Interconnection Requirements for Renewable Generation and Energy Storage in Island Systems: Puerto Rico Example

Preprint

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Interconnection Requirements for Renewable Generation and Energy Storage in Island Systems: Puerto Rico Example

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***Abstract*— On September 20, 2017, Hurricane Maria made landfall in Puerto Rico, incapacitating the central power system and leaving the entire island without power. To ensure the long-term recovery of Puerto Rico's electric power grid in the most secure and resilient way, the U.S. Department of Energy funded research to develop recommendations for a cohesive new framework of interconnection standards for utility-scale renewable electrical generation and energy storage that ensure cross-technology compatibility and enable high deployment levels without compromising grid reliably, safety, or security. This paper provides a summary of work conducted by the National Renewable Energy Laboratory to analyze and address many shortcomings and areas of improvement to help the Puerto Rico Electric Power Authority (PREPA) establish minimum technical requirements for interconnecting single-technology and hybrid renewable generation because of their importance for PREPA system security and impacts on future integrated resource planning scenarios. Results and findings presented in this paper are important for any island power system.**

Keywords-component; renewable power plants, energy storage systems, grid services, interconnection requirements

I. INTRODUCTION

The future of Puerto Rico's still-recovering electricity system does not rely only on repairing the island's grid but also on rebuilding and modernizing it to make it resilient, low-carbon, and less dependent on imported fuels. The new "post-Hurricane Maria" integrated resource plan (IRP) is under development by the Puerto Rico Electric Power Authority (PREPA) to identify potential strategies to meet the island's electricity needs through 2035, including new renewable generation, new or modernized conventional generation, retirements of existing units, transmission buildup and reinforcement, and large-scale deployment of other enabling technologies such as energy storage [1]. The main goal of the IRP is to achieve a least-cost, reliable, resilient, renewable-dominated power system for Puerto Rico [2]. On October 2018, a regulatory framework and energy policy bill was introduced in the Puerto Rico Senate. This new legislation calls for generating 100% of the Puerto Rico's power using only renewable energy by 2050. The traditional approach to renewables as a provider of bulk variable power to the grid might no longer be sufficient to meet the evolving expectations for enhanced resilience in the island. Advanced power electronics-coupled renewable generation and energy storage technologies can be controlled to contribute to system-wide reliability. The deployment of utility-scale, grid-friendly solar photovoltaic (PV) and wind power plants as well as energy storage systems that incorporate advanced capabilities to support grid stability and reliability is essential for the large-scale integration of variable renewable generation into PREPA's power grid.

Modern PV and wind power plants as well as energy storage systems can be used to mitigate the impact of variability on the grid, a role reserved by PREPA for conventional generators. For example, it was demonstrated in [3] how very large PV power plants can provide essential reliability services to the grid, enabling PV to become a provider of a wide range of grid services, including spinning reserves, load-following, ramping, frequency response, variability-smoothing, frequency regulation, and voltage support. It was also demonstrated in [4] how a utility-scale 20-MW PV plant can provide reliability services to the PREPA transmission grid in the form of PV plant participation in automatic generation control (AGC), the provision of programmable frequency droop, and fast frequency response (FFR).

To ensure the long-term recovery of Puerto Rico's power grid in the most secure and resilient way, the U.S. Department of Energy (DOE) convened experts from many national laboratories to develop a cohesive set of recommendations based on the expert opinions of the varied stakeholders to ensure a strong technical rational for Puerto Rico's energy investment decisions. A resilient electric grid is vital to Puerto Rico's security, economy, and way of life and will provide the foundation for essential services upon which people and businesses on the island rely every day. The goal of work described in this paper was to develop recommendations for a new framework of interconnection standards for utility-scale renewable electrical generation and energy storage that ensure cross-technology compatibility and enable high deployment levels without compromising grid reliably, safety, or security. Modification of the existing and development of new valid interconnection requirements for grid-level variable renewable generation and energy storage are important tasks in this process because all reliability evaluation efforts for future planning assessments for the Puerto Rico grid must rely on them. This consideration is one important motivation behind the National Renewable Energy Laboratory's (NREL's) research effort described in this paper.

II. INCREASING NEEDS IN RALIABILITY SERVICES IN ISLAND SYSTEMS

Many island utilities, such as Hawaiian Electric Companies, are considering renewable resources and enhancing technologies such as energy storage and demand response to play an integral role in the grid of the future; meanwhile, the role of fossil fuels is expected to diminish from the energy mix in the islands [5]. Energy storage is also one potential resource for flexibility and reliability services within a diverse resource portfolio. Many island utilities are evaluating energy storage technologies and roles they can play to increase the operational flexibility of the existing (but often aging and slow) generating units. The deployment plans for energy storage must be developed in concert with other operating practices, such as generating unit dispatch, load-shedding schemes, load management, and customer-focused solutions [5]. In addition, advanced reliability services by energy storage systems such as synthetic inertia and FFR stacked on top of more common applications—such as frequency regulation, renewables ramp limiting, and voltage support—should be considered when defining the role of storage in island systems for enhanced security and resilience.

On international power sector scenes for islands and isolated power systems, there is widescale adaptation and increasing experience, especially in frequency control measures of any variable generation and energy storage [6]. Most international experiences in frequency control for power systems with very high shares of variable generation revolve around key areas of managing power systems with low inertia (and therefore a high rate of change of frequency [ROCOF]), using faster frequency control characteristics offered by inverter-coupled variable generation and energy storage. A few large international jurisdictions (500 MW or more) are experiencing issues related to high ROCOF [6], such as EirGrid/ System Operator for Northern Ireland (SONI), National Grid in Great Britain, and Cyprus [7]. The Australian Energy Market Operator (AEMO), EirGrid, and SONI have performed significant research work on challenges related to the operation of low-inertia grids [8]. SONI proposed interim grid code standards of 1 Hz/s over 500 ms for the Ireland system and 2 Hz/s for the Northern Ireland system. A high ROCOF was experienced in the South Australia system during the blackout event on September 28, 2016, [9] and issues related to ROCOF are investigated in the Future Power System Security Program at AEMO. Simulations are performed to demonstrate the behavior of the system for different fast frequency responses from wind turbines [10]. WEB Aruba is using flywheel energy storage for frequency regulation in their power system, which has high levels of wind and solar generation.

PREPA's system will be trending toward lower levels of synchronous inertia, meaning that there are significant advantages to targeting a future system for the island capable of withstanding extreme ROCOF scenarios. This process needs to commence early to ensure that generation installed during various stages of IRP deployment has the capabilities to operate in the future high-ROCOF environment and can demonstrate functionality to mitigate ROCOF. The process of retrofitting plants to ensure compliance for existing plants would be much more complicated and costlier. In combination with other active power control (APC) features such as FFR, primary frequency response (PFR), and AGC participation by variable generation and energy storage, the acceptable levels of frequency response can be achieved in the future PREPA system.

The effects of the widespread electricity loss in Puerto Rico triggered discussions on possible pathways for improving island electric system reliability and system resilience. The challenges in achieving both goals are different because system reliability and system resilience are related but depend on different scopes and regulatory environments. Reliability is often referred to as the ability of a system or its components to withstand transient and dynamic instability, uncontrolled events, cascading failures, or unanticipated loss of system components [11]. On the other hand, reliability is also referred to as the ability of a system or its components to adapt to changing conditions and withstand and rapidly recover from disruptions. The reliability metrics, standards, and indices have historically been well defined and enforced by the Federal Energy Regulatory Commission (FERC) for the bulk power system through several orders, and they have been less formalized but still well studied for many island communities. From this perspective, the evolving development of interconnection requirements for island systems—and PREPA, in particular—although still challenging, can be considered more or less a straightforward process; however, incorporating resilience-related controls for variable generation and energy storage is more challenging, especially considering the fact that there are no commonly used metrics for measuring grid resilience. As of today, electric system resilience for any jurisdiction is not mandated by federal, state, or territorial legislations. A 2016 report from several DOE national laboratories focused on this changing environment and the need to maintain a resilient power system [12]. This report provided recommendations "to guide future decision-making to enhance resilience of the U.S. electricity system," including a recommendation on the development of a robust and scalable system of resilience metrics for the electricity system. This report provides some initial recommendations for interconnection requirements for variable generation and energy storage technologies related to resilience, such as grid-forming and black-start capabilities. More on this topic will be covered in the Phase II activities along with progress on the IRP development and work on better defining the resilience metrics for PREPA.

III. RENEWABLES INTEGRATION CHALLENGES IN PUERTO RICO

PREPA has a modern electric power system that serves the entire main island of Puerto Rico and its two adjacent islands of Vieques and Culebra. The subsea cable to Vieques was damaged during the hurricane, so both Vieques and Culebra are now disconnected from the PREPA grid. Currently, the total installed generation capacity in Puerto Rico is close to 6 GW, which includes almost 200 MW of wind and solar PV generation (Figure 1).

Puerto Rico's power system exhibits an interesting cycle of a daytime peak, followed by a solar and wind power ramp-down, followed by an evening system load ramp-up that reaches a nighttime peak that is higher than the daytime. This cycle is extremely important to the challenges of integrating wind and solar into Puerto Rico’s power system.

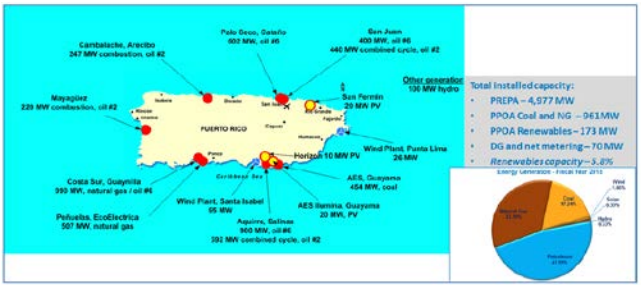

Figure 1. Installed generation capacity in Puerto Rico (2016 data)

Some hypothetical scenarios for PREPA net load at different installed PV capacities calculated by NREL are shown in Figure 2 (similar to the California Independent System Operator “duck” curve). High levels of PV generation will cause sharp changes in the real-time ramping needs, so more resources with faster ramping capacity will be needed to meet these stiff evening and morning net load ramps. At very high PV penetration levels, the “belly of the duck” could actually go negative, requiring either curtailment or energy storage capacity to shift it. As described earlier, energy storage can be a potential resource for flexibility and the provision of reliability services within such PV resource portfolios.

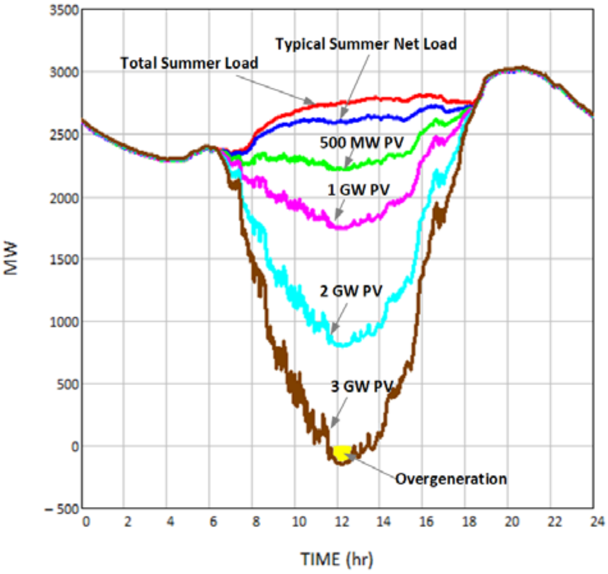

Figure 2. Hypothetical net load profiles at different PV capacities

IV. PREPA’s Exisiting MTRs

In 2012, PREPA developed its own set of interconnection requirements, or minimum technical requirements (MTRs), with which all transmission-level utility-scale wind and solar PV generators shall comply [13]. A 2014 Siemens Power Technologies International (PTI) study [14] confirmed the importance of 100% compliance with PREPA’s MTRs for the planned target of 579.4 MW of renewable generation (419.4 MW of PV and 160 MW of wind). In addition, the same study stressed the importance of existing and future renewable generation to provide frequency regulation. The new, post-Hurricane Maria IRP, also being developed with help by Siemens, will define new feasible levels of variable generation and required levels of energy storage in the PREPA grid to ensure an affordable, reliable, and secure gird of the future in Puerto Rico. From this perspective, it is anticipated that PREPA’s MTRs will constantly evolve as the level of renewable penetration increases, modeling tools are improved, and experience with system performance is gained.

PREPA’s existing MTRs for PV generation already required that utility-scale PV projects should have many reliability controls available, including:

- Low-voltage ride-through (LVRT) and high-voltage ride-through (HVRT) controls
- Voltage regulation controls
- Steady-state and dynamic reactive power controls
- Frequency fault ride-through (FRT) controls
- Frequency response and frequency regulation controls
- Ramp-rate controls
- Active power management.

In addition, requirements such as transient FRT, power quality compliance, and resource forecast have been listed in the 2012 MTRs.

A 2015 project funded by DOE’s Solar Energy Technologies Office was designed to provide PREPA with an opportunity to spur the adoption of and contribute to improving advanced grid-friendly controls of utility-scale PV generation [4]. These goals were achieved by conducting such tests and demonstrations on a 20-MW grid-connected PV power plant located along the south coast of Puerto Rico (AES Ilumina PV power plant). This NREL-led demonstration project laid the foundation for understanding what types of benefits can be provided to PREPA’s reliability by using advanced reliability service controls of modern utility-scale PV power plants. A joint NREL, AES, PREPA, and GPTech team modified the AES plant controls to provide new types of reliability services, including plant participation in AGC and the provision of PFR and FFR. In fact, at the time, it was the first and largest project of its kind ever conducted using a utility-scale PV power plant. For AGC tests, it is remarkable to notice that during certain periods of testing the AES Ilumina PV power plant was the only resource in PREPA participating in AGC. The results of one AGC test from August 14, 2015, are shown in Figure 3, where 40% curtailment from available solar power was used to provide headroom for following the AGC signal provided by PREPA.

The results of the 2015 NREL project showed clearly that it is mainly a matter of implementing controls and/or communications upgrades to provide a full suite of grid-friendly controls from hardware components that are already in existence in many utility-scale PV plants. Carefully designed new or modified existing interconnection requirements should help PREPA unleash these capabilities from renewable resources and use them as one of many tools in PREPA’s tool set for achieving the broader objective of a resilient, reliable, low-carbon grid for Puerto Rico.

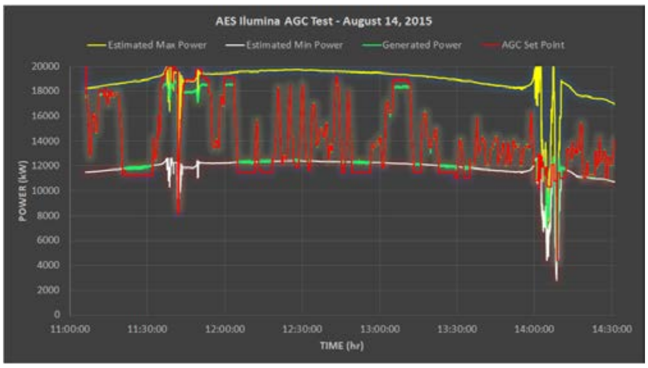

Figure 3. Example of AGC test conducted in 20-MW AES Ilumina PV plant in Puerto Rico

V. RECOMMENDATIONS ON MTR MODIFICATIONS

A. Inertial Reponse

Inertial response is the important characteristic of any power system that impacts the initial ROCOF during contingency events, similar to the one shown in Figure 4. This event was recorded in August 2017.

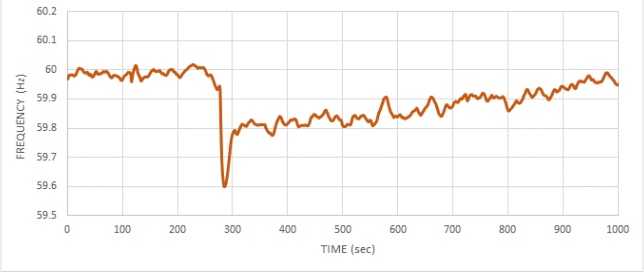

Figure 4. Frequency event recorded in Puerto Rico

PREPA's existing MTRs for wind power require the provision of inertial response; however, it does not specify characteristics of such response such as magnitude of the response and frequency/ROCOF deadbands.

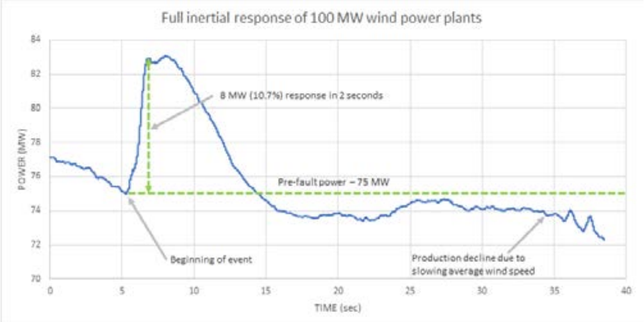

Figure 5. Aggregate inertial response of 100-MW wind power plant

Based on these considerations, NREL recommended including requirements on ranges for inertial control deadbands for frequency and ROCOF and also including requirements on the magnitude of inertia response as a percentage of prefault power level or total plant capacity. For example, the programmable frequency deadland for inertial response can be within a range of 0.025–0.3 Hz. The programmable ROCOF deadland can be within a range of 0.1–2 Hz/s. The magnitude of inertial response can also be programmable within a range of 0–0.15 p.u. The exact values for deadbands need to be verified during integration studies. PREPA can request plant operators to change these values at later times if changes in the system occur and retuning inertial parameters is needed.

B. Primary Frequency Response

The primary frequency response (PFR) requirement is very well defined in the existing MTRs for both wind and solar generation; however, it is important to point out that both wind and PV power plants can reduce their power outputs very fast during frequency events, so nonsymmetric droop characteristics are possible. This way, more aggressive down-regulation droop settings can be used to arrest fast overgeneration events.

Figure 6 shows test results for a 1.5-MW wind turbine generator (WTG) exposed to real step changes in frequency emulated by NREL's medium-voltage grid simulator. As shown, the turbine first provides inertial response immediately after the frequency drops, then it deploys and maintains its primary reserve in accordance with the 3% droop setting until the frequency returns to nominal, and it can provide these services at any wind speed conditions.

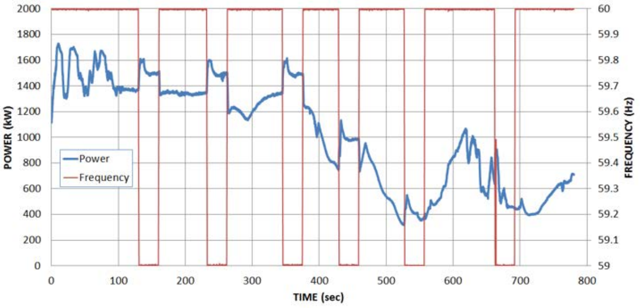

Figure 6. Utility-scale 1.5-MW WTG providing inertial response followed by droop response

C. Automatic Genmeration Control

The existing PREPA MTRs for wind and solar do not have a clause for AGC participation by wind and solar generation, so renewable plants in Puerto Rico are not AGC capable. The purpose of the AGC functionality for renewable generation is to enable a wind or solar PV power plant to follow the active power set points sent by PREPA's AGC system. When in AGC mode, the power plant controller (PPC) of renewable plants initially sets them to operate at power levels that are lower than the estimated available peak power to have headroom for following the up-regulation AGC signal. The lower boundary of AGC operation can be set at any level below the available peak power, including full curtailment, if necessary. PREPA's AGC is normally set to send a direct MW set-point signal to all participating units every 2 s. For more efficient participation in an AGC scheme, all ramp-rate settings in the PV and wind power plant's PPC should be set at a very high level.

PREPA's area control error (ACE) is expected to have strong correlation with grid frequency because it is an islanded system. Figure 7 shows 2-s ACE data plotted against PREPA's frequency. It can be observed from the plot that ACE correlates very well with frequency (correlation factor 0.87), and it essentially represents the "sensitivity" (or bias) of PREPA's frequency to load-generation imbalances. During this day, PREPA system exhibited B≈9.1 MW/0.1 Hz. Of course, the distribution of the frequency bias B needs to be analyzed for the whole year; however, even this preliminary value allows estimating the amount of frequency regulation reserves for different renewable penetration levels to maintain PREPA's frequency within predefined limits.

The ability of utility-scale PV generation and WTGs to follow AGC set points was tested by NREL in collaboration with industry partners [3], [15]. Note that PV plants should be able to maintain the desired regulation range, so the plant PPC must be able to estimate the available aggregate peak power that all the plant's inverters can produce at any point in time. A similar requirement is true for wind power plants as well. Many utility-scale PV power plants in Puerto Rico are already capable of receiving curtailment signals from grid operators; each plant is different, but it is expected that the transition to AGC operation mode will be relatively simple with modifications made only to the PPC and interface software.

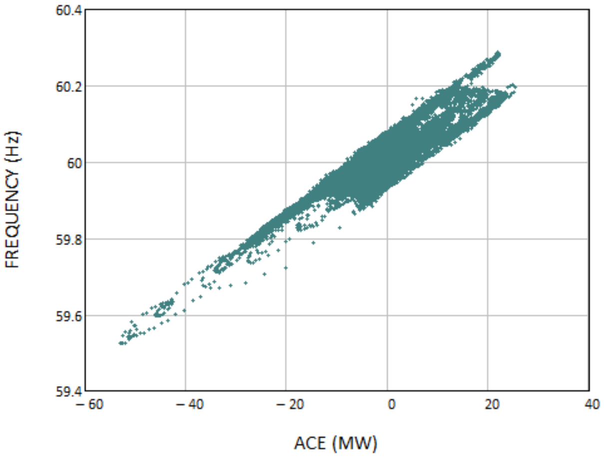

Figure 7. Typical 2-s ACE

NREL recommended including AGC functionality in the modified MTRs for both wind and solar PV generation. New renewable plants should be able to have two-way communications with compatible protocols and hardware as well as proper scaling for set-point signals. The plants should be able to maintain their predetermined headroom and follow the AGC signal from RPEPA with a high level of accuracy. The plants should always be able to accurately determine their available reserves and communicate that information to PREPA's SCADA.

D. Ramp Limiting

PREPA's 10% of nameplate capacity per minute ramp-rate limitation for renewable plants has been a topic of industry-wide discussion for several years now. The purpose of PREPA's 10% limitation was to protect the system from significant changes in power from wind and PV power plants. Because of the added costs imposed by complying with this limit, it makes sense to put effort into reassessing this rule criticality based on improved analysis methods. Large energy storage systems or other ramp mitigation equipment (even diesel generators) have been used by several plant developers in Puerto Rico to comply with the 10% limitations.

The combined distribution of all wind and solar PV ramps from all plants in PREPA is shown in Figure 8 for a typical summer month. As shown, the aggregate wind and solar ramp distribution as a percentage of combined capacity is much smaller than for individual plants. This fact provides enough reason to reevaluate the blanket 10% capacity/min ramp-limiting requirement for all renewable plants in Puerto Rico imposed by the existing MTRs. It is obvious that geographical smoothing of ramps can reduce the aggregate renewable ramps across the whole system, thus requiring less per-unit energy storage capacity for the same benefit.

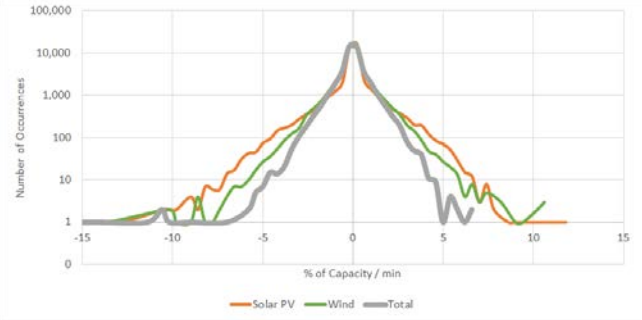

Figure 8. Aggregate wind and solar 1-min ramps

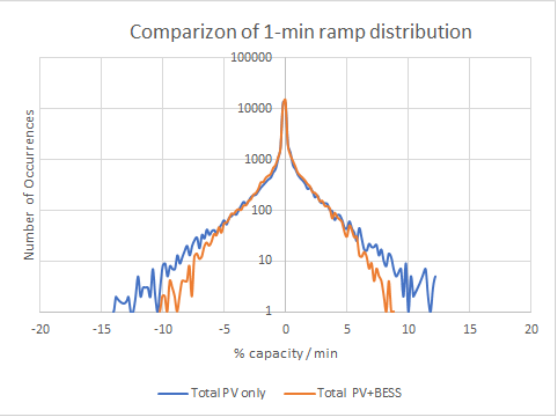

Figure 9. Comparison of total PV and PV+BESS ramps for a typical summer month

A comparison of total PV-only and PV+battery energy storage system (BESS) ramp rate distributions are shown in Figure 9 for the same month. As shown, the BESS provides only marginal improvements in the tails of the distributions (orange trace vs. blue trace in Figure 9). A similar analysis conducted by NREL using other historic data from Puerto Rico demonstrating that using a BESS coupled with individual PV plants for ramp-limiting purposes provides no or marginal benefits to the system in terms of PV ramp limiting. Even if PV plants are equipped with energy storage, the storage can be controlled to provide the most benefits on an aggregate system level rather than responding to resource variability within only the plant footprint.

E. Acitve Power Reserves by PV plants

Establishing a headroom for up-regulation is not a problem for the conventional generation fleet, but the varying nature of solar and wind generation makes it challenging to set and maintain adequate headroom for these varying resources. To provide active power reserves (or a headroom margin) for up-regulation that can be automatically dispatched as needed, a PV plant needs to operate below its maximum power point (MPP); however, evaluating that MPP in curtailed mode is not a trivial task, especially for large PV power plants during various types of variable conditions caused by clouds. One example of such uncertainty is shown in Figure 10 during operation when the PV plant was responding to an AGC signal sent from system operator. The AGC system assumed that there was still some available headroom for up-regulation because its evaluation was based on the available plant power value that was communicated by the PPC; however, the calculated available power is overly optimistic, and inverters are not able to produce as much power because they are already operating at their peak power point.

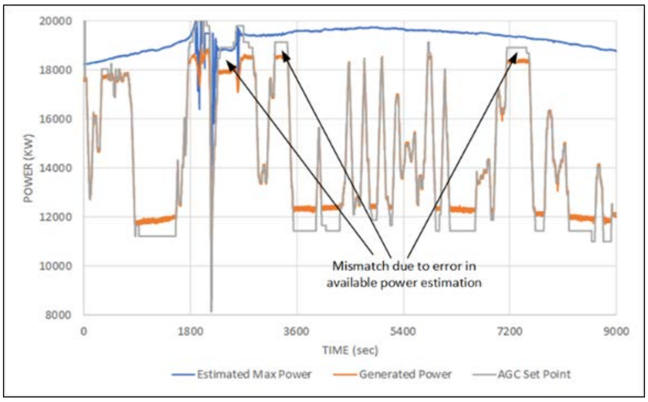

Figure 10. Example of inaccurate maximum potential power estimation (NREL test conducted in Puerto Rico)

A different method for estimating the maximum power was used during a demonstration testing a 300-MW PV power plant in California [3]. In this case, a single 4-MVA inverter was taken from the AGC scheme and set to operate at the power level determined by its maximum power point tracking (MPPT) algorithm. The measured AC power of this inverter was used as an indicator of available power for the other 79 inverters (80 inverters total), so the plant was able to operate with a fixed 30 MW of headroom. In recent years, NREL developed a more advanced method based on the use of multiple reference inverters to achieve high levels of real-time maximum peak power estimation under conditions of extreme variability [16].

Calculations performed for different variability cases (moderate, intense, and extreme) demonstrated continuous improvements in the accuracy of the estimated maximum PV plant power with increasing numbers of reference inverters (N=1 .. 48). This can be observed from both 1-s time-series graphs for the extreme variability case (Figure 11).

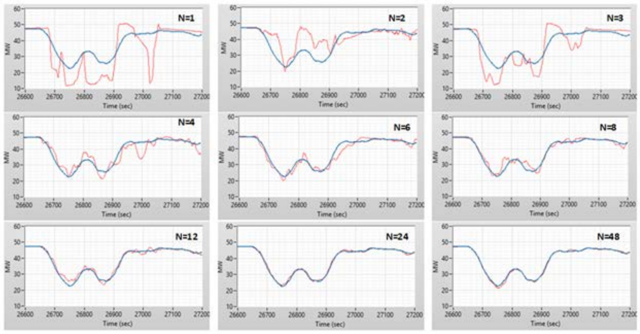

Figure 11. Improving accuracy of potential power estimation for 48-MW PV plant under conditions of extreme variability

Based on these considerations, NREL recommend that PREPA include a requirement for new solar PV and wind power plants to have the capability for accurate real-time active power reserve estimation. Such capability is important for the provision of plant controls for both AGC and frequency response. Different vendors can use different methods for such estimation. It should be demonstrated during the plant commissioning stage that the reserve estimation error stays within tolerance bands under conditions of extreme various resource variability. We also recommend that RPEPA conduct a study determining the minimum tolerance bands for reserve estimation by variable generation.

F. *Reactive Power and Voltage Control*

Reactive power capabilities defined in current MTRs require a wide range for MVAR support. NREL has conducted testing and demonstrated that many modern PV and BESS inverters and some wind turbine topologies can meet and exceed PREPA's reactive power requirements [17], [18]. For example, a per-unit comparison of PREPA's requirements with reactive power capability of BESS measured by NREL is shown in Figure 12.

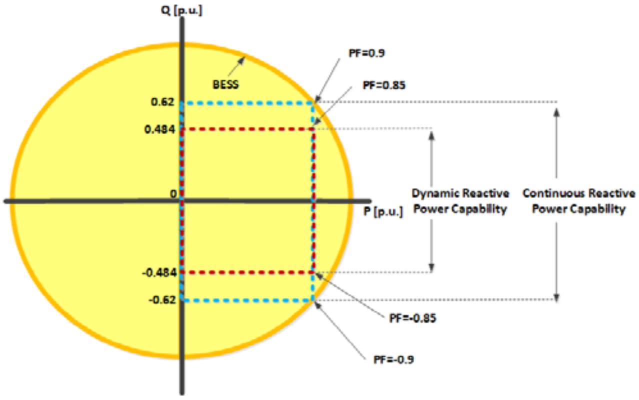

Figure 12. Comparison of BESS reactive power capability with existing PREPA MTR

PREPA's current reactive power capability requirement listed in the existing MTRs seem to be adequate; however, NREL's advice is to reevaluate it based on two scenarios: (1) all renewable plants are coupled with energy storage to meet the existing PREPA MTRs, and (2) there are centralized energy storage plants providing system-level services for both active and reactive power controls. A comparison between two scenarios might indicate that less reactive power capability from individual renewable plants might be needed for scenario (2).

VI. RECOMMENDATIONS FOR ESTABLISHING NEW MTR FOR ENERGY STORAGE SYSTEMS

A. *Active Power Controls by BESS*

The current PREPA MTRs are applicable for solar PV and wind power plants only, and they do not include stand-alone energy storage plants that can be located elsewhere in PREPA's power system and provide centralized active and reactive power services to PREPA's grid. Such services can include:

- Provision of dispatchability for variable generation in Puerto Rico
- Aggregate ramp limiting, variability smoothing, and cloud-impact mitigation on system levels

- Provision of spinning reserves
- AGC functionality
- Renewables forecast error correction services
- PFR with programmable droop
- FFR
- Inertial response—programmable synthetic inertia for a wide range of H constants emulated by BESS
- Reactive power/voltage/power factor control
- Advanced controls: ability of the plant to modulate its output for the provision of power system oscillation damping services
- Stacked services (ability to provide several services at the same time).

FFR is an evolving method to use the BESS to compensate for sudden generation or load losses. This can become a very efficient frequency response tool for system operators but requires precise knowledge of loss magnitude, so the BESS can be commanded to change its power output accordingly. This method is dependent on the ability of the control system to rapidly determine the magnitude of the loss and communicate the set point to BESS control. The speed of response (or how fast the BESS deploys all available reserves) will depend on power system stability impacts: the BESS can deploy all available reserves very fast, which can cause unwanted oscillations in the system. In some cases, FFR activation by the BESS can be based on frequency thresholds such as underfrequency load-shedding schemes or based on the ROCOF. This will require determination of precise FFR magnitudes based on system frequency or frequency ROCOF by conducting system-level modeling studies. NREL measured approximately 20–30 ms consistent response times by a commercial 1-MW/1-MWh Lithium-ion (Li-ion) BESS with an inverter demonstrating that battery storage can be an efficient provider of FFR service.

NREL explored the question of what frequency response services by a BESS are most impactful in terms of improving power system performance during and after large contingencies. For this purpose, we used a power system model for a system such as PREPA consisting of synchronous generators with steam, gas, and hydro governors; static loads; inertia-less wind and solar generation; and a BESS. In this hypothetical case, there was a 20% share of combined wind and PV generation, and the combined rated power of the BESS is 3.5% of the total load. We simulated a large contingency by tripping off a generator that supplies 3% of the load. The combined inertia constant for all conventional generators H=5 s. In this modeling exercise system, both wind and solar generation were providing only bulk power with no reliability service. The BESS operated at zero power, so it had ability to operate at full power in both charge or discharge modes. At t=50 s, a generator tripped, causing the system frequency to decline, as shown in Figure 13. The base case (black trace) is when inertia and droop response by only conventional generators are available, causing a frequency nadir at about 59.6 Hz. The results of the simulations for this hypothetical case are explained in Figure 13a and b.

The following services by BESS are activated to demonstrate the impacts on system frequency:

- Case 1: BESS providing inertial response (200-ms delay)
- Case 2: BESS providing droop response (200-ms delay)
- Case 3: BESS providing inertial response and droop (200-ms delay)
- Case 4: BESS providing FFR (2-s delay)
- Case 5: BESS providing inertia (200-ms delay) and FFR (2-s delay).

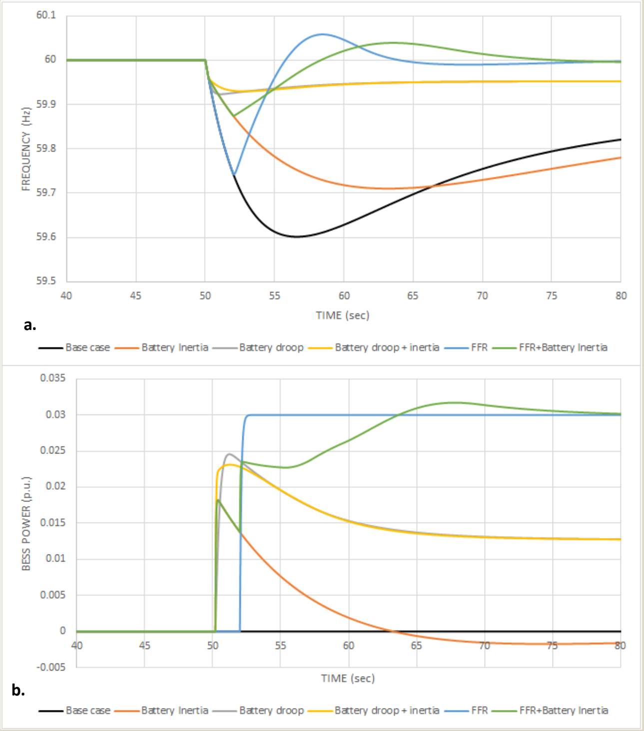

Figure 13. System frequency (a) and BESS response (b)

B. Reactive Power Controls by BESS

The P-Q capability of NREL's 1-MW/1-MWh BESS consisting of LG Li-ion batteries and SMA 2.2-MVA, 400-VAC inverter/charger with 1.1-MVA 13.2-kV/400-V transformer was verified using an experimental grid simulator setup. The inverter was commanded by various combinations of active and reactive power set points to cover the whole range of P-Q operation, as shown in Figure 14.

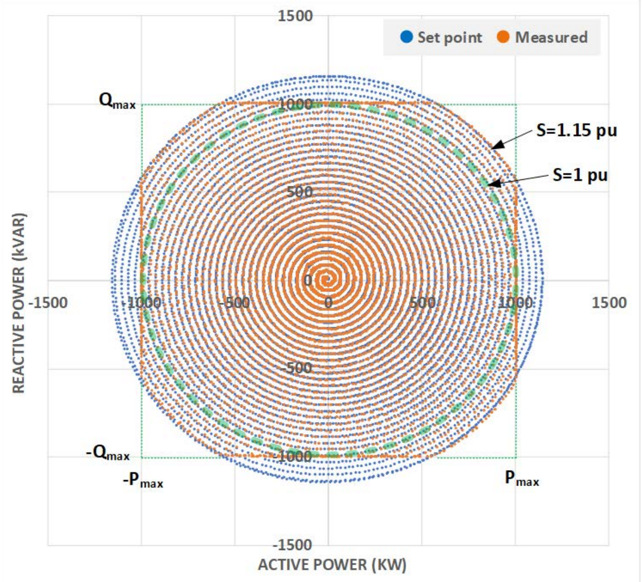

Figure 14. Results of BESS P-Q characterization test

The reactive power capability of a colocated hybrid renewable power plant is larger than the reactive power capability of individual components of the plant. One measured example of such expanded reactive power capability of a hybrid plant consisting of a 1.5-MW doubly-fed induction generator WTG, 500-kW PV power plant, and 1-MW BESS is shown in Figure 15.

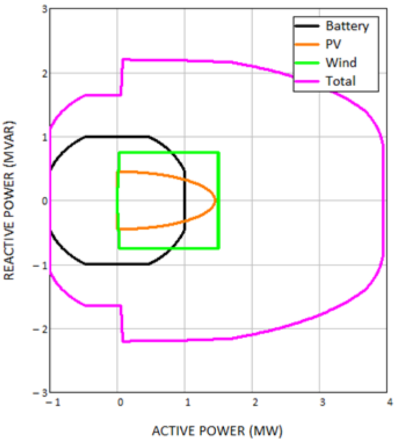

Figure 15. P-Q characteristics of hybrid power plant

C. Grid-Forming Controls by BESS

Grid-forming- and black-start-capable BESS can effectively replace the on-site diesel generators that have traditionally provided this service. Black-start capability will increase the value proposition of battery resources in Puerto Rico while avoiding some of the costs associated with retrofitting existing generators for black-start service. It will also help increase the level of power supply security, resilience, and fact recovery of the PREPA system during and after natural disasters. We recommend that PREPA include black-start capability by BESS in studies related to the IRP process to better understand the imitations of battery chemistries and impacts on inverter power capabilities for black-start service.

The grid-forming capability of 1-MW BESS inverters tested by NREL are demonstrated in Figure 16. In this case it was demonstrated that the inverter operating as a voltage source in isochronous mode (constant 60-Hz operation) can provide fast active and reactive power control based on both external set-point and droop operation. Figure 16 shows that inverter active power is ramped up and down in a controlled way while maintaining stable voltage amplitude frequency with acceptable power quality.

D. Recommendations on New NTRs for Energy Storage Systems

NREL recommend that PREPA to develop a new dedicated MTR document for utility-scale energy storage systems. Such a new MTR should cover:

- All aspects related to active and reactive power grid services by energy storage systems
- Black-start and grid-forming capability
- Transient FRT capabilities of storage inverters
- Power quality requirements
- Protection issues
- Provision of validated energy storage plant models
- All new grid-scale BESS in Puerto Rico need to operate under direct control by PREPA for participation in AGC with enabled local frequency-responsive controls.
- In case of Power Purchase Agreements (PPA) renegotiations with the existing PV plants equipped with energy storage take place in the future, this could be a good chance to upgrade the controls and communications and use the existing energy storage assets to provide system-level benefits to PREPA.

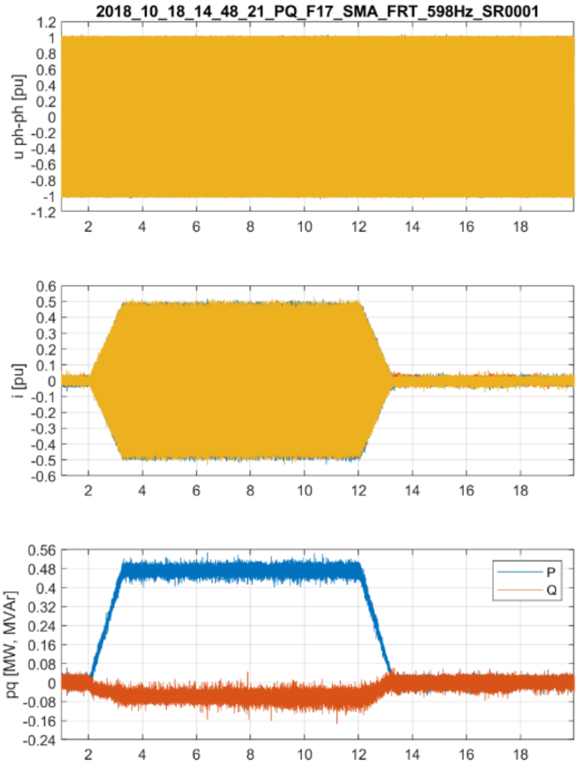

Figure 16. Active power control of 1-MW BESS inverter operating in grid-forming mode

A list of required services by BESS and related parameters that need to be specified in MTR should include:

- Inertial response capability with programmable inertia constant H
- Fast frequency response capability with response time and maximum possible power up- and down-ramp rates
- Frequency droop control capability with programmable droop setting and deadbands
- Ability to follow 2-s active power set-point commands from PREPA's AGC system
- Voltage droop control capability with programmable droop setting and deadbands
- Steady-state and dynamic reactive power injection or absorption capability
- Short-circuit current control capability (including control over positive-, negative-, and zero-sequence components) under balanced and unbalanced fault conditions
- Voltage and frequency FRT capability
- Grid-forming capability:
    - The concept of a virtual synchronous machine (VSM) is emerging in the industry as a flexible option to allow operation under a wide range of

system conditions, including seamless transition between grid-connected and stand-alone operation.

- Control of short-circuit current in grid-forming mode under various fault scenarios.

VII. CONCLUSIONS

The NREL team conducted activities to analyze and address some shortcomings or areas of improvement in PREPA's MTRs because of their importance for PREPA's system security and impacts on future IRP scenarios. The review presented in this paper is largely based on NREL and industry experience in conducting large-scale demonstration projects featuring multi-megawatt variable generation plants with the provision of many types of reliability services to the grid.

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