Use of Grid-Forming Medium-Voltage Power Electronics Hub in a Microgrid Setting

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***Abstract*—This paper presents the application of a new design of a multiport, modular, medium-voltage power electronics hub (M3PE-HUB) in a microgrid setting. The M3PE-HUB system was modeled in a digital real-time simulator (DRTS) and integrated into the Banshee microgrid test system. This paper presents the preliminary DRTS simulation-based results of the M3PE-HUB system connected in a test microgrid system. Verification and validation of the M3PE-HUB architecture and controls in the test microgrid setting are the primary contributions of this work. The results of the operation during the islanding and resynchronization process indicate the feasibility of the proposed architecture in a microgrid setting. This paper also presents results for a system reconfiguration use case where the M3PE-HUB was used to reconfigure the system under a fault condition.**

***Index Terms*—Controller-hardware-in-the-loop, Grid-following controls, Grid-forming controls, Microgrids, Multiport modular medium-voltage power electronics hub.**

I. Introduction

Distribution power systems with microgrids face a variety of challenges related to feeder loading, reliability, efficiency, and power quality. The integration of distributed energy resources (DERs) results in bidirectional power flow, low fault currents, and has presented operational challenges [1]. To mitigate these challenges, traditional power grid components can be replaced with advanced power electronics devices to form a resilient alternative current (AC) distribution systems, which provides flexibility and multi-functionality such as phase balancing, voltage support, frequency support, and the integration of renewable energy and energy storage devices [2].

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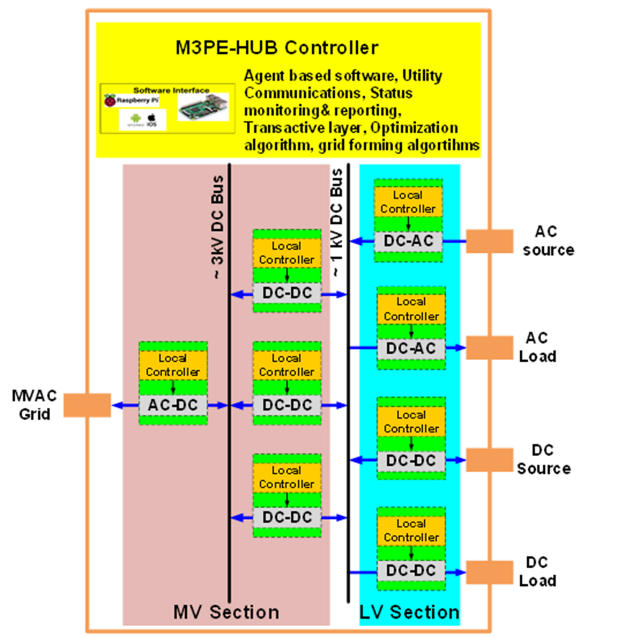

Fig. 1: Multiport, modular, medium-voltage power electronics hub with its associated control architecture

To obtain more functionalities, advanced power electronics devices for distribution systems are typically designed as series-connected devices or parallel-connected devices. Although series-connected devices can provide more services than parallel-connected devices, they have stricter control and protection requirements, and faults on a single device will lead to cascading failure to the remaining system [3]. Thus, different topologies have been proposed for implementing series-connected devices, with the back-to-back converter topology

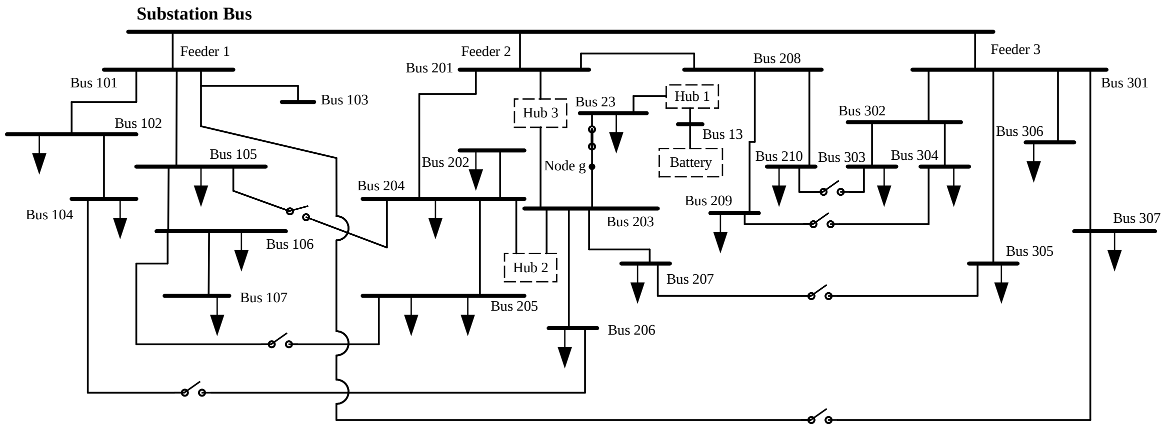

Fig. 2: Banshee microgrid model - one line diagram

being one of the most promising topology. Applications of medium-voltage back-to-back converters as hubs have been presented in [4], where control approaches and simultaneous grid services were first addressed. These power electronics based converters serve as intelligent hubs to coordinate and control DERs and loads to address challenges associated with power electronic-interfaced devices. However, existing works only focus on local grid support functions. This paper extends the design and development for multiport power electronic energy hubs with a special focus on the demonstration of system-level advanced controllers. The multiport hub presented here includes new features, such as standardized interfaces, local decision-making capability of individual grid-tied power electronic converters, and the decentralized control of distribution feeder sections, as presented in [5]. This paper presents the development of advanced grid-support control algorithms and coordination strategies for integrating the multiport, modular, medium-voltage power electronics hub (M3PE-HUB) model into the distribution system, thereby improving the understanding of the effectiveness and interconnection of the M3PE-HUB system. The medium-voltage power converter models are developed in a commercially available digital real-time simulator (DRTS). These converter models in the DRTS platform are interfaced with a test microgrid system (Banshee model [6]). This paper presents results from the real-time simulations of the M3PE-HUB system integrated in the test microgrid sytem. This developed DRTS model with the test microgrid model and the M3PE-HUB will be critical for future controller-hardware-in-the-loop (CHIL) experiments and power-hardware-in-the-loop (PHIL) experiments. The rest of the paper is organized as follows: Section II describes the concept and architecture of the M3PE-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.

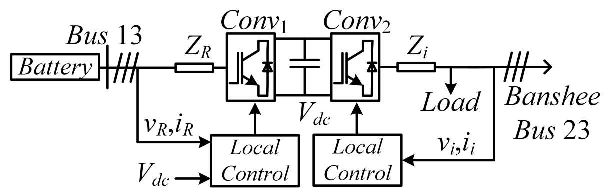

Fig. 3: Expanded view of the M3PE-HUB architecture

II. Medium-Voltage Power Electronics Hub Concept and Architecture

The higher level conceptual block diagram for the overall M3PE-HUB architecture is presented in Fig. 1. The overall control architecture has local control blocks as well as a global decision-making block to optimize the power from various connected assets [7], [8]. To illustrate the value of the M3PE-HUB concept under this high-level architecture, this work leverages the multiport, direct grid-tied, medium-voltage AC architecture along with its various functionalities under different realistic conditions. The M3PE-HUB has a low-voltage section for 480-V to 1-kV DC conversion and a medium-voltage section for 1-kV to medium-voltage (up to 13.8-kV) conversion. We use an average model to represent the individual converter model in the DRTS platform. Use cases were designed and executed in the DRTS environment to demonstrate and validate the capability of the M3PE-HUB.

III. Architecture and Implementation of the Central Controller

The newly developed power electronics interface as well as the controls are incorporated into a test microgrid to demonstrate the advantages brought about by the proposed M3PE-HUB. The Banshee microgrid serves as our prototype microgrid, and the single line diagram is shown in Fig. 2. The simplified overall circuit diagram of the M3PE-HUB architecture connected to the Banshee model Bus 23 is presented in Fig. 3. Information on this microgrid is available in the literature [6], and the Banshee test microgrid model is

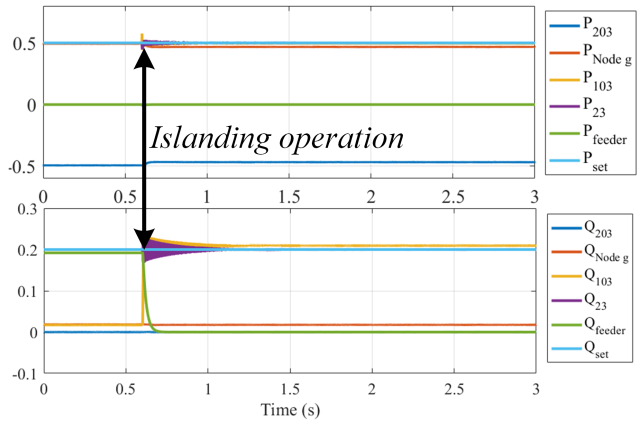

Fig. 4: Islanding Operation First: Active/Reactive power at bus 203, Second: Active/Reactive power at node g, Third: Active/Reactive power at 13, Fourth: Active/Reactive power at 23, Fifth: Active/Reactive power of the feeder, Sixth: Active/Reactive power set point

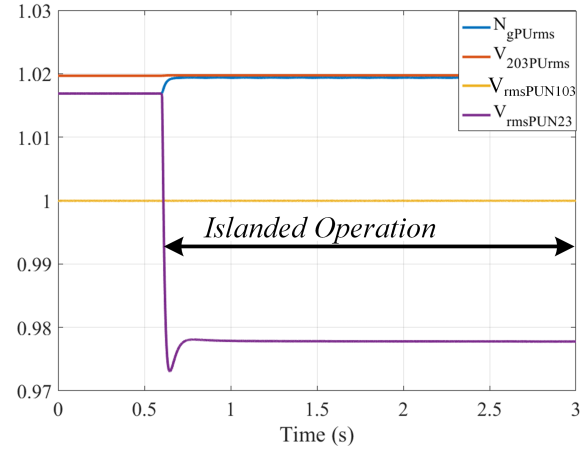

Fig. 5: Islanded operation First: RMS voltage of node g, Second: RMS voltage of bus 203 Third: RMS voltage of bus 13 Fourth: RMS voltage of bus 23

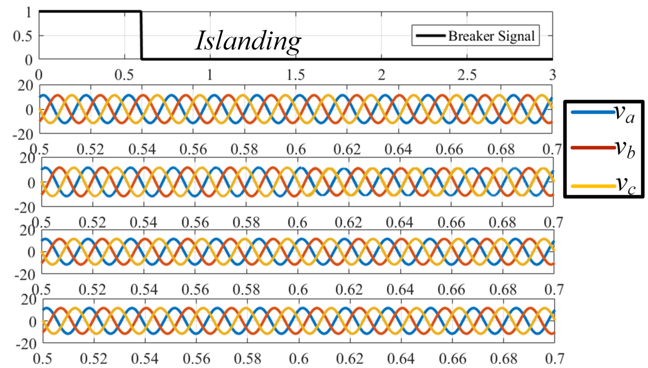

Fig. 6: Islanding operation - From the top: First: Breaker signal, Second: Bus 203 voltage, Third: Node g voltage, Fourth: Bus 13 voltage, and Fifth: Bus 23 voltage

also available in many DRTS platforms, allowing the readers to reproduce this work and the use various corner cases to demonstrate the efficacy of the connected M3PE-HUB. The M3PE-HUB architecture consists of two back-to-back converters which converter $Conv_1$ operates as a rectifier and the $Conv_2$ as an inverter. These converters are connected to the grid through an impedance represented by $Z_{R/i}$. In this setup, $Conv_1$ is responsible for converting the AC input power from the grid into DC power, which is then fed into the DC bus. The dq decouple voltage control is used in $Conv_1$ where the d-axis voltage is managed by the DC link voltage q-axis voltage is controlled by the reactive power at the AC terminal. Thus, $Conv_1$ can be connected to the Banshee test system or external sources. On the other hand, $Conv_2$ takes the DC power from the bus and converts it back into AC power to be supplied either to the grid or to local loads. The dq decouple voltage control is also used in $Conv_2$ with P-f and Q-V droops considering voltage dynamics at the DC bus. This bidirectional power flow allows for energy transfer in both directions, enabling features such as energy storage and power injection to or extraction from the grid, flexible power flows that redistribute power to supply local loads and ensure grid continuity. The Banshee microgrid is modeled in a commercially available DRTS platform (Real Time Digital Simulator (RTDS) is used in this work) in an electromagnetic transient (EMT) domain with a time step of 50 microseconds. This simulation could also be performed in non-real-time EMT software, but DRTS allows us to run the simulations for multiple tens of minutes; collect long-duration, high-fidelity data; and alanyze the performance over a long duration. This is a key requirement for our work because the simulation scenarios might need longer simulation time periods. Another advantage is the ability to leverage this DRTS model for CHIL/PHIL experiments to evaluate microgrid controllers and the M3PE-HUB controller.

IV. M3PE-HUB Grid-Forming Control Evaluation

The overall system has been integrated with the Banshee test microgrid system [6] modeled in a commercially available DRTS, and the M3PE-HUB is connected at Bus 203 to present the grid supports to the overall system. The M3PE-HUB is used to interface the DERs and loads in the Banshee system with the distribution grid. The active/reactive power response results demonstrate the M3PE-HUB's power flow control capability.

A. Islanding Transition

A grid-forming (GFM) M3PE-HUB with dispatchable capability is used in this case, and it was connected to Bus 23 with an external battery source modeled as controllable voltage source and dispatched to supply a 0.5MW load while the feeder provides the reactive power. When the system goes from grid-connected mode to islanded mode, the feeder breaker between Bus 203 and Bus 23 is opened, and the proposed M3PE-HUB (HUB 1) switches to GFM mode and supplies loads. Fig. 4 shows the monitored active and reactive power and Fig. 5 shows the voltage at the grid side (Bus 203, Node g), battery side (Bus 13), and load side (Bus 23) before and after

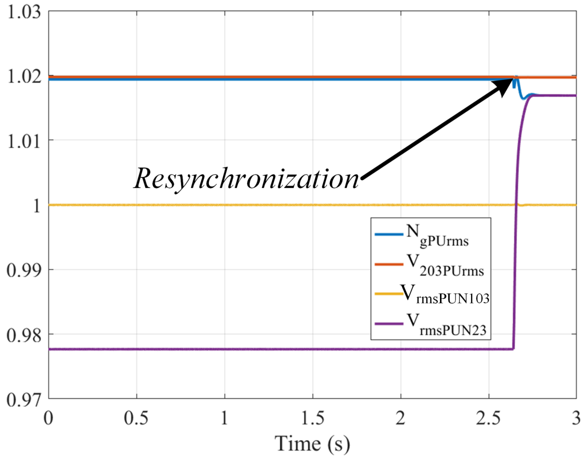

Fig. 7: Bus voltages during resynchronization, First: RMS voltage of node g, Second: RMS voltage of bus 203, Third: RMS voltage of bus 13, Fourth: RMS voltage of bus 23

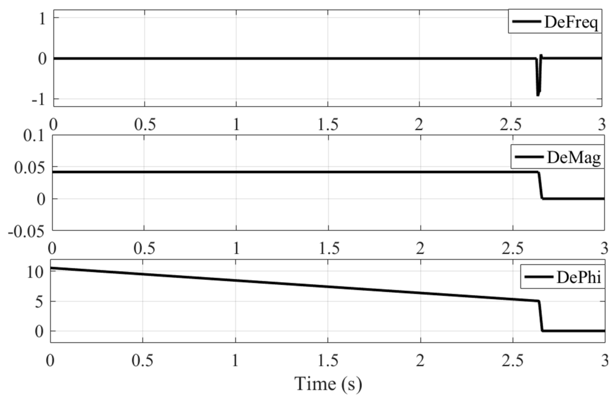

Fig. 8: Frequency difference, voltage magnitude difference, and phase angle difference during resynchronization

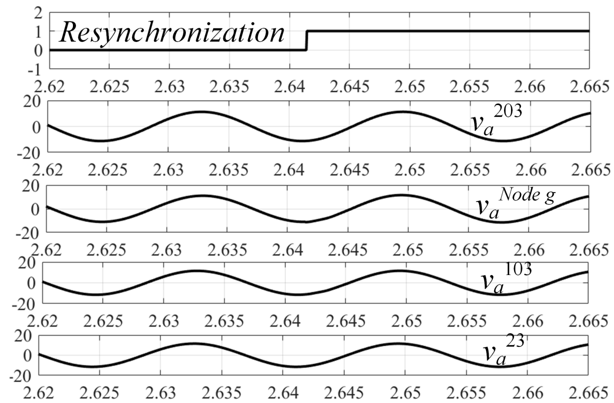

Fig. 9: Resynchronization operation - From the top: First: Breaker signal, Second: Bus 203 voltage, Third: Node g voltage, fourth: Bus 13 voltage, and Fifth: Bus 23 voltage

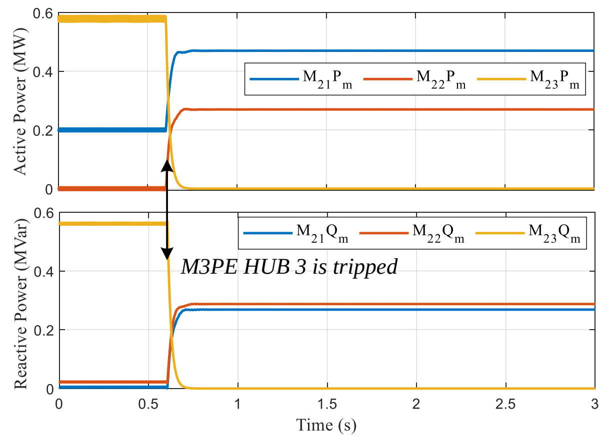

Fig. 10: Dynamics of active and reactive power from the operation of multiple M3PE-HUBs

the system transitions from grid-connected mode to islanded mode of operation. It is observed from Fig. 4, that during islanding operation a small amount of oscillation ($< 10\%$) is observed in the reactive power ($Q_{monload}$). This can be attributed to nonzero initial condition, low damping as well as presence of shunt capacitive branches near that bus. However, it is observed from this result that the oscillation is quickly damped out and power is restored to its commanded value indicating the efficacy of the proposed system. In Fig. 6 the sine waveforms during the islanding process and the smooth transition of the M3PE-HUB from GFL mode of operation to GFM mode of is presented.

B. Resynchronization

We then present the analysis of system behaviors during the resynchronization process using the resynchronization approach presented in [9]. Similar to Fig. 5, Fig. 7 showcases the bus voltage at the grid side, BESS side, and load side when HUB 1 tries to close the breaker for Bus 23, while Fig. 8 offers a comprehensive view of the dynamics of system frequency, voltage magnitude, and phase. These results capture system transitions before and after the resynchronization which are crucial indicators of the system stability and adherence to grid requirements. Fig.9 presents the voltage waveform for phase a of different busses of the Banshee model Fig. 2 during the resynchronization process. It is observed from this result that the phase of the voltages before and after synchronization is maintained proving the efficacy of the overall system. Use cases for islanding and resynchronization unambiguously show that the M3PE-HUB successfully works with the Banshee test microgrid model in grid-connected mode, islanded mode and successfully transitions between the two modes of operation seamlessly. The M3PE-HUB demonstrates its extraordinary capacity to adapt to the islanded operation effortlessly, improving the resiliency and reliability of the test microgrid system.

C. Multiple M3PE-HUBs for system reconfiguration

In addition, with GFM and power dispatching capabilities, multiple M3PE-HUBs can be deployed in a smart grid environment to increase the interconnection capabilities and grid resilience. Using multiple M3PE-HUBs provides several benefits. First, it enhances grid flexibility and dependability by facilitating intelligent power routing and load balancing.

This functionality aids in minimizing transmission losses, preventing overloads, and ensuring that the grid operates efficiently. Second, the resilience of the grid is improved by the redundancy provided by multiple M3PE-HUBs. If one M3PE-HUB experiences a malfunction or requires maintenance, the remaining hubs can automatically reconfigure and redistribute power to ensure grid continuity. This fault-tolerant architecture helps mitigate disruptions and reduce downtime. Figure. 10 shows both active and reactive powers, demonstrating how the system operates during an unanticipated fault occurrence. In this case, three M3PE-HUBs are linked to the Banshee system where Hub 1 is connected to Bus 23 with extra battery source, Hub 2 connects Bus 204 and 203, and Hub 3 connects Bus 201 and 203. M3PE-HUBs are dispatched to provide the load with active power commands at 0.2MW, 0MW, and 0.55MW, respectively ($M_{21}P_m$, $M_{22}P_m$, and $M_{23}P_m$ in Fig. 10), and reactive power commands at 0MVar, 0MVar, and 0.55MVar, respectively ($M_{21}Q_m$, $M_{22}Q_m$, and $M_{23}Q_m$ in Fig. 10), prior to the fault occurrence. When M3PE-HUB 3 experiences a specific problem around 0.6 s, its protective system trips the device. Then, M3PE-HUB 1 and M3PE-HUB 2 quickly redistribute electricity to 0.47MW/0.27MW and 0.27MVar/0.27MVar which achieves new stable power flows and load supply. Results of the transits for loads, voltage, and frequency at the load bus are depicted in Figs. 11-12, which also demonstrates that multiple M3PE-HUBs can dynamically manage power flow with droop controls, and system voltage and frequency can reach stable operations.

V. Conclusion

This paper demonstrated the concept of the M3PE-HUB in a test microgrid system. The architecture of the advanced grid-support function for M3PE-HUB, its implementation, and a preliminary evaluation in DRTS were presented, and use cases were executed in the DRTS platform to present the capabilities of the proposed architecture. Although the proposed M3PE-HUB offers several advantages including the integration of multiple energy sources and loads, and efficient power flow management, it also comes with limitations such as the complexity of integration and scalability due to the modularity. Implementing multiple M3PE-HUBs in DRTS environment also exacerbate the need for communication and coordination. As a follow on work, Use cases will be conducted using the CHIL interface and go beyond the basic demonstration by presenting several additional corner cases to further emphasize the benefits, efficiency, and challenges achieved through the integration of M3PE-HUBs into the existing microgrid model.

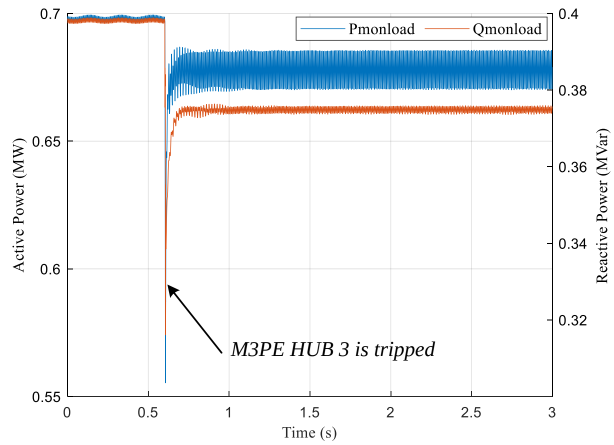

Fig. 11: Transits of load consumption during the fault event

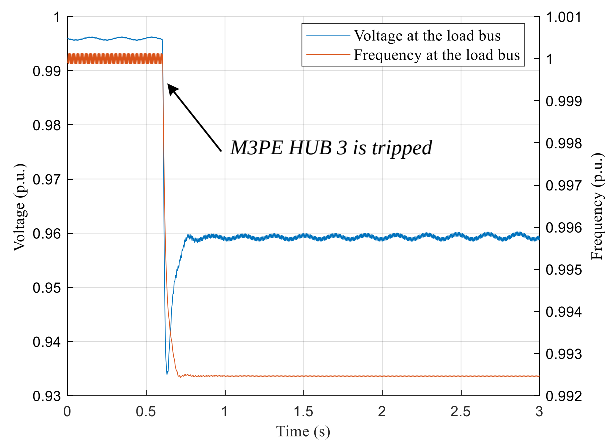

Fig. 12: Voltages and frequency at the load connection bus

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