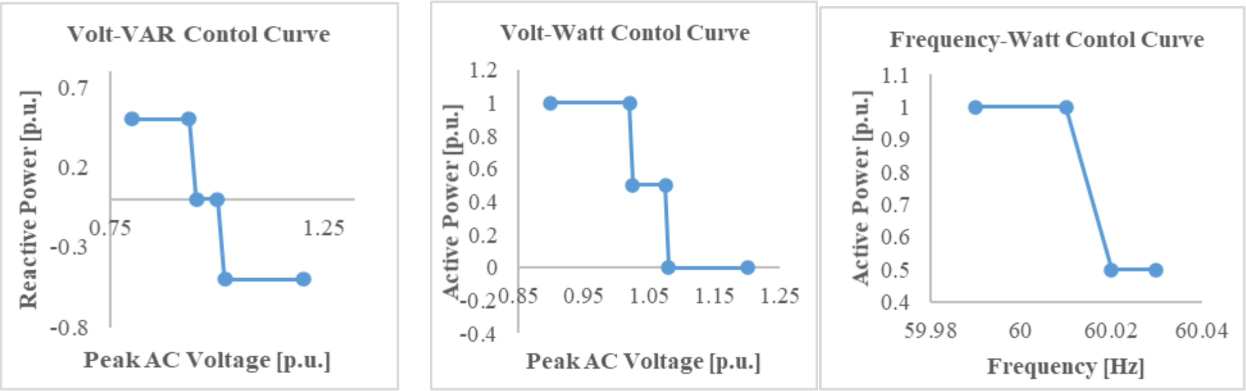


Fig. 2. Concept for controls and optimization architecture in CHIL setup.



(a) (b) (c)

Fig. 3. Grid-support function curves used for voltage and frequency regulation.

support mode. The aggregate active power (P) and reactive power (Q) required by the grid is then computed based on the operation mode and the state of the grid at that point. For the PQ set point control mode, these set points are directly received from the DMS dispatch commands. For the grid-support controls, the PQ set points are computed based on the default volt-var (VVAR), volt-watt (VWATT), and frequency-watt (FWATT) curves or from curves received from the DMS. The details of these controls and their implementations are presented in the next section. After the determination of aggregate the PQ set points, these are transferred to the next layer, which implements the transactive part of the controls and optimizes the energy absorbed and supplied through various assets. This optimization then generates the PQ set points for each asset connected to the HUB, which are then transferred to the lower-level controls for the operation of the low-voltage side of the HUB. When the grid conditions are determined to be abnormal (caused by faults, voltage sag/swell, frequency changes, etc.), the optimization and transactive controls of the system are bypassed (see Fig. 2). The HUB central control determines the state of operation and sends the operating points to the lower-level controls. During abnormal operations, the central controller also determines the ride-through regions and settings as well as makes decisions on the cease-to-energize region and system disconnection from the grid. The next subsection provides details on the grid-support control algorithms developed.

B. *Central Controller Algorithms*

The inverter test functions considered for the control algorithms development are listed in Table I. These test functions are broadly classified into three domains and use the sensed grid voltages, currents, and frequency to obtain the required grid-support functionality. These controls algorithms are developed considering the M3PE-HUB as a Category III DER as specified in IEEE 1547-2018 [1]. Furthermore, the conformance evaluation tests were also developed based on IEEE 1547.1-2020 [2].

In order to implement advanced grid-support functionality, a real-time automation control (RTAC) device was used from Schweitzer Engineering Laboratories (SEL). The advanced grid functions implemented with RTAC equipment include: VVAR, VWATT, FWATT, voltage ride-through, and frequency ride-through functions. The RMS voltage and frequency sensed from the grid at the point of common coupling (PCC) are sent as feedback to the RTAC equipment as analog signal references. The outputs from the RTAC include set points for real and active power as well as shutdown or cessation commands grid operating conditions. Fig. 3 shows the curves used for the VVAR, VWATT, and FWATT inverter functions. The purpose of VWATT control is to dynamically change the active power set point depending on the grid voltage input. The curve for VWATT control is shown in Fig. 3b. VVAR control is used to dynamically change the reactive power set point depending on the grid voltage input to support the grid voltage regulation. The curve for VVAR control is shown in Fig. 3a. FWATT control provides a power set point depending on the measured frequency (nominal of 60 Hz) to support the grid by providing frequency regulation. The curve for FWATT control is shown in Fig. 3c. Similarly, the ride-through functionalities, in general, are for giving the system the ability to provide power for a limited amount of time during a grid abnormality, which can cause sag or swell in voltage or frequency. The frequency ride-through functionality determines how much time until a shutdown or cessation command is initiated depending on the input frequency conditions. The voltage ride-through functionality determines how much time until a shutdown or cessation command is initiated depending on the input RMS voltage conditions.

TABLE I. GRID-SUPPORT FUNCTIONS DEVELOPED.

Domains	**Test Functions**
Voltage Functions	Volt-VAR
	Volt-Watt
	High/Low-Voltage Ride-through
	Dynamic Voltage Support
	Power Factor
Frequency Functions	Frequency Watt
	High/Low Frequency Ride-through
Others	Normal and Delayed Ramp Rate Control

IV. CONTROL IMPLEMENTATION AND EVALUATION

In this section, the implementation of the algorithms discussed in the previous section is described. This section also presents the evaluation of the implemented algorithms. The grid functionality described in the previous section was implemented using the SEL RTAC 3555. The inputs to this device are analog

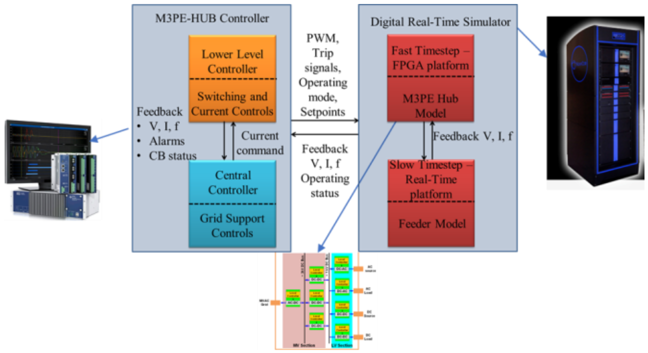


Fig. 4. Hosting components and architecture of the demonstration CHIL platform.

references of the RMS voltage and frequency as sensed at the PCC. The outputs from the RTAC device are the power set points, shutdown commands, and cessation commands based on the grid functionality algorithms. The implementation of the HUB along with the system evaluation is through a multi-time step CHIL platform. The hosting components and the architecture of the platform are shown in Fig. 4. In this CHIL setup, the central controller implemented on the SEL RTAC 3555 is connected to the HUB model, which is hosted on a digital real-time simulator (DRTS). The HUB model is implemented on a fast time step FPGA platform of the DRTS. This implementation has been discussed and presented in [3]. The HUB model is a part of large feeder model. The feeder model is hosted on slow time step real-time platform. The full system hosted in the DRTS is executed in multi-time step as shown in Fig. 4, in order to accurately capture the dynamics of the system. In order to validate that the controller is operating as expected after interfacing and integrating with the DRTS, the RTAC is set to online mode. Values can be changed locally to see if the logic is changing as expected during the operation of the program. Two main use cases were validated using this setup. The first is the verification of the voltage support functionality through the VVAR and VWATT controls and the second is the verification of the FWATT function.

A. Voltage Support Controls Verification

The RMS voltage and frequency of the system (both in per-unit scale) from the DRTS system were used as inputs for the verification. The system voltage was varied for this evaluation, whereas the frequency was held at a constant 60 Hz for the modeled system. The voltage reference input was varied throughout the test following the profile shown in Fig. 5 (pink). The control set point changes in P and Q are demonstrated in Fig. 5 based on the analog input reference voltage. The VVAR and VWATT control curves that are followed by the controller are the same as those presented in Fig. 3. These curves are treated as the default grid-support curves for this system. The curves can be modified by receiving new curves from the DMS. The P and Q measured set point profiles presented in Fig. 5 (yellow and green, respectively) accurately follow the expected values from the curves in Fig. 3.

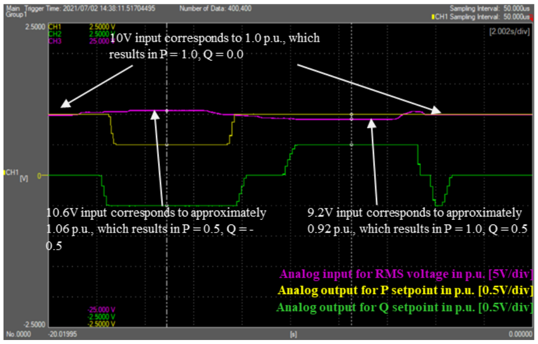


Fig. 5. Verification of voltage-support controls showing change in P and Q set points as the measured voltage from the DRTS changes.

B. Frequency Support Control Verification

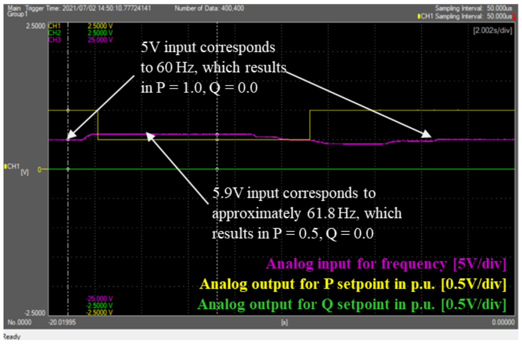


Fig. 6. Verification of FWATT showing change in P and Q set points as the measured frequency from the DRTS changes.

Fig. 6 shows a similar example as above, however, the voltage in the modeled system was set to a constant 1 p.u. value, whereas the frequency of the system was varied, as per the profile shown in Fig. 6 (pink). The control set point changes in P and Q are demonstrated in Fig. 6 (yellow and green, respectively) based on the measured input frequency. The FWATT control curve shown in Fig. 3 is used for this control. The P and Q measured set points profiles presented in Fig. 6 accurately follow the expected values from the curve in Fig. 3.

V. CONCLUSION AND NEXT STEPS

In this paper, a new concept of M3PE-HUB for future power grid has been introduced. The architecture of the central control, its implementation, and preliminary evaluation has also been presented in this paper. Future work includes the demonstration of the HUB concept that can support and enable future grid applications, such as:

- Autonomous, smart, transactive devices that can provide real-time grid services to maximize the value of DERs
- Open-source, agent-based software, and smart hardware interfaces to accelerate the adoption of PE-based solutions across the grid
- Development of the CHIL interface connected with a real-time feeder model for the evaluation of multiple M3PE-HUBs in the system
- Design guidelines, standards, and specifications for MEDIUM-VOLTAGE grid-tied power converters and the associated controls.

ACKNOWLEDGMENTS

This research was supported by the Grid Modernization Initiative of the U.S. Department of Energy (DOE) as part of its Grid Modernization Laboratory Consortium, a strategic partnership between DOE and the national laboratories to bring together leading experts, technologies, and resources to collaborate on the goal of modernizing the nation’s grid.

The authors gratefully acknowledge the support from U.S. Department of Energy Grid Modernization Initiative and the Office of Electricity as well as the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office, via the Multi-Port Modular Medium-Voltage Transactive Power Electronics Energy Hub project, in the form of guidance, advice, and funding for this work.

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