Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation

Article *in* IEEE Transactions on Smart Grid · June 2012
DOI: 10.1109/TSG.2012.2190113

5 authors, including:

Cody Hill
LS Power

W.M. Grady
Baylor University and University of Texas at Austin

Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation

Cody A. Hill, *Member, IEEE*, Matthew Clayton Such, *Member, IEEE*, Dongmei Chen, *Member, IEEE*, Juan Gonzalez, *Student Member, IEEE*, and W. Mack Grady, *Fellow, IEEE*

***Abstract*—As solar photovoltaic power generation becomes more commonplace, the inherent intermittency of the solar resource poses one of the great challenges to those who would design and implement the next generation smart grid. Specifically, grid-tied solar power generation is a distributed resource whose output can change extremely rapidly, resulting in many issues for the distribution system operator with a large quantity of installed photovoltaic devices. Battery energy storage systems are increasingly being used to help integrate solar power into the grid. These systems are capable of absorbing and delivering both real and reactive power with sub-second response times. With these capabilities, battery energy storage systems can mitigate such issues with solar power generation as ramp rate, frequency, and voltage issues. Beyond these applications focusing on system stability, energy storage control systems can also be integrated with energy markets to make the solar resource more economical. Providing a high-level introduction to this application area, this paper presents an overview of the challenges of integrating solar power to the electricity distribution system, a technical overview of battery energy storage systems, and illustrates a variety of modes of operation for battery energy storage systems in grid-tied solar applications. The real-time control modes discussed include ramp rate control, frequency droop response, power factor correction, solar time-shifting, and output leveling.**

***Index Terms*—Battery energy storage systems, photovoltaic, renewables, smart grid, solar.**

I. Introduction

THE integration of significant amounts of photovoltaic (PV) solar power generation to the electric grid poses a unique set of challenges to utilities and system operators. Power from grid-connected solar PV units is generated in quantities from a few kilowatts to several MW, and is then pushed out to power grids at the distribution level, where the systems were often designed for 1-way power flow from the substation to the customer. In climates with plentiful sunshine, the widespread adoption of solar PV means distributed generation on a scale never before seen on the grid. The resulting challenges can best be thought of as opportunities for both manufacturers and utilities as they roll out various Smart Grid initiatives.

Grid-connected solar PV dramatically changes the load profile of an electric utility customer. The expected widespread adoption of solar generation by customers on the distribution system poses significant challenges to system operators both in transient and steady state operation, from issues including voltage swings, sudden weather-induced changes in generation, and legacy protective devices designed with one-way power flow in mind [1].

When there is plenty of sunshine during the day, local solar generation can reduce the net demand on a distribution feeder, possibly to the point that there is a net power outflow to the grid. In addition, solar power is converted from dc to ac by power electronic converters capable of delivering power to the grid. Due to market inefficiencies, the typical solar generator is often not financially rewarded for providing reactive power support, so small inverters are often operated such that they produce only real power while operating a lagging power factor, effectively taking in or absorbing reactive power, and increasing the required current on the feeder for a given amount of real power. A radial distribution feeder with significant solar PV generation has the potential to generate most of its own real power during daylight hours, while drawing significant reactive power. Utilities in the southwestern United States have started to encounter power factor violations of the operating rules laid down by the regional transmission organizations (RTO) and independent system operators (ISO) who have oversight over their systems, and may incur fines for running their systems outside of prescribed operating conditions. An example of such regulations is that set by the Electric Reliability Council of Texas (ERCOT), which operates the electric grid and manages the deregulated market for 75 percent of the state Texas. ERCOT regulations require that distribution system operators (DSO) on their system to maintain at least a 0.97 lagging power factor for the maximum net active power supplied from a substation transformer at its distribution voltage terminals to the distribution system [2].

Solar power's inherent intermittency poses challenges in terms of power quality and reliability. A weather event such as a thunderstorm has the potential to reduce solar generation from maximum output to negligible levels in a very short time. Wide-area weather related output fluctuations can be strongly correlated in a given geographical area, which means that the set of solar PV generators on feeders down-line of the same substation has the potential to drastically reduce its generation in the face of a mid-day weather event. The resulting output

Manuscript received November 22, 2010; revised June 20, 2011; accepted January 18, 2012. Date of publication May 11, 2012; date of current version May 21, 2012. This work was supported in part by Xtreme Power Systems, Kyle, TX. Paper no. TSG-00256-2010.

C. A. Hill and J. Gonzalez are with the University of Texas, Austin, TX 78712 USA (e-mail: chill@xtremepower.com; jgonzales@xtremepower.com).

M. C. Such is with Xtreme Power Systems, Kyle, TX 78640 USA (e-mail: csuch@xtremepower.com).

D. Chen is with the Department of Mechanical Engineering, University of Texas, Austin, TX 78712 USA (e-mail: dmchen@me.utexas.edu).

W. M. Grady is with the Department of Electrical and Computer Engineering, University of Texas, Austin, TX 78712 USA (e-mail: grady@mail.utexas.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2012.2190113

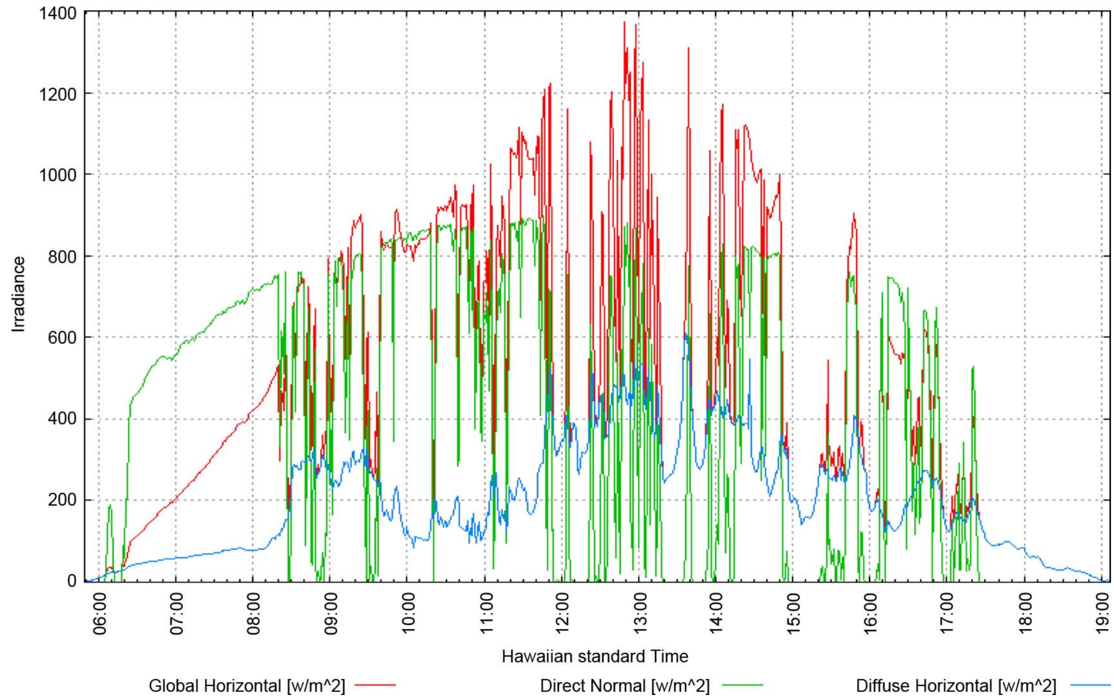

Fig. 1. Solar power measured over 24 hours at the La Ola solar installation at Lanai, Hawaii [5].

fluctuations can adversely affect the grid in the form of voltage sags if steps are not taken to quickly counteract the change in generation. In small power systems, frequency can also be adversely affected by sudden changes in PV generation. Battery energy storage systems (BESS), whether centrally located at the substation or distributed along a feeder, can provide power quickly in such scenarios to minimize customer interruptions [3]. With the right control schemes, grid-scale BESS can mitigate the above challenges while improving system reliability and improving the economics of the renewable resource, thus providing a true smart grid solution to the integration of distributed renewable energy sources to the 21st century grid.

This paper describes the operation and control methodologies for a grid-scale BESS designed to mitigate the negative impacts of PV integration, while improving overall power distribution system efficiency and operation. The fundamentals of solar PV integration and BESS technology are presented below, followed by specific considerations in the control system design of solar PV coupled BESS installations. The PV-coupled BESS systems described in this paper utilize the XP-Dynamic Power Resource (XP-DPR), a megawatt-scale integrated BESS developed for renewable energy applications, manufactured by Xtreme Power in Kyle, TX. The system is currently operating in a solar-coupled mode on 12.47 kV power systems in the Hawaiian Islands, at a solar technology testing facility in Colorado under the auspices of Xcel Energy and the National Renewable Energy Laboratory (NREL), and at the high-power hardware-in-loop test facility at Xtreme Power's Kyle, TX headquarters, described in [4].

II. Photovoltaic Integration

Modest levels of solar PV generation on distribution circuits can be easily managed by the distribution system operator (DSO). However, both the DSO and the customers of electric retail service may soon feel the undesirable impacts on the grid as PV penetration levels increase. The extent of the intermittency challenge is suggested by Fig. 1, depicting solar power measured at a site in Hawaii on a normal spring day [5]. Solar PV generation is becoming more economical every year, and accommodating increased penetration levels is a central challenge for the next generation smart grid. In the United States, increased solar PV generation capacity is being driven in part by targets established under the auspices of the Renewables Portfolio Standard (RPS), laws now on the books in a majority of states that require utilities to source certain amounts of generation from renewable resources like wind and solar power [6]. Between RPS laws and improving economics, solar PV generation is well positioned to become a significant source of electricity in coming years. As solar PV generation penetration increases, the electricity grid will increasingly be subjected to sudden changes in generation and power flow at various points on the system. A BESS can assist with orderly integration of solar PV generation by managing or mitigating the less desirable effects from high solar PV generation penetration.

As a cloud passes over solar collectors, power output from the affected solar generation system drops. When the cloud moves away from the collector, the output returns to previous levels. Importantly, the rate of change of output from the solar generation plant can be quite rapid as solar PV systems have no inertia in the form of rotating mass. The resulting ramping increases the need for highly dispatchable and fast-responding generation such as simple cycle combustion turbines to fill in when clouds pass over the solar collector [6]. Solar irradiance and the resulting power output of PV can change by as much as 80% in a matter of seconds due to the passing of a cloud. If the surface area of the solar PV system is relatively small compared to the cloud that is passing over it, the power output of the system will be reduced significantly.

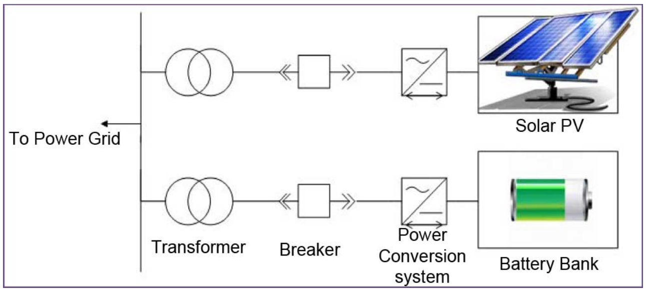

Fig. 2. Simplified one-line diagram of a BESS in parallel with a Solar PV facility connected to the grid on a common bus.

Steady-state impacts of intermittency are often manifested as voltage swings caused by the variability of electric current flowing through the system impedance on the feeder to which the PV is interconnected. These fluctuations in voltage can have adverse interaction with switched shunt capacitor banks, load tap changers, and line voltage regulators. The intermittent output of the solar PV generation can cause an increase in frequency of actuation of these devices, which reduces the life expectancy of these components. Also, after a PV generation change, the reactive power profile of the line is likely not to be the most efficient possible in terms of line losses. For these reasons, dispatchable energy storage can accommodate the integration of large-scale solar generation and increase the operational efficiency across the entire electric power distribution system.

III. Battery Energy Storage

A. *Battery Energy Storage Basics*

A grid-scale BESS consists of a battery bank, control system, power electronics interface for ac-dc power conversion, protective circuitry, and a transformer to convert the BESS output to the transmission or distribution system voltage level. The one-line diagram of a simple BESS is shown in Fig. 2. Note that a BESS is typically connected to the grid in parallel with the source or loads it is providing benefits to, whereas traditional uninterruptible power supplies (UPS) are installed in series with their loads. The power conversion unit is typically a bi-directional unit capable of four-quadrant operation, meaning that both real and reactive power can be delivered or absorbed independently according to the needs of the power system, up to the rated apparent power of the converter.

The battery bank consists of many batteries connected in a combination series-parallel configuration to provide the desired power and energy capabilities for the application. Units are typically described with two numbers, the nameplate power given in MW, and the maximum storage time given in MWh. The BESS described in this paper is a 1.5/1 unit, meaning it stores 1 MWh of energy, and can charge or discharge at a maximum power level of 1.5 MW. In renewable energy applications, it is common to operate a BESS under what is known as partial state of charge duty (PSOC) [8], a practice that keeps the batteries partially discharged at all times so that they are capable of either absorbing from or discharging power onto the grid as needed. Details of several recent BESS projects are given in [9] and [10]. Grid connected lead-acid battery systems built in the 1980s and 1990s have demonstrated good longevity and reliability [11].

There are two main schools of thought regarding deployment of BESS technologies on the electric power distribution system. One is to provide centralized storage at the MW level at the distribution substation. The other camp would prefer to see smaller energy storage systems distributed on the distribution feeders, networked together and remotely controlled at the substation. Advantages to centralized storage include easy access to substation electrical and SCADA equipment, simplified control schemes, economies of scale, and the fact that there is already utility-owned land available behind the substation fence. The argument for small scale, also known as community energy storage (CES) is made in [12] by engineers from American Electric Power. The ideal sizing and location will vary from site to site. In the case of large solar PV installations, it typically makes the most sense to install a comparably sized battery system tied in to the grid at the same substation. This enables power quality to be better maintained at the point of common connection, and the renewable resource can be better dispatched. This paper focuses on MW scale batteries connected with multi-MW scale PV facilities at the distribution substation.

Most BESS control systems can be operated via automatic generation control (AGC) signals much like a conventional utility generation asset, or it can be operated in a solar-coupled mode where real and reactive power commands for the converter will be generated many times per second based on real-time PV output and power system data. In the case of the XP-DPR, three-phase measurements from potential and current transducers (PTs and CTs) are taken in real-time on an FPGA device, and once digitized these signals become the input for proprietary real-time control algorithms operating at kHz speeds. Various control algorithms have been used for PV applications, providing control of ramp rates, frequency support, voltage/reactive power support, and services designed to optimize the financial returns of the PV installation, including peak-shifting and leveling.

B. *Ramp Rate Control*

As discussed above, solar PV generation facilities have no inertial components, and the generated power can change very quickly when the sun becomes obscured by passing cloud cover. On small power systems with high penetrations of PV generation, this can cause serious problems with power delivery, as traditional thermal units struggle to maintain the balance of power in the face of rapid changes. During solar-coupled operation, the BESS must counteract quick changes in output power to ensure that the facility delivers ramp rates deemed acceptable to the system operator. Allowable ramp rates are typically specified by the utility in kilowatts per minute (kW/min), and are a common feature of new solar and wind power purchase agreements between utilities and independent power producers. Note that the ramp rate refers only to real power, and that the reactive power capabilities of the BESS can be dispatched simultaneously and independently to achieve other power system goals.

The Ramp Rate Control algorithm used in the XP-DPR continuously monitors the real power output of the solar generator, and commands the unit to charge or discharge such that the total

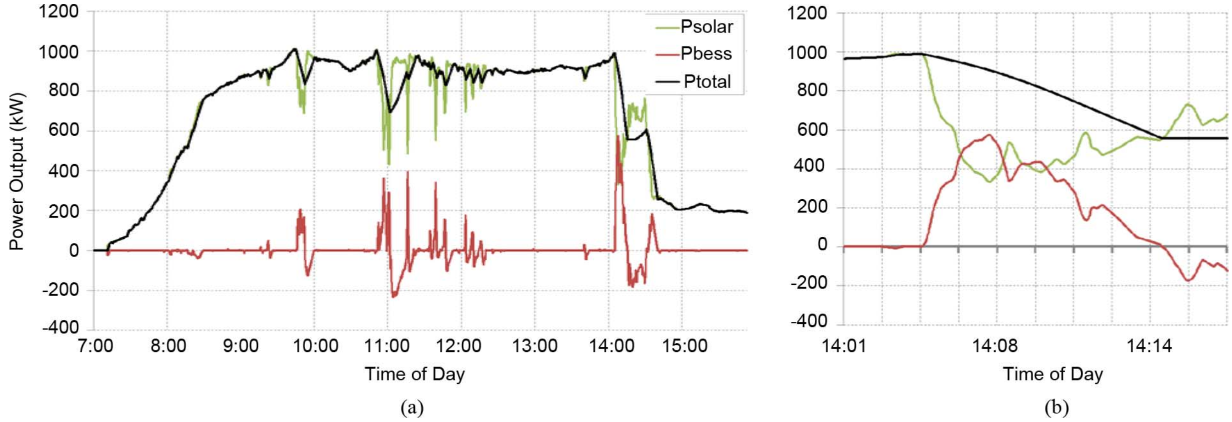

Fig. 3. Ramp Rate control to 50 kW/min for a 1 MW photovoltaic installation and a 1.5 MW/1 MWh BESS. (a) Full day. (b) Detail of largest event.

power output to the system is within the boundaries defined by the requirements of the utility. For more information on this algorithm, see [16].

Fig. 3 depicts the operation of an XP-DPR BESS smoothing the volatile power output of a 1 MW solar farm. Note that the system ramp rate is maintained to less than 50 kW/min, whereas the solar resource alone had a maximum second-to-second ramp rate of over 4 MW/min. This behavior translates to a significant reduction in wear and tear on the diesel generators supplying the rest of the grid, and helps the thermal units maintain power balance and the system electrical frequency. It is typically the case that the specifics of the thermal units on the system will be a major factor in determining the allowable ramp-rates for the PV asset. Ramp-rate control is often referred to as smoothing.

C. Frequency Response

Even with ramp-rate control, there are still going to be occasional frequency deviations on the system. On small, low-voltage systems, it is not uncommon to see frequency deviations of 1–3 Hz from the nominal 50 or 60 Hz frequency. Compare this to power systems in the continental United States, where many thousands of megawatts of generation are interconnected and 0.1 Hz deviation is considered significant. Such frequency deviation has adverse effects on many types of loads as well as other generators. Frequency deviation is caused by a mismatch in generation and load, as given by the swing equation for a Thevenin equivalent power source driving the grid. The system inertia is typically described using a normalized inertia constant called the H constant, defined as

$$H = \frac{stored\ kinetic\ energy\ at\ synchronous\ speed}{generator\ voltampere\ rating} \tag{1}$$

and H can be estimated by the frequency response of the system after a step-change such as a unit or load trip. From the definition of H in [13], the equation can be re-written so that the system H is easily calculated from the change in frequency of the system after a generator of known size has tripped off, according to

$$H = \frac{\frac{1}{2}J\omega_s^2}{P_{post}} = \frac{1}{2}\left[\frac{-\Delta P_m}{\frac{d\omega_s}{dt}}\right]\frac{\omega_s}{P_{post}} = \frac{-\Delta P_m f_s}{2P_{post}\left(\frac{df_s}{dt}\right)} \tag{2}$$

where the unit of H is seconds, ω_s is system angular speed, f_s is the system frequency, P_{post} is the remaining generation online after the unit trip, and ΔP_m is the size of the generator that has tripped. Large, densely interconnected power systems have H values of 6 seconds or higher, a value which can be interpreted as how many seconds worth of energy is effectively stored as mechanical inertia in the power system's rotating machines. The smaller the power system, the smaller the resulting H value, and the more the frequency will be affected by a step change in generation or load. Note that the H value discussed here is for an entire power system, and that every individual generator has its own H value as well.

When frequency crosses a certain threshold, it is desirable to command the BESS to charge in the case of over-frequency events, typically caused by loss of load, or to discharge for under-frequency events, which often result when a generator has tripped offline. Using proportional control to deliver or absorb power in support of the grid frequency stabilization is referred to as droop response, and this is common behavior in generator governors equipped with a speed-droop or regulation characteristic. Droop response in a governor is characterized as a proportional controller with a gain of 1/R, with R defined as

$$\% R = \frac{percent\ frequency\ change}{percent\ power\ output\ change} \times 100$$
$$\% R = \left(\frac{\omega_{NL} - \omega_{FL}}{\omega_0}\right) \times 100 \tag{3}$$

where ω_{NL} is steady-state speed at no load, ω_{FL} is steady-state speed at full load, and ω_0 is the nominal or rated speed of the generator [14]. This means that a 5% droop response should result in a 100% change in power output when frequency has changed by 5%, or 3 Hz on a 60 Hz power system.

Since the BESS uses a power electronics interface, there is no inertia or "speed" in the system, and we must approximate this desirable behavior found in thermal generators. The straightforward implementation is to digitally calculate an offset for the BESS output power command as response proportional to the frequency. The response has units of kW and is determined as

$$Response = \left(\frac{\left(\frac{f_{grid} - f_{DB}}{f_{DB}}\right)}{\% R}\right) \times kVA_{BESS} \tag{4}$$

where f_{grid} is the grid frequency, f_{DB} is the frequency deadband, and kVA_{BESS} is the power rating of the BESS in kVA.

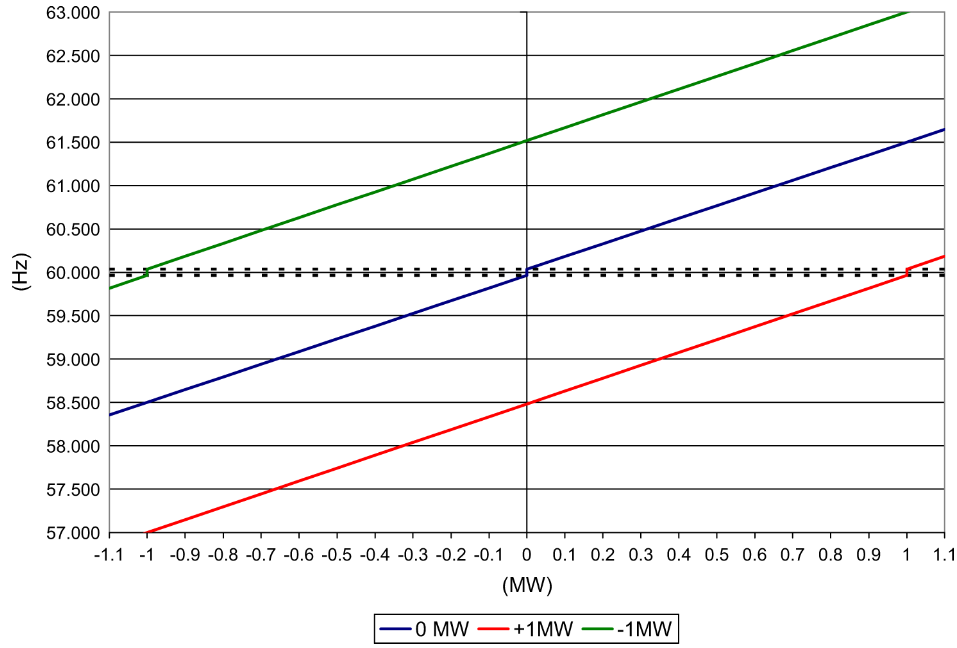

Fig. 4. Frequency droop response curves for 5% response on a 1 MW BESS.

As an example, setting the frequency deadband to 60.5 Hz means that the BESS droop response would not engage until there is a 0.5 Hz frequency deviation on the power system. Implementing a droop response that discharges in the case of under-frequency events is accomplished using the same equation, with a deadband below nominal frequency, and a sign change on Percent R. After the frequency has returned to the normal range, the BESS can automatically return to ramp-rate control. A set of droop characteristic curves for a 1 MW BESS is depicted in Fig. 4. The separate lines show the resulting power output of the BESS based on how much power it was delivering or absorbing at the time the frequency event begins.

D. Reactive Support

In large interconnected power systems, system inertia and a diversity of generation and loads make frequency control and ramp rates a less significant concern for the distribution system operator, but rapid power flow changes can still cause adverse effects. In these cases, delivering reliable power to end-users within a specified voltage range is the most important goal. An important technical challenge for electric grid system operators is to maintain necessary voltage levels with the required stability. A distribution feeder will typically employ a combination of voltage regulators and switched or static shunt capacitors to deliver power at a consistent voltage and power factor to all customers on the line. Power factor pf is defined as

$$pf = \frac{P}{S} = \cos\theta \tag{5}$$

where P is the real power flow (in watts), S is the apparent power flow (in volt-amperes or VA), and θ is the angle difference between the voltage and current waveforms on a given phase. Power factor is continuously variable between 0 and 1, and can be either leading or lagging. Lagging power factor indicates a component that absorbs reactive power (in units of Vars), while a leading power factor component is said to generate reactive power. The natural inductance of overhead power lines, transformers, and many kinds of loads results in the absorption of reactive power and a low, lagging power factor. The lower the power factor, the more current must flow on the line to supply a given power P as governed by the basic ac power equations. Therefore, it is desirable to maintain a pf near 1.0 in order to minimize insulation requirements and as well as to minimize I^2R and I^2X losses, and to counteract voltage drop across the system impedance.

On ac power distribution systems, voltage is a local phenomenon closely related to reactive power flows. Switched capacitors are often installed on the bus to provide reactive power and regulate voltage. The capacitors are often switched in and out of the circuit several times a day because reactive power needs fluctuate according to load. The change in voltage from the insertion of a capacitor is approximated as

$$\text{Percent } \Delta V = \frac{kvar_{cap} Z_{tx}}{kVA_{tx}} \tag{6}$$

where ΔV is the change in voltage, $kvar_{cap}$ is the rating of the capacitor, Z_{tx} is the per-unit impedance of the upstream step-down transformer, and kVA_{tx} is the step-down transformer rating. This formula uses the step-down transformer rating as an approximation of the local stiffness of the grid, which is acceptable as the transformer typically provides the majority contribution to the system total impedance at the point of capacitor installation [15]. Shunt capacitor banks are cheap and effective at providing reactive power support, but have drawbacks in terms of large switching transients, and the "all-or-nothing" nature of switching the bank in. Reactive support with power electronics enables continuous changing of the reactive power delivered into the system with no transients, and this capability comes with no extra equipment necessary once a BESS has been installed.

The four-quadrant power electronic converter on a BESS can inject reactive power to the bus to maintain either a power factor

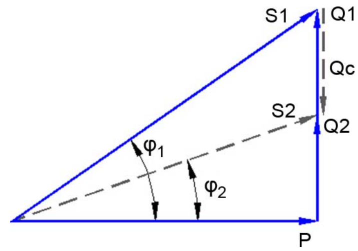

Fig. 5. Control architecture of the real-time HIL testbed at the Xtreme Power facility in Kyle, TX.

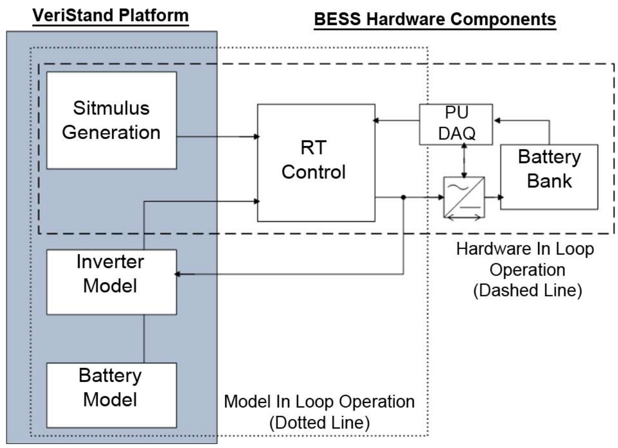

Fig. 6. Power triangle used for the calculation of reactive power needed for power factor correction.

or voltage setpoint on the bus, providing improved system efficiency, and lower losses. When maintaining a given power factor, the power triangle can be used as depicted in Fig. 5. Applying trigonometry to the power triangle and substituting in (5), we see that the necessary reactive power correction Q_C to move from an initial power factor of Q1 to Q2 is equal to

$$Q_C = P[\tan(\cos^{-1}\varphi_1) - \tan(\cos^{-1}\varphi_2)] \tag{7}$$

and Q can be readily adjusted to maintain the desired power factor as the measured real power P at the bus changes.

Due to a market inefficiency that may be addressed with time, the typical solar generator today is often not financially rewarded for providing reactive power support, so solar inverters are often operated such that they produce real power with no concern for reactive power contributions. The result is poor power factor, which can be corrected by installing capacitors or power electronics devices. The benefits of improved power factor can be quantified as reduced power system losses $\%\ \mathrm{loss}_{\mathrm{reduction}}$, and reduction in line current $\%\ \Delta I$ upline of the reactive power source, whether capacitor or BESS. These benefits are quantified according to

$$\%\ \mathrm{loss}_{\mathrm{reduction}} = 100\left[1 - \left(\frac{pf_{original}}{pf_{corrected}}\right)^2\right] \tag{8}$$

$$\%\ \Delta I = 100\left[1 - \left(\frac{\cos\theta_{original}}{\cos\theta_{corrected}}\right)\right] \tag{9}$$

where pf is power factor, and $\cos\theta$ is the power factor angle from the power triangle [15].

IV. Methodology

There are two main types of distribution systems where BESS are currently being used to help with high penetration PV. The first is the common utility distribution feeder, which in North America is typically a radial design, with all power originally sourced from a transformer that steps down transmission voltages to 60 kV or less. Various solar installations in the 1 MW to 20 MW range have been connected to the grid at these substations, with significant impacts on the feeders downstream of the substation. The other type is remote area power systems, where small power systems are used that are not interconnected with any of the major continental grids. These systems tend to experience significant frequency events and service interruptions that are relatively more common. Additionally, the cost of fuel in these remote locations is often very high, as it is typically diesel fuel delivered by boat or plane. The economics of these situations has made for favorable conditions for a BESS in such locations as the Hawaiian Islands, islands and cities in Alaska, and some parts of West Texas, to name a few.

The Xtreme Power facility in Kyle, TX is equipped with a real-time Hardware-in-the-Loop (HIL) test-bed for BESS control systems, so that algorithms and control system components can be adequately tested before deployment to the field. The design of the HIL facility is discussed in [4]. Fig. 6 depicts the functional parts of the HIL test platform, and indicates information flows between them.

The HIL facility can be operated with or without a 1.5 MW BESS online. When operated without full hardware, software simulations are used of the battery and power conversion system, in a mode referred to as model-in-loop operation (MIL). In the sections above, ramp-rate, droop response and reactive power support operational modes have all been extensively tested in Kyle in both MIL and HIL test modes, and the algorithms have been deployed to renewable energy installations as part of an integrated 1.5 MW/1 MWh BESS and control system solution. All results and graphs in this paper are from testing in HIL mode at the Kyle facility.

V. Market Oriented Operation

In addition to using a BESS to help with the physical aspects of integrating large quantities of solar such as ramp rates, frequency, and voltage regulation, a BESS can also be used to improve the economic profile of the distribution system to which it is attached. To date, two of the main types of market-oriented BESS operation that have been developed are time-shifting and leveling. The specifics of the price structure of the energy markets that apply to a given distribution system operator vary considerably from place to place depending on the local market rules and implementation. We present a general overview of BESS market-oriented considerations, noting that the specifics of each market are unique and must be considered independently.

Time-shifting is a well established practice with pumped-hydroelectric technology, a traditional form of energy storage. Pumped hydro typically operates by pumping water to a higher elevation at night when energy is cheap or there is extra capacity, and letting the water flow back down through a hydroelectric generator when energy is expensive. Using energy storage in

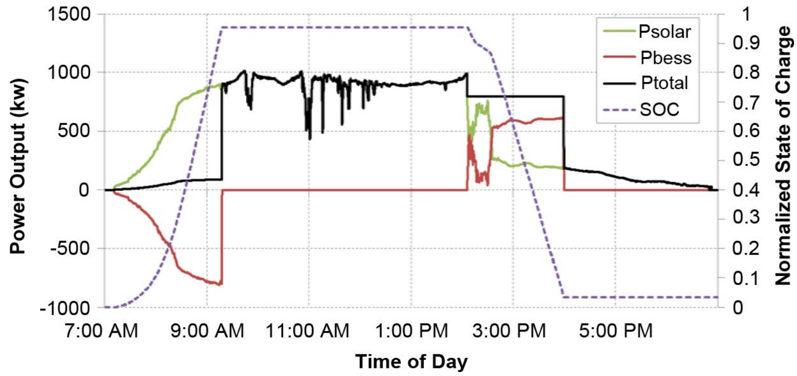

Fig. 7. Full day output of the solar time-shift application.

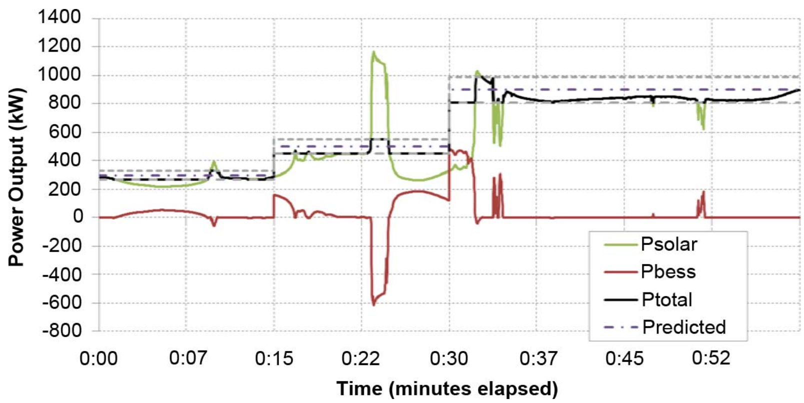

Fig. 8. One hour of solar leveling application with 15-min output predictions and 10% tolerance on power bids.

this form transmits power across time in a way that is analogous to what the electrical transmission system does across physical space. A BESS used for a time-shifting application with PV is often smaller than typical pumped hydro units, which are frequently sized in the hundreds of Megawatts range, and is more likely to be connected at a distribution substation. This can provide various benefits from the perspective of the DSO, including reduced demand from the transmission system step-down transformers when prices are highest.

Solar power generation is somewhat coincident with peak demand times, and PV connected BESS units can enhance this characteristic by applying a time-shift algorithm optimized for a given set of solar generation and load forecasts. By charging from the grid at night, or from some percentage of the solar generation during the day, a BESS can be used to discharge as power from the solar facility begins to drop off in the afternoon hours, thereby offsetting the reduction in solar power at a time when energy is expensive. This behavior is depicted in Fig. 7. Both the peak extension duration period and the power output magnitude can be made user-configurable. The economic benefit of the time-shift application is calculated by cost weighting the integral of power delivered with the energy prices throughout the day, and comparing the scenarios with and without solar time-shift. Other benefits may include a reduction in congestion, line-losses, and pollution from inefficient "peaking" power plants that are only operated at peak demand times.

In some energy markets the ability to schedule power generation ahead of time comes with significant economic benefits. When this is the case, bidding the generation of 10 MWh over some time period, and delivering it to within a specified accuracy can be worth much more than generating 10 MWh whenever the sun happens to be shining. In these situations, BESS controls can be integrated with weather forecasts and market signals to deliver power at a consistent output level. Control logic on the BESS will use the battery to minimize deviations between scheduled and actual power output throughout the day, thus ensuring the maximum financial return on the day's generation. Fig. 8 depicts results of a Solar Leveling application using the Xtreme Power DPR at the Kyle test facility. Note that the total power output from PV and BESS is maintained around the power bid to within a user-specified tolerance of $\pm 10\%$. Such behavior greatly improves the dispatchability of the PV resource, and in many markets this will command a premium in price compared to PV units without BESS support.

VI. Conclusion

Integration of energy storage systems into the smart grid to manage the real power variability of solar by providing rate variation control can optimize the benefits of solar PV. Using the BESS to provide voltage stability through dynamic var support, and frequency regulation via droop control response reduces integration challenges associated solar PV. Coupling solar PV and storage will drastically increase reliability of the smart grid, enables more effective grid management, and creates a dispatchable power product from as-available resources. The rapid-response characteristic of the BESS makes storage especially valuable as a regulation resource and enables it to compensate for the variability of solar PV generation. Battery energy storage systems can also improve the economics of distributed solar power generation by reduced need for cycle traditional generation assets and increasing asset utilization of existing utility generation by allowing the coupled PV solar and BESS to provide frequency and voltage regulation services.

REFERENCES

[1] F. Katiraei and J. R. Aguero, "Solar PV Integration Challenges," *IEEE Power Energy Mag.*, vol. 9, no. 3, pp. 62–71, May/Jun. 2011.

[2] ERCOT Protocols Section 5 [Online]. Available: http://www.centerpointenergy.com/staticfiles/CNP/Common/SiteAssets/doc/Load%20Management_ERCOT_Emergency_Operation_Guidelines.pdf

[3] N. Miller, D. Manz, J. Roedel, P. Marken, and E. Kronbeck, "Utility scale battery energy storage systems," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Minneapolis, MN, Jul. 2010.

[4] C. Hill and D. Chen, "Development of a real-time testing environment for battery energy storage systems in renewable energy applications," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Detroit, MI, Jul. 2011.

[5] National Renewable Energy Laboratory—Measurement and Instrumentation Data Center [Online]. Available: http://www.nrel.gov/midc

[6] J. Eyer and G. Corey, "Energy storage for the electricity grid," Sandia National Labs Publications, Feb. 2010 [Online]. Available: http://www.sandia.gov/ess/publications/

[7] A. Nourai and C. Schafer, "Changing the electricity game," *IEEE Power Energy Mag.*, vol. 7, no. 4, pp. 42–47, Jul./Aug. 2009.

[8] R. H. Newnham, W. G. A Baldsing, and A. Baldsing, "Advanced management strategies for remote-area power-supply systems," *J. Power Sources*, vol. 133, pp. 141–146, 2004.

[9] C. D. Parker and J. Garche, "Battery energy-storage systems for power supply networks," in *Valve-Regulated Lead Acid Batteries*, D. A. J. Rand, P. T. Mosely, J. Garche, and C. D. Parker, Eds. , Amsterdam, The Netherlands: Elsevier, 2004, pp. 295–326.

[10] N. W. Miller, R. S. Zrebiec, R. W. Delmerico, and G. Hunt, "Design and commissioning of a 5 MVA, 2.5 MWh battery energy storage," in *Proc. 1996 IEEE Power Eng. Soc. Transm. Distrib. Conf.*, pp. 339–345.

[11] "Analysis of a valve-regulated lead-acid battery operating in utility energy storage system for more than a decade," 2009.

[12] A. Nourai, R. Sastry, and T. Walker, "A vision & strategy for deployment of energy storage in electric utilities," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, Minneapolis, MN, Jul. 2010.

[13] J. D. Glover, M. S. Sarma, and T. J. Overbye*, Power System Analysis and Design*. Stamford, CT: Cengage, 2008, p. 698.

[14] P. Kundur*, Power System Stability and Control*. New York: McGraw-Hill, 1994, pp. 589–594.

[15] R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty*, Electrical Power Systems Quality*. New York: McGraw-Hill, 2002, p. 295.

[16] "Managing Renewable Power Generation, Xtreme Power," U.S. Patent 20110273129, 2011.

Cody A. Hill received the B.S. ECE degree from the University of Missouri, Kansas City. He is currently a graduate student in electrical and computer engineering at the University of Texas at Austin.

He is a Power Systems/Controls Engineer for Xtreme Power in Kyle, TX, and works primarily on the design of control systems for battery energy storage systems in renewable energy applications.

Matthew Clayton Such received a B.S. ECE degree from the University of Texas at Austin. He is currently a part-time graduate student in mechanical engineering at the University of Texas at Austin.

He is a Principal Engineer at Xtreme Power Systems, Kyle,. TX. He is responsible for design, validation, and maintenance of controls systems in XP products, specifically the large scale storage products. Primary is focus on control and systems functions improvements and development.

Dongmei Chen received the B.S. degree from Tsinghua University, Beijing, China, and the M.S. and Ph.D. degrees, both in mechanical engineering, from the University of Michigan, Ann Arbor, in 2001 and 2006, respectively.

She is currently an Assistant Professor in the Department of Mechanical Engineering at the University of Texas at Austin. Her research interests are in dynamic systems and controls, especially in non-minimum phase, multivariable, and mode switching systems, with applications in wind and solar energy integration, energy storage, and electrical vehicles.

Dr. Chen was a recipient of the University of Michigan Rackham Graduate School Fellowship from 2000 to 2005. She received several awards for technical excellence while working in the automotive industry.

Juan Gonzalez received the B.S. ECE degree from Simon Bolivar University, Venezuela, and the M.S. ECE degree from the University of Texas at Austin.

He is a Power Systems Engineer for Xtreme Power in Kyle, TX, where he currently is involved in the design and interconnection of battery storage systems in renewable energy applications.

W. Mack Grady (F'00) received the B.S.E.E. degree from the University of Texas at Arlington in 1971, and the M.S.E.E. and Ph.D. degrees from Purdue University, West Lafayette, IN, in 1973 and 1983, respectively.

He is a Professor and the Associate Chairman of Electrical & Computer Engineering at the University of Texas at Austin. He is the Jack S. Josey Centennial Professor in Energy Resources at the Cockrell School of Engineering.

Dr. Grady is a Registered Professional Engineer in Texas. He holds a security clearance and works on power grid and power distribution issues for the Scientific Applications and Research Associates (SARA) team on Department of Defense (DOD) Defense Threat Reduction Agency projects.