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Changing the World's Energy Future

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High-Penetration Microgrids Providing Grid Stability Using Frequency-Watt Control

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***Abstract*—The U.S. grid is rapidly transitioning towards utilizing inverter-based renewable energy resources such as solar, wind, and batteries, reducing the carbon emission footprint. Inverter-based microgrid control architectures remain a critical focus to address power system stability issues in future high penetration markets lacking spinning generation assets. Idaho National Laboratory (INL) is researching an active layered inverter-based frequency-Watt control scheme that provides distribution level stability in high-penetration markets where grid inertia is lacking. Hardware in the loop case study was implemented using INL's Microgrid Testbed to combat scalable frequency deviations ranging from 60 Hz down to 50 Hz initialized by a hydropower model implementing step loads using a 540-kW grid emulator. Our research findings demonstrate the importance of distribution level, inverter-based active frequency-Watt controls utilizing a battery energy storage system (BESS) to provide adequate frequency support at the point of common coupling without major power infrastructure upgrades.**

***Index Terms*—High-Penetration (HP), Microgrid, Battery Energy Storage Systems (BESS), Grid Stability, frequency-Watt Controls.**

I. Introduction

As the United States is aggressively targeting the 2050 net-zero goal, with the help of government incentivization, power consumers are installing inverter-based generation assets, including photovoltaic (PV) and battery energy storage system (BESS), at an all-time high [1]. It is essential to understand the growing grid stability concerns on high penetration markets that prosumers are introducing on local distribution power networks with reduced grid inertia support compared to the increase of new inverter-based power production [2]. Targeting high-penetration distribution grids utilizing PV installations with a BESS with an integratable active frequency-Watt control scheme can provide grid stability in areas lacking inertia while avoiding interconnection disturbances. To obtain and grow the distribution grid's resiliency, decentralization must accommodate the additional inverter-based assets [3]. Decentralization of the grid is an idea that utilities must adopt to minimize grid stability concerns at a lower cost versus the other traditional options. Corresponding with the grid decentralization ideology, it can be shown that using active frequency-Watt controls integrated with a BESS will be able to respond to frequency deviations, providing an adequate replacement for governor-controlled spinning generation assets. Adopting this dynamic frequency-Watt control method will allow current electrical grids to avoid interconnection disturbances while reducing the number of significant infrastructure upgrades necessary to support the grid in high-penetration areas [4]. Currently, spinning generation assets provide the power grid's natural inertia and frequency response to maintain the frequency stability of the grid. Still, there are limitations to these types of power resources, including slow response times, limited frequency recovery range, generator control limitations, and precision tuning [5]. By replacing these assets with decentralized microgrids consisting of a BESS, instantaneous ramping and advanced controllability can be accomplished through active frequency-Watt control schemes, providing a better alternative while increasing the grid's resiliency. Batteries have become part of standard PV installations at a prosumer level, allowing for greater adaptability of the proposed control scheme and providing more reliable and stable energy injection [6]. Identifying and targeting these characterized markets for frequency support encourages optimized control policies, ensuring resilience against an instantaneous loss of loads, generation, and damping scenarios.

The rest of the paper is organized as follows: Section II presents the methodology adopted to design the layered frequency-Watt framework. Section III describes the Idaho National Laboratory (INL) Microgrid Testbed configuration for the hardware in the loop test, where the developed frequency-Watt architecture is implemented on a natural system to substantiate our test results. Section IV provides the conclusion of the paper and potential future work.

II. Methodology

A. Frequency-Watt Framework

1) Traditional Inverter frequency-Watt Control Schemes: Typical inverter frequency-Watt controls have been successful in past applications. Still, there is a demand to enhance traditional control schemes, allowing for more adaptable stability approaches, including active primary frequency response and synthetic inertia. The standard control schemes relies on governor controls, which respond slower to frequency regulation. Another issue is the ability to actively change specific setpoints without powering off the unit, which is becoming more relevant in high-penetration applications. Typical readily available distributed-scale commercial inverters

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do not have the integrated control functionality to respond to a change in frequency by increasing or decreasing their available active power output [7]. Also, these same inverters have a standard frequency operating range that cannot be changed unless the unit is powered off. This adds additional complications as DERMs are implemented into the market to monitor distributed resources. The ability to change operational deadbands, droop curve, active power reserves, and real power obligations is the enhanced functionality that INL is implementing on a hardware-in-the-loop case study covered in this paper.

2) INL Layered frequency-Watt Control Approach: INL has been developing and testing multiple active grid stability control methodologies that provide one solution in replacing the standard inverter-based controls. An advanced frequency-Watt control approach has been developed and implemented on hardware in the loop case study to showcase the importance of the role that active inverter controls will place on supporting grid stability issues utilizing common inverter resources containing a BESS. The control architecture is currently under review and protected under a patent disclosure preventing us from disclosing the specifics [8]. Nonetheless, here a high-level description is provided and its performance is demonstrated. The architecture integrated with an RTAC is an active control method with operator-specified control characteristics, including an adjustable frequency setpoint, dead band, saturation limits, and a power bias. Each setpoint provided can be actively and automatically adjusted without going offline. The frequency-Watt control is active feedback that changes based on the metered frequency at the point of interconnection.

A high-level description of the proposed charge and discharge algorithms are given by (1)–(2), respectively.

$$P_{1_{\%\max_{chg}}} = m_{1_{chg}}(f_{1_{midpt}}) + P_{1_{bias_{chg}}} \quad (1)$$

$$P_{2_{\%\max_{dischg}}} = m_{2_{dischg}}(f_{2_{midpt}}) + P_{2_{bias_{disch}}} \quad (2)$$

where $m_{1_{chg}}(f_{1_{midpt}}), m_{2_{dischg}}(f_{2_{midpt}})$ give the natural power flow, and $P_{1_{bias_{chg}}}, P_{2_{bias_{disch}}}$ account for the operator controlled power flow. When frequency is above the nominal value, $m_{1_{chg}}(f_{1_{midpt}})$ causes power to be absorbed from the grid by charging the microgrid batteries. The reverse happens when frequency is below the nominal value where $m_{2_{dischg}}(f_{2_{midpt}})$ causes power to be injected into the grid by discharging the batteries. Depending on the generation from solar PV and other energy inputs, the setpoints $P_{1_{bias_{chg}}}, P_{2_{bias_{disch}}}$ can be chosen by the operator to discharge and charge the batteries while also maintaining the frequency at the point of interconnection. Considering these functionalities, (1)–(2) allow to charge and discharge the batteries by generating the overall charging $P_{1_{\%\max_{chg}}}$ and discharging $P_{2_{\%\max_{dischg}}}$ profiles, respectively. Note that in the implementation of (1)–(2), the parameters $m_{1_{chg}}, m_{2_{dischg}}$ are all operator-controlled and these can be selected on the fly depending on the improvement that is expected in the frequency regulation. This also determines the rate at which the batteries are to be charged or discharged. This feature provides operational flexibility as opposed to traditional implementations.

The center setpoint is user-defined based upon the nominal frequency of 60 Hz in the United States with a typical supported dead band abiding by the appropriate utilities dead band and droop setting ranges [6]. When the frequency deviates outside of the operational bounds, the microgrid testbed is set to initiate frequency-Watt controls using the batteries to stabilize the frequency back within its tolerated bounds. It is essential to understand the different setpoints and how they interact to avoid equipment failure and interconnection disturbances. Figure 1 represents the human-machine interface (HMI) used for the developed architecture to receive active monitoring and initialize any changes as seen as necessary. In automized applications, an overall distributed energy resource management system (DERMs) can be used to determine these setpoints congregating multiple units to provide the equivalent support required for frequency support.

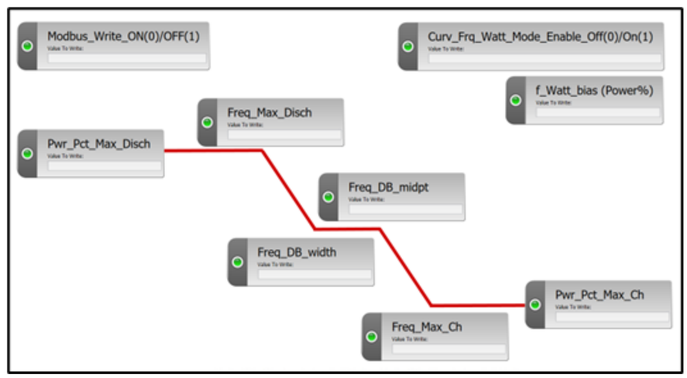

Fig. 1. HMI control screen developed for frequency-Watt control

B. Optimization

The active frequency-Watt control methodology enhances the standard inverter controls that are typically limited and cannot change multiple setpoints essential for dynamic responses. Some traditional inverters might be able to change some points, adding adaptability, but they must be turned off to change these setpoints. Our implemented frequency-Watt control architecture utilizing batteries will combat natural frequency deviations by providing instantaneous support withstanding the typical loss of load occurrences and uncommon frequency support situations. The importance of using this method is to prevent unnecessary expensive upgrades on existing infrastructure while achieving the exact frequency stability more efficiently. The architecture developed integrated a scalable power bias, allowing for a higher-level functionality to support local loads while providing frequency support. The importance of this functionality creates additional purpose for prosumers by allowing future incentivization for both utility and oneself, offering support at the point of interconnect. It also creates future opportunities for other consumers to install PV and BESS without restrictions in high-penetration markets.

III. Scenario Study

A. System Description

INL is using its multi-functional microgrid testbed utilizing various distributed energy resources, allowing multi-islandable microgrids, grid-tied forming and following inverters, and the ability to couple to a grid emulator controlled by a Real-Time Automation Controller (RTAC) providing flexible testing capabilities with additional models. This case study implements our developed active frequency-Watt controls, which are programmed into an RTAC controlling one of the islanded microgrids coupled with a grid emulator controlled by a Real-Time Digital Simulator (RTDS). A hydropower model was developed to initiate frequency deviations to test the response of our controls paired with a BESS and PV, illustrating the capabilities active frequency-Watt controls provide in high penetration markets lacking spinning generation assets [7], [9]. The islanded microgrid in this case study consisted of a 250-kW/320-kWh BESS supplied by a 64-kW solar array, a 540-kW grid emulator, and an 8.3 MW turbine/8.9 MW synchronous generator hydropower model. INL's Microgrid Testbed used for this case study can be seen in Figure 2.

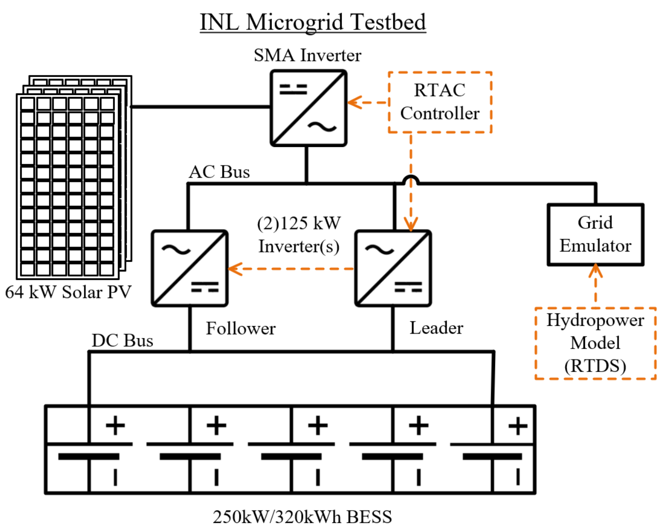

Fig. 2. Hardware-in-the-Loop test configuration with INL microgrid

B. Case Scenarios

A hardware-in-the-loop test was performed utilizing the hydropower model to initiate frequency deviations, allowing the microgrid consisting of a typical battery and PV installation to respond to frequency disturbances, creating grid stability. The microgrid uses the developed active frequency-Watt control as its primary frequency response. Testing was run disregarding interconnection disturbances by reaching the frequency cutoff limits, causing local tripping to display further the recovery responses of the architecture implemented with a BESS. This methodology is scalable to abide by the standard frequency support recommendations based on the local utilities operational guidelines [10]. Testing includes several step load changes causing relatively large frequency deviations to represent a base case illustrating a natural grid frequency response lacking a microgrid or batteries. A microgrid test case was conducted with a step load causing a natural frequency response dropping to 58.5 Hz, comparing it to the same step load met with our active frequency-Watt control architecture utilizing the BESS to support the grid's frequency.

C. Results and Discussion

1) Base Case Without Microgrid Controls Result: The base case ran without allowing the microgrid to respond to the frequency deviations. Various frequency steps were initialized, showing the predictable response of the grid responding to the decrease in frequency. Figure 3 is the natural frequency response of different load steps. In some cases, the frequency dropped well below the standard cutoff limits. Ride-through capabilities were accounted for, eliminating the operational dead band cutoff setpoints. There is also a significant overshoot in most cases as the system returns to its nominal frequency of 60 Hz. This overshoot stems from over-ramping the turbine, allowing a natural return. The overshoot in most test cases reached a standard system cutoff that would've caused interruptions at the point of interconnect. There are many drawbacks associated with spinning generation assets and their ability to respond to step load changes. Using the base case test results, it can be seen that without the additional microgrid support utilizing batteries, a quick dynamic response cannot be obtained, resulting in a frequency overshoot with major instability concerns. It is essential to recognize the limitations of having limited spinning generational capacities previously responsible for providing grid inertia relative to the increasing inverter-based resources.

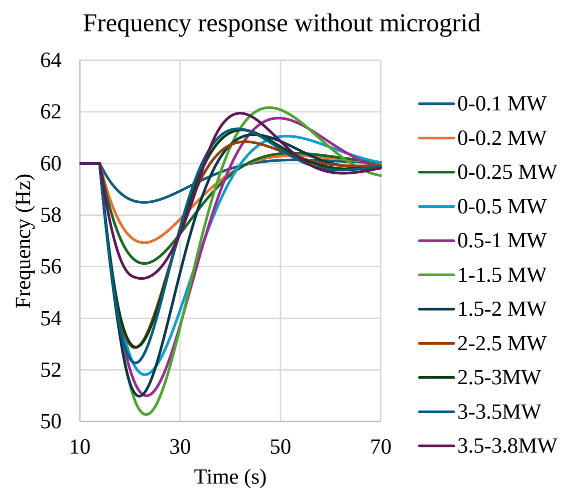

Fig. 3. Frequency response without microgrid and proposed control

2) Case With Microgrid Controls Result: The hardware in the loop case was run with the addition of the microgrid coupled to the grid emulator controlled by the RTDS. A base case result was compared to the same step load initiated on the system but with the active frequency-Watt controls response. The base case resulted in a deviation of 1.5 Hz from the system's nominal state of 60 Hz. The system's natural response also responded with a slight overshoot before dropping back to its steady state. The same step load was run with the microgrid in the loop, allowing our active frequency-Watt controls to respond quickly to the same deviation, resulting in a faster response while only allowing the frequency to decrease to 59.25 Hz. It is essential to notice how quickly the frequency recovered almost half the time utilizing the batteries versus the system's natural response. This allows for a faster response time with operational smoothness, avoiding rapid changes that could cause interconnection disturbances. Reducing the ramp rate using the active frequency-Watt control provides a smooth transition to return the system to 60 Hz. The active frequency-Watt case using the microgrid is adaptable and allows for precise frequency regulation control without the significant overshoot in the base case result. The hardware in the loop test, featuring an actual frequency response, is a resilient demonstration of the vital impact the developed active frequency-Watt controls coupled with batteries can have on maintaining grid stability. The synergistic relationship between PV and batteries significantly reduced the frequency disturbance, as seen in Figure 4, mitigating load imbalance generation fluctuations, and reducing the response time due to standard frequency deviations.

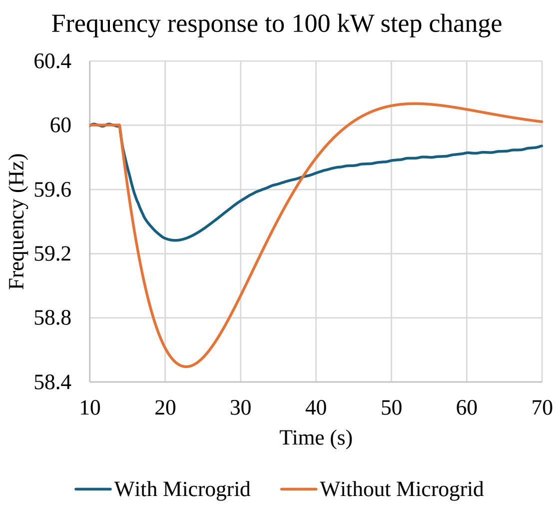

Fig. 4. Frequency response with microgrid with proposed control

IV. Conclusion and Future Work

Advanced control methodologies utilizing microgrids through decentralization have been proven capable of providing frequency support as the equivalence of grid inertia decreases. The hardware-in-the-loop case study conducted using INL's microgrid test shows a successfully implemented advanced fast frequency-Watt methodology to support grid stability at a more significant level. Using an adaptable active control technique utilizing a BESS reduced the considerable dip in frequency from 58.5 Hz in the base case to approximately 59.25 Hz using the microgrid. It also avoided the natural frequency swing, resulting in an overshoot, providing a soft ramp recovery and restoring the system to its nominal frequency of 60 Hz. A BESS can provide a fast dynamic frequency response, allowing more inverter-based resources to be added to the grid without restrictions. In high penetration areas, coordinated decentralization with distributed energy resources controls must be developed, tested, and standardized, creating a resilient power distribution network that minimizes interconnection disturbances. Our tested frequency-Watt controls provide fast frequency stability in areas where grid inertia is now lacking while addressing active load demands. Ongoing research is being conducted to refine our architecture and provide alternative frequency recovery methods, including synthetic grid inertia focusing on high-penetration areas. Future microgrid testing configurations will allow for multiple islanded testing scenarios with real hardware, allowing us to view real-time data to refine our control implementations, creating an optimized approach.

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