Utility Forum - Task 3

Capabilities of Photovoltaic Solar and Battery Energy Storage Systems in Supporting the Power Grid

Performed at Wind Energy Institute of Canada (WEICan)

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Disclaimer

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1 Symbols, Abbreviations, and Glossary

AC	Alternating Current
AEMO	Australian Energy Market Operator
AESO	Alberta Electric System Operator
AGC	Automatic Generation Control
API	Application Programming Interface
BESS	Battery Energy Storage System
CAISO	California Independent System Operator
DC	Direct Current
DNP3	Distributed Network Protocol 3
ERCOT	Electric Reliability Council of Texas
Hz	Hertz
IESO	Independent Electric System Operator
IREQ	Institut de recherche en électricité du Québec
kVA	Kilovolt-ampere
kVAR	Kilovolt-ampere reactive
kW	Kilowatt
kWh	Kilowatt-hour
MPP	Maximum Power Point
MW	Megawatt
OPC DA	Open Platform Communications Data Access
PJM	Pennsylvania – Jersey - Maryland
PPA	Power Purchase Agreement
PMU	Phasor Measurement Unit
PSCo	Public Service Company of Colorado
PV	Photovoltaic
Reg D	Regulation D, a fast, dynamic signal that requires Regulation Market Resources in PJM to respond almost instantly
RTAC	Real Time Automation Controller
SCADA	Supervisory Control and Data Acquisition
SEL	Schweitzer Engineering Laboratories
SMC	Site Master Controller
SOC	State of Charge
WEICan	Wind Energy Institute of Canada

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3 Executive Summary

Increasing the amount of inverter-based energy sources on electrical power grids, such as wind and solar, can impact grid stability. Decreases in grid stability can result from the renewable energy resource's variability, unpredictability of forecasts, and effects on both distribution and transmission networks. While conventional synchronous generators traditionally provide both energy and ancillary services (inertia, voltage regulation, frequency support, etc.), non-synchronous generators typically contribute only energy and not ancillary services. These factors all create challenges in increasing the amount of renewable energy on the power grid. The ability of renewable energy generators, as well as energy storage systems, to overcome these challenges is seen as increasingly critical to maintain grid stability. Photovoltaic (PV) integration may benefit from battery energy storage systems (BESS) in various ways by enhancing power system flexibility due to their enormous diversity of uses and configurations.

The Utility Forum convened a selection committee to determine a demonstration of interest for Task 3. The Task 3 Selection Committee was interested in a demonstration of solar PV with battery storage. The goals of this demonstration were to examine:

1. Role and ability of storage to reduce morning and evening power ramps
2. Ability of solar + storage to provide fast regulation e.g. PJM’s Reg-D signal. Combining generation with storage shifts the regulation burden away from storage and allows better response over several hours.
3. Ability of combined system to provide firm capacity (i.e. MW) on the market

This work demonstrated the capabilities of the Wind Energy Institute of Canada’s solar PV-BESS power plant to provide a range of reliability services to the grid. While procurement of ancillary services from inverter-based energy sources is becoming more common in the US and Europe, it is still relatively rare in Canada. Most jurisdictions do not offer compensation for the benefits that solar PV and energy storage can offer. Carrying out and publishing results from real world demonstrations such as that carried out in this work helps utilities and system operators realize the capabilities of the inverter-based energy sources to provide ancillary services and will help them in the creation of markets for such services.

While simple controls and algorithms were used in this work, results could improve if forecasts and more complex algorithms are incorporated. Nevertheless, the results from this demonstration serve as a proof-of-concept that can show transmission-connected equipment owners the capabilities of the technology.

4 Background

As the amount of electrical energy generated by renewable energy sources increases on electrical power grids, increased attention is focused on their impacts on grid stability.[1-10] Decreases in grid stability can result from the renewable energy resource's variability and inaccurate forecasts. Renewable energy generators typically have many differences from conventional energy generators, such as having a smaller capacity, being more numerous in quantity, being spread over larger geographical areas, requiring power electronics to connect to the power grid, and often contributing only energy and not ancillary services, such as inertia, fast frequency response, primary frequency, response, etc. These factors all create challenges in increasing the amount of renewable energy on the power grid. The ability of renewable energy generators, as well as energy storage systems, to overcome the challenges is seen as increasingly critical to maintain grid stability.

While there is some type of market for ancillary services provided by invertor-based generators in several jurisdictions (eg. EirGrid, PSCo, ERCOT, AEMO, National Grid UK, IESO), many jurisdictions across North America are still investigating the capabilities of these generators with the aim of creating a market. For example, the New York Independent System Operator recently investigated the technical capability of renewable generators to provide a variety of grid services[6] and the Nova Scotia government recently commissioned a study recommending changes to the standard form Power Purchase Agreement (PPA) and procurement process to support the provision of ancillary services by variable output renewable energy resources.[11]

Although the majority of research in investigating the abilities of inverter-based generators to provide ancillary services has focused on simulations, several groups have carried out demonstrations of these services on grid-connected systems. In past work, WEICan has demonstrated the capabilities of Type 4 and Type 5 wind energy generators and battery energy storage systems (BESS) to provide ancillary services to the power grid.[12-21] The Cowessess First Nation in Saskatchewan owns a 800 kW wind turbine, 400 kW/744 kWh battery energy storage system, and a 500 kW solar photovoltaic array. With the Cowessess system, Saskatchewan Research Council Smart Grid Test Center used the BESS to demonstrate 85% reduced volatility of the renewable energy generators and consistent hour-ahead power with predictive firming.[22] NREL carried out a series of demonstrations with CAISO and First Solar which demonstrated use cases for PV-BESS systems, including (1) load following, (2) frequency regulation, (3) voltage support, (4) using grid-forming BESS to enable black-start and islanded applications for PV-BESS systems, (5) spinning reserves, (6) ramping, and (7) variability smoothing.[1-3]

To decide on the Task 3 demonstration, the Utility Forum formed a Task 3 Selection Committee, consisting of:

- Amr Abdellaoui – Hydro-Québec
- David Jacobson – Manitoba Hydro
- Nickie Menemenlis – Institut de recherche en électricité du Québec (IREQ)
- Eldrich Rebello – Wind Energy Institute of Canada (WEICan), now with Natural Resources Canada

- Roghoyeh Salmeh. – Alberta Electric System Operator (AESO), now with the Pacific Gas and Electric Company
- Daniel Sohm – Independent Energy System Operator (IESO)

The selection committee was interested in a demonstration of solar PV with battery storage. The goals of this demonstration were to examine:

1. Role and ability of storage to reduce morning and evening power ramps.
2. Ability of solar + storage to provide fast regulation e.g. PJM's Reg-D signal. Combining generation with storage shifts the regulation burden away from storage and allows better response over several hours.
3. Ability of combined system to provide firm capacity (i.e. MW) on the market

For more markets for these services to develop, it is necessary for utilities and system operators to learn from jurisdictions that have already developed markets and from demonstrations of the services. In this work, WEICan demonstrates the capabilities of solar PV and a BESS to provide stability to the power grid using WEICan's PV and BESS infrastructure.

5 Site and Measurement Setup

5.1 Solar Photovoltaic Array

Figure 1. Aerial view of WEICan's PV array

The Wind Energy Institute of Canada (WEICan) owns a solar photovoltaic (PV) array, manufactured by Jinko Solar, with a capacity of 109 kW. The array uses fixed tilt PV modules with a 30-degree tilt angle facing south, combined in 16 parallel rows, as shown in Figure 1. The array is split into two smaller arrays, each of which is linked to a separate string inverter. An aerial view of WEICan's PV array is shown in Figure 1.

5.2 SMA Sunny Tripower PV Inverter

WEICan's Sunny Tripower is a transformerless PV inverter with 6 maximum power point (MPP) tracers that convert the direct current of the PV array to grid-compliant, three-phase current and feeds it into the utility grid. The inverters are equipped with an integrated webserver, SMA Speedwire (type of communication based on the Ethernet standard), Webconnect function (to enable direct data transmission between the inverter and Sunny Portal), WLAN interface, and a Modbus interface. WEICan has two PV inverters, each of which have a maximum apparent power of 66 kVA and active power range up to 62.5 kW.

5.3 Battery Energy Storage System

WEICan's battery energy storage system (BESS) is rated for 111.5 kVA/223 kWh and it is from Tesla Energy. The BESS includes the Tesla Site Management Controller (SMC) that actively monitors the system's performance, displays operating information, offers multiple automated modes of

Figure 2. WEICan's battery energy storage system (BESS) ,

operation, and integrates with third party controllers. The Tesla Powerpack System is a lithium-ion battery system that operates through an inverter and is connected via the 480 V grid. An image of WEICan's BESS is shown in Figure 2.

The PV inverters and the battery are AC coupled. The system converts all power to AC and then combines all inputs on a common AC bus.

5.4 Data Management System

WEICan gather data via dedicated energy meters. The energy meters provide the standard set of power system data such as currents, voltages, phase angles, energies, etc. All energy meter data is logged at 1 Hz into the OSISoft PI System. WEICan's data topology is shown in Figure 3.

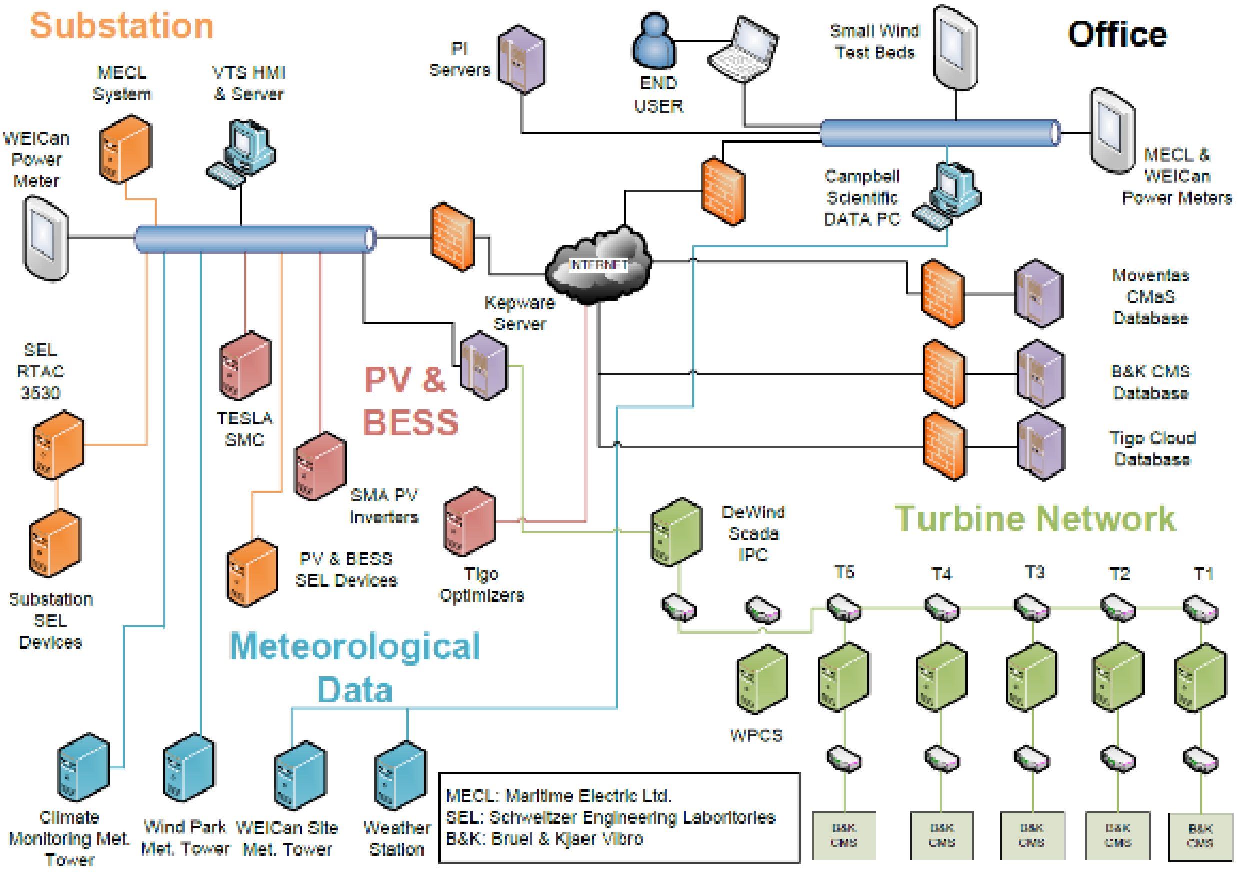

Figure 3. WEICan data topology

5.5 Real Time Automation Controller

A Schweitzer Engineering Laboratories (SEL) Real Time Automation Controller (RTAC) is used to provide control to the PV and BESS. The RTAC is a powerful multipurpose controller/communication device that can run and execute logic, sending out commands to control the PV and BESS and regulate output. The RTAC supports industry standard protocols like Modbus and DNP3. In addition to the control RTAC for the PV and BESS, WEICan has added a second RTAC to provide additional functionality without modifying the original RTAC.

5.6 WEICan Wind R&D Park Line Diagram

A line diagram of WEICan's Wind R&D Park, which includes the PV array and BESS, is shown in Figure 4. As co-located resources, the PV and BESS share the same infrastructure, including the substation, point of interconnection, and tie-lines. WEICan also owns and operates five 2 MW wind turbines with cut in speed at 4 m/s, full production at 10.5 m/s, cut out wind speed at 25 m/s, and a direct medium voltage tie-in of its 13.8 kW synchronous generator. WEICan operates a diesel generator only when emergency power is required for the turbines. The voltages of the PV and BESS are stepped up to 13.8 kV to tie-in with WEICan's electrical infrastructure, and then, with the wind turbines, stepped up for the 69 kV interconnection with the electrical power grid.

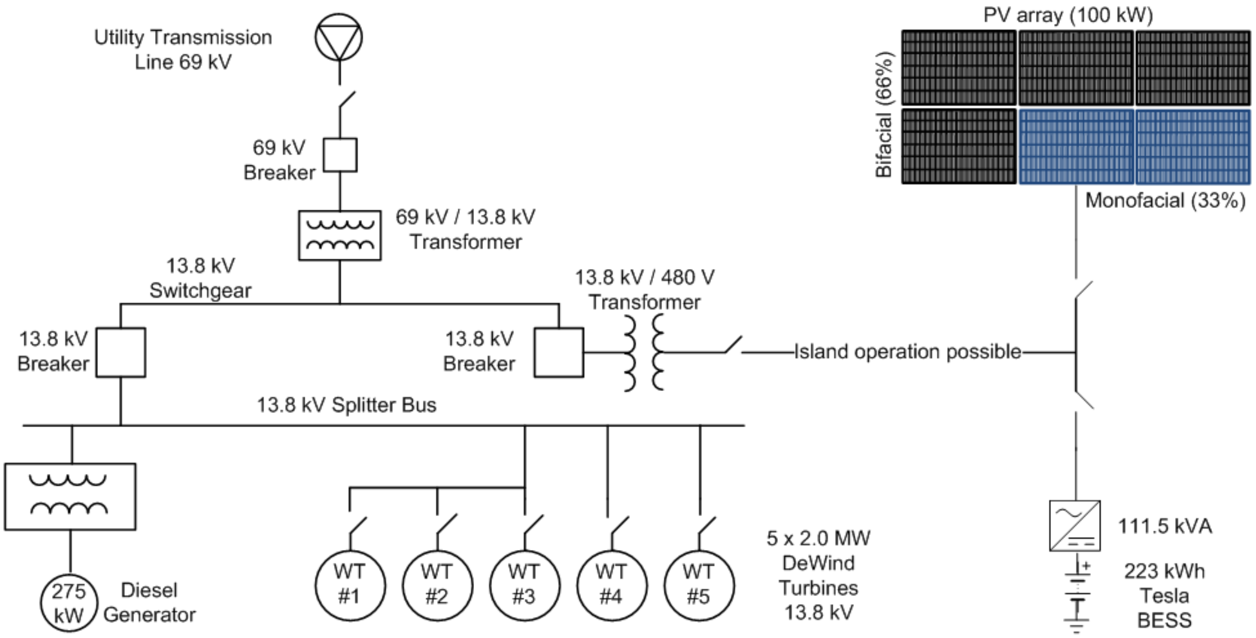

Figure 4. Line diagram of WEICan's Wind R&D Park

Applicable standards for WEICan PV and BESS are shown in the table below.

	Solar PV	Battery Storage
1.	IEC 61215	IEEE 1547
2.	IEC 61464	UL/CAN 9540
3.	ANSI/UL 1703, IEC 61730/61215, ANSI/UL 61730/61215, CSA 61730/61215	UL 9540A
4.	ANSI/UL 2703	IFC NFPA 1, 855
5.	ANSI/UL 1741, UL/CSA 62109	NEC (NFPA 70) CEC (CSA C22.1)
6.	IEC 62108, UL 62108	C22.2 No. 107.1 UL 1741
7.	IEEE 1547	UL 991, 1998 IEC 61508

6 Demonstrations and Results

6.1 Built-In Grid Support Programs on PV Inverters and BESS

WEICan's PV inverters and BESS each have a control system that has several built-in modes of operation for providing grid support. These modes can be activated by web interface, Rest API, DNP3, or Modbus commands.

Built-in modes on the Tesla BESS include:

- Specific Site Load
    - Minimum and maximum power parameters can be set to control the amount of fluctuation in the overall site load.
- Peak Shaving
    - The battery output changes to keep the total site load below a defined threshold.
- Non-Export
    - The user can prevent export at the point of common coupling.
- Renewable Firming
    - Provides a constant site level response with intermittent generation sources.
- Load or Renewable Smoothing
    - Minimizes real power fluctuations due to fast changing renewable output or loads.

Built-in modes on the SMA inverter include:

- Grid Support Depending on Grid Voltage
    - Three thresholds for minimum grid voltage and two thresholds for maximum grid voltage are defined. The inverter continuously checks the grid voltages and reacts to undervoltages and overvoltages according to the operating mode.
- Grid Support Depending on Power Frequency
    - Two thresholds both for minimum and maximum power frequency are defined. The inverter continuously checks the power frequency and continues to feed in up to a set point in time when the frequency is exceeded or undershot and then starts the shutdown process.
- Ramp Rate During Normal Operation
    - The inverter gradually increases the power per second by the rate of increase set in this parameter.
- Ramp-Up After Grid Fault
    - The user can define how the inverter is to begin with active power feed-in after a grid fault.
- Fixed specification of a power factor cos ψ
    - The reactive power is controlled as a function of a fixed power factor cos ψ.
- Reactive Power Control as a Function of Grid Voltage
    - The reactive power is controlled as a function of the grid voltage. By supplying reactive power, the inverter performs voltage-stabilizing measures in the event of overvoltage or undervoltage.
- Active Power Limitation Depending on Power Frequency

  - In the case of active power limitation depending on power frequency, the inverter constantly checks the connected power frequency and if necessary regulates the active power feed-in.
- Active Power Limitation Depending on Grid Voltage
  - The active power is controlled as a function of the grid voltage. By supplying active power, the inverter performs voltage-stabilizing measures in the event of overvoltage.

None of the built-in programs were used in this work. Instead, demonstrations focused on using custom-built programs from the RTAC. This method of control was chosen to keep the native control systems in place and automate inputs to it.

6.2 Setting Reactive Power

6.2.1 Overview

WEICan's PV inverters and BESS can both provide active and reactive power. These modes can be operated together. In the BESS, if the system reaches an apparent power limit, the system prioritizes the real power command and limits the reactive power demand. Provision of reactive power is important in voltage stabilization of the electrical power grid. By controlling these outputs, we can demonstrate various grid support scenarios.

The as-designed PV and BESS system uses a control RTAC to convert DNP3 inputs and outputs from a controller to Modbus commands which are then sent to the devices. This RTAC was setup with limits to ensure input value quality and to interact with a custom SCADA system for manual control over the system. An additional feature of the SCADA system is a remote mode where the SCADA system inputs can be changed via DNP3 outputs. A second RTAC was used to read in values from the control RTAC and send DNP3 signals to the control RTAC. Additional code, using structured text format, was added to the second RTAC to provide operational limits and values to the automated control values.

Reactive power setpoints were supplied to the RTAC for both the BESS and the PV inverter. The setpoints changed every five seconds and use most of the available setpoint range. When wind turbines are running at WEICan, kVAR values can range from -3000 kVAR to 2000 kVAR with rapid fluctuation. Seeing any grid effects from our system is only possible on low wind days when there is no wind generation on the line. This demonstration took place when wind speed was 2.5 m/s at 80 m, so there was no production from the wind turbines.

6.2.2 Results

Historical data was retrieved from WEICan's OSISoft PI system. Each device in the system has its inputs and outputs controlled by Modbus registers. To input the Modbus data into the PI system, it is first converted to DNP3 in the control RTAC. A DNP3 to OPC DA server converts the DNP3 data to OPC format where a PI data collector sends the data to the PI system. The data collection rate for the PV and BESS system is set to 1Hz. This data can then be recalled for analysis or visualization.

The reactive power setpoints that were supplied for both the BESS (SMC Set Point) and PV inverter (SMA Set Point) and the corresponding meter reactive power (kVAR) values are shown in Figure 5. This chart shows that it is possible to control both the BESS and PV inverters to separate values.

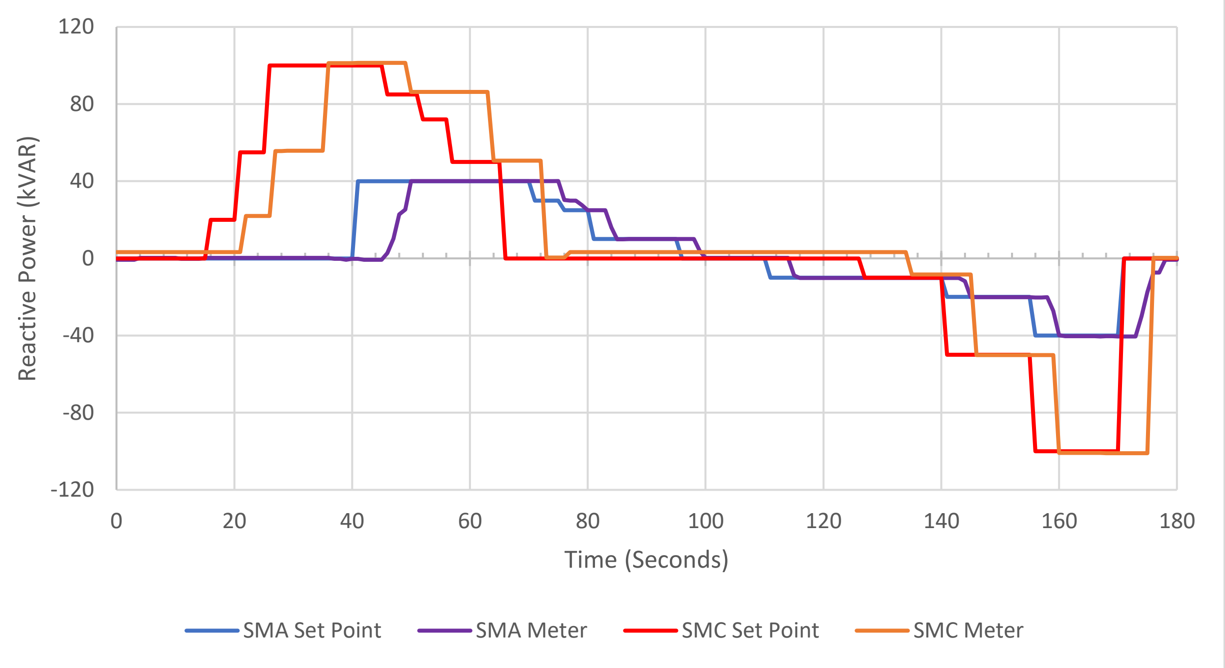

Figure 5. PV inverter (SMA) and BESS (SMC) input signal set points and reactive powers

The 3-phase voltages from the net meter and the net kVAR values from both the BESS and the SMA inverter referenced to the grid are shown in Figure 6. Because it is referenced to the grid, we see negative values of the setpoints. In each phase the negative reactive power increases the voltage and the positive reactive power decreases the voltage.

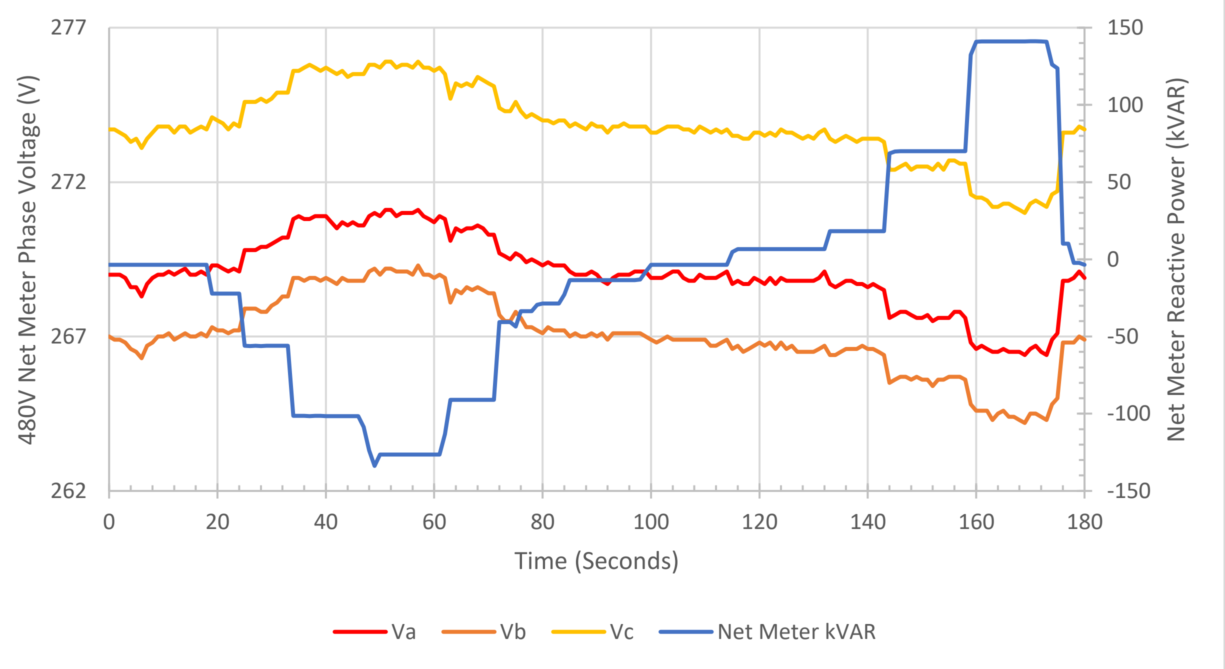

Figure 6. Net meter phase voltages and net meter reactive power

When the net meter phase a voltage was compared to the grid phase a voltage (Figure 7), it is clear that the kVAR setpoint impacted the 69 kV grid phase as well. Note that the same results were also observed for the other two phases although they are not shown in this report to avoid redundancy.

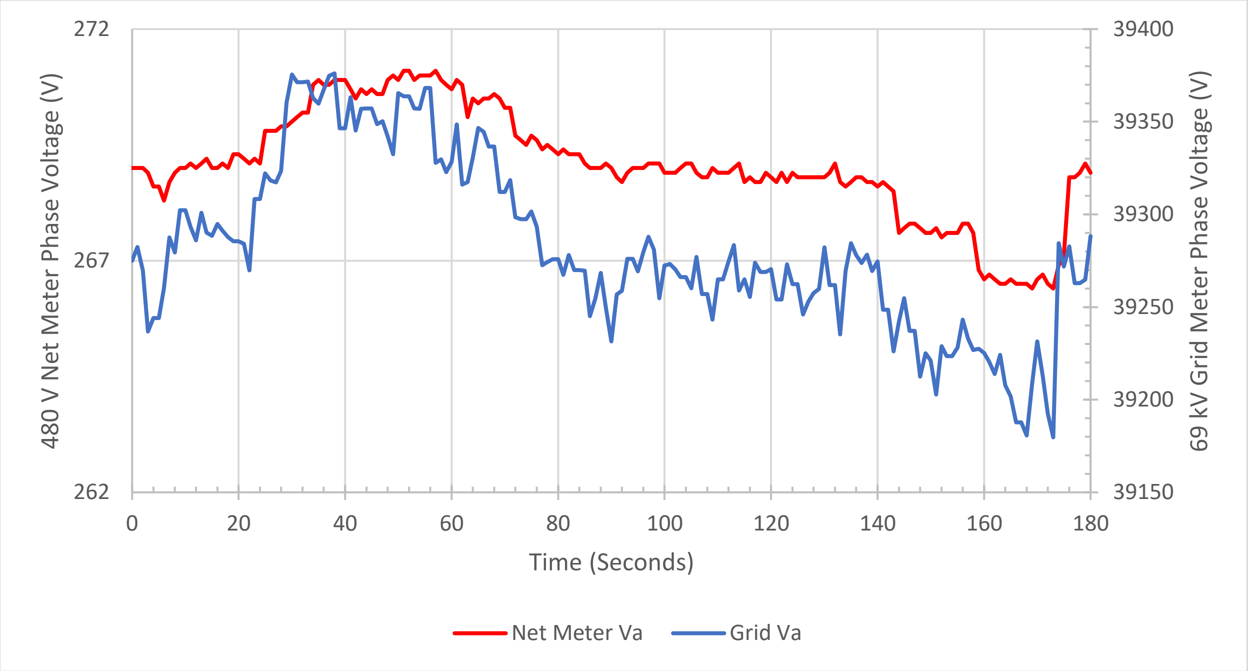

Figure 7. PV and BESS net meter phase a voltage compared to grid phase a voltage

Figure 8 shows the active power from both meters. The net meter negative values show that the PV inverter was providing 15 kW to 17 kW active power to the system, but the net connection to the grid was receiving 50 kW to 120 kW from the grid, which was mainly to supply power to WEICan’s wind turbines (heating, pumps, etc.) during the period of low wind.

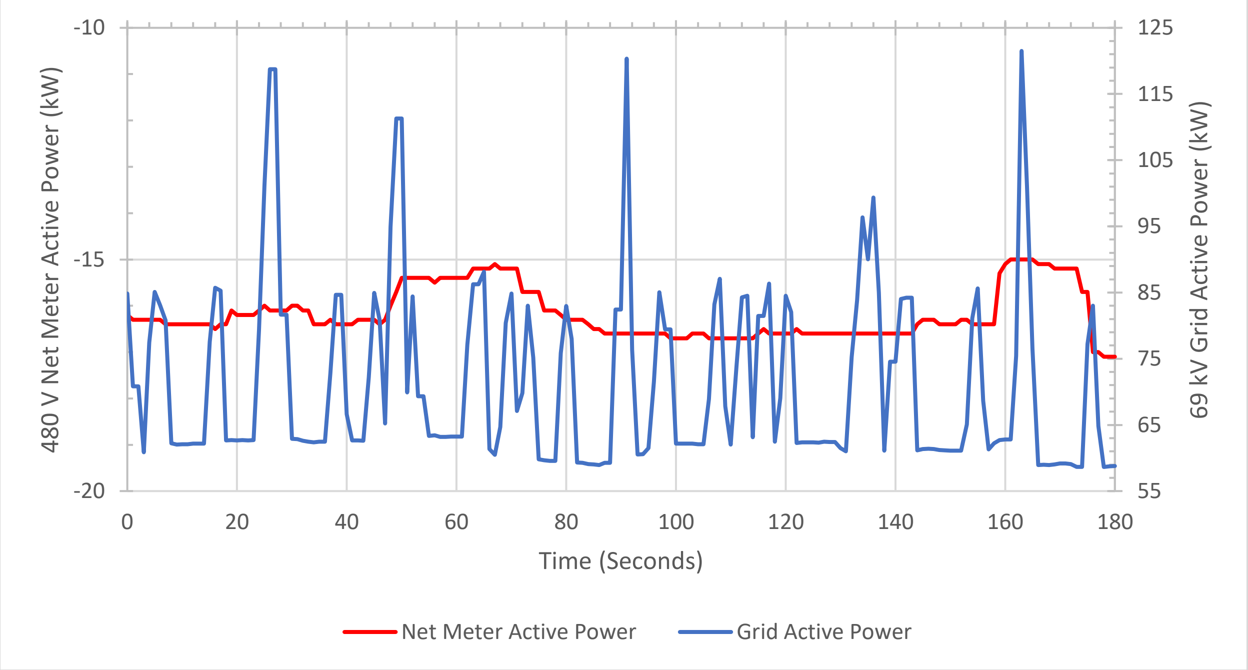

Figure 8. PV and BESS net meter active power compared to the grid active power

In Figure 9 the PV and BESS net meter reactive power is compared to the grid reactive power. While both have the same trends, there is an offset between 110 kVAR to 120 kVAR between the two values. This difference is believed to be the result of kVAR loss due to the impedance of cable, circuit breakers, transformer windings, etc., as well as the kVAR losses from the magnetic induction of the 480 V/13.8 kV and 13.8/69 kV power transformers between measurement points. See the line diagram of the WEICan site in Figure 4 in Section 5.6 for reference.

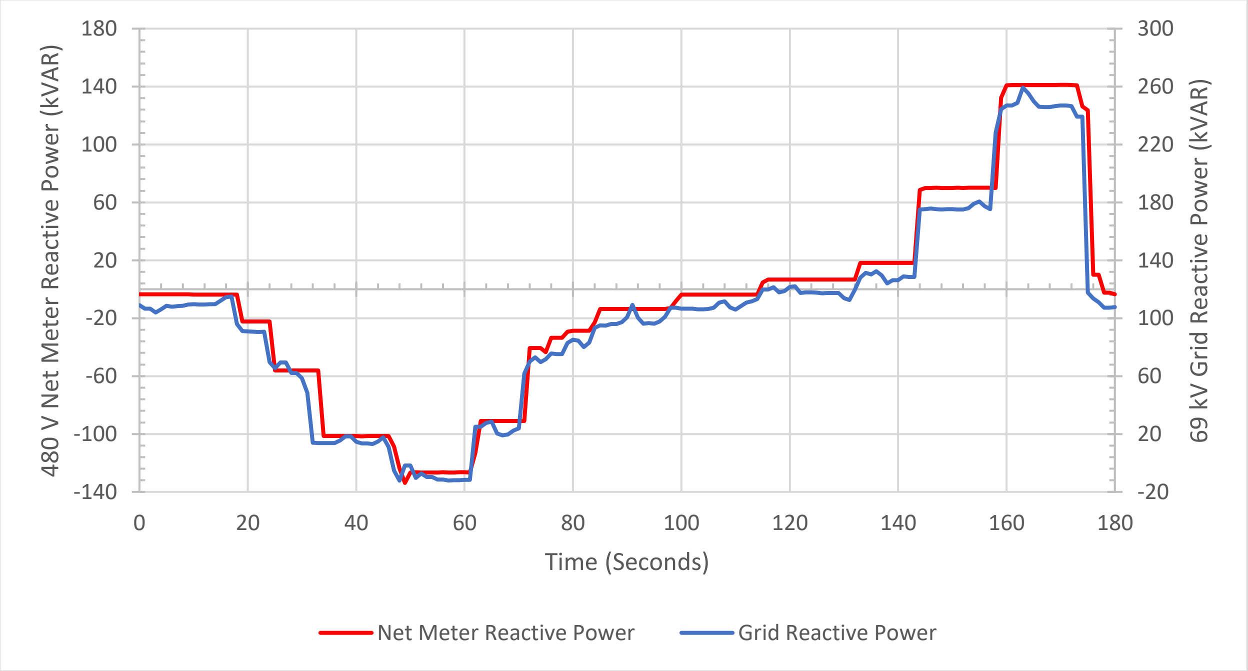

Figure 9. PV and BESS net meter reactive power compared to grid reactive power

This demonstration showed that both the PV inverter and the BESS could control reactive power setpoints. Reactive power services are typically used in voltage support. This functionality could be used in an algorithm to provide such grid support.

6.3 PV Leveling

6.3.1 Overview

A major challenge related to incorporating PV into the power grid is related to the high variability in the power output, especially morning and evening power ramps and throughout the day with cloud variability conditions. Therefore, it is advantageous to investigate the ability of using a battery with PV to provide a firm capacity, creating a dispatchable power plant.

Inputs from the RTAC were used to control the net output from the PV and BESS systems. A net power profile was chosen to start ramping up the net power before the PV system started to produce power at 7:45 am. This power would ramp to a set value by 10 am and hold that set value until 3 pm. At 3 pm the net power would ramp to zero by 7 pm. This profile can be seen for a 30 kW set value in the ideal ramp-chart in Figure 10.

To produce this profile, the following inputs were used in the RTAC:

- SMA Inverter 1 Active Power (SMA1AP)
- SMA Inverter 2 Active Power (SMA2 AP)
- Tesla SMC Active Power setpoint

The expression to control the Tesla setpoint was the following:

Equation 1:

$$\text{Tesla SP} = \text{Desired Net Power} - \text{SMA1AP} - \text{SMA2AP}$$

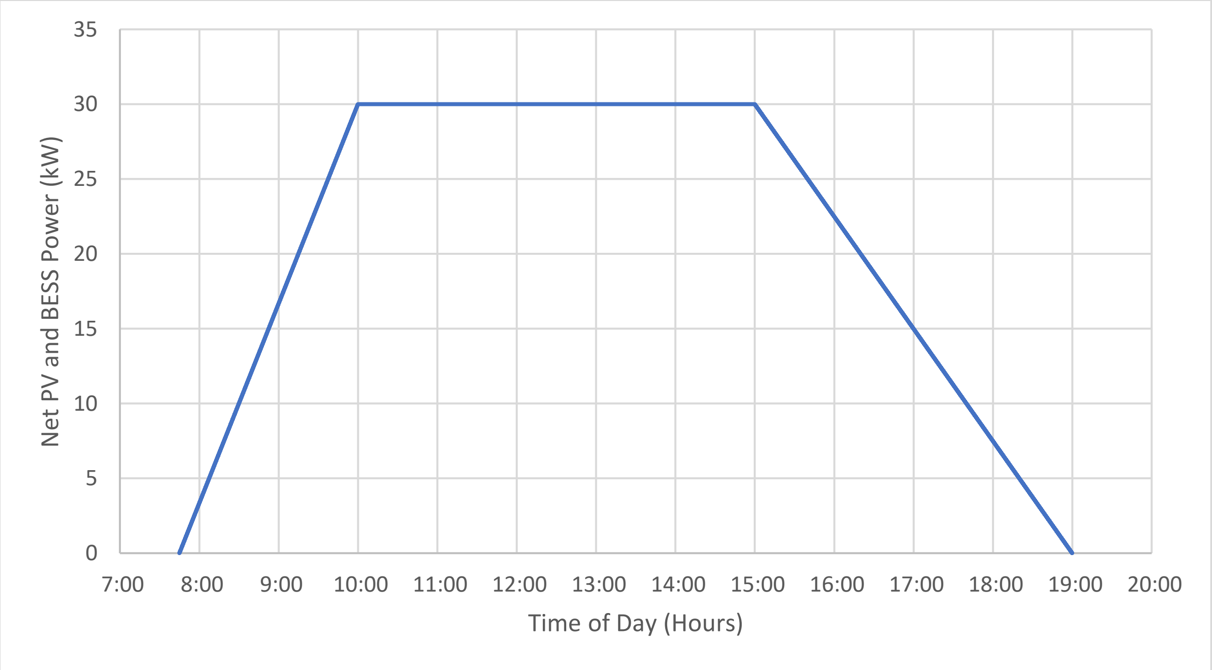

Figure 10. Example net power ramp profile for a 30 kW set value

6.3.2 Results

The controls to produce a net power profile similar to that shown in Figure 10 were input to the RTAC for several days. Figure 11 shows an example of the BESS leveling the net power output of PV and BESS to 30 kW from 10:00 am to 5:48 pm. Although the program was set to level the output until 7:00 pm, the BESS state of charge (SOC) reached WEICan's operational limit at 5:48 pm and then the BESS setpoint was set to zero. Despite variable PV power throughout the day, when operating to level the output, the net power followed quite well, with some discrepancies when there were rapid changes of the PV power. The simple expression was lagging behind the rapid changes and not compensating quickly enough.

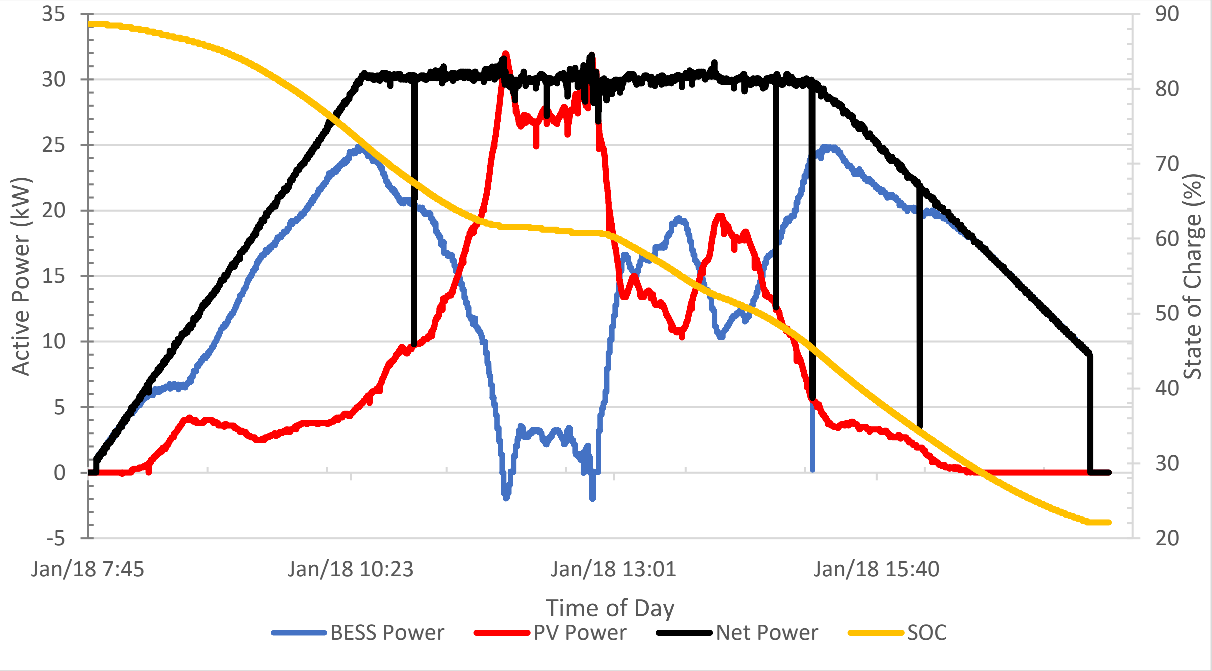

Figure 11. PV Power Levelling to 30 kW via BESS 1 Hz data

To improve the response of the RTAC to levelling, the polling times of the Modbus registers were increased from 1000 ms to 200 ms, changing from 1 Hz to 5 Hz collection in the RTAC. Figure 12 shows an example of the increased data rates and the net output power. Here we see improved stability to the leveled output as a result of the increased data rates. Similar to the previous example, the BESS reached its operational limit at 3:37 pm and the test had to be ended early.

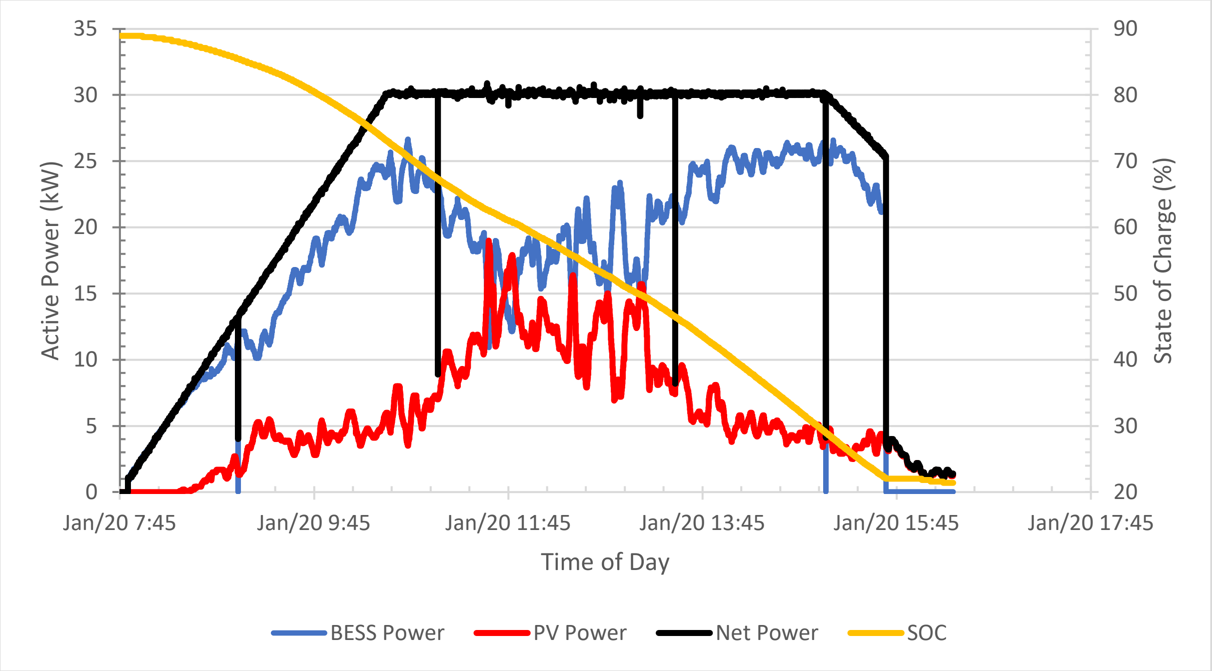

Figure 12. PV Power leveling to 30 kW via BESS 5 Hz data

While this demonstration showed the capabilities of limiting ramp rates and providing firm capacity, a difficulty in this test was predicting the static power value based upon the next day weather forecast. The results for this work could be improved by incorporating forecasting into the algorithm.

6.4 PV and BESS Following Signals

The ability of PV and BESS's to follow external signals is important when considering their abilities to provide services to the grid. This section shows results in signal following for WEICan's PV and BESS.

One method of maintaining the balance between supply and demand on the grid in the time frame of minutes is secondary frequency regulation. This involves small changes to the power outputs of several generators to keep the grid frequency as close to 60 Hz as possible. Secondary frequency regulation is coordinated by the system operators over a significant geographical area, typically an entire province or several states.

When a generator participates in the secondary frequency regulation market, it is paid for two services:

1. Remaining on standby to provide regulation services
2. Responding to a regulation signal and providing regulation services

The payment for remaining on standby depends on the quantity of regulation offered (in MW) and is paid even if the generator provides no regulation.

The response of the generator to an external regulation signal determines the payment for the second quantity. A performance score is used to quantify this response. Performance scores range from 0 to 1 and are usually expressed as a percentage with a 100% performance score corresponding to an ideal response.

In this work, two methods were used to evaluate the capabilities of the solar PV and the BESS in following the AGC signal – the Pennsylvania – Jersey – Maryland (PJM) system operator method and the California Independent System Operator (CAISO) method.

PJM is moving towards using a Precision Only score rather than using a performance score that has three components (1/3 Accuracy, 1/3 Delay, and 1/3 Precision).[23] Therefore, the Precision Score was used in this work. The disqualification from Regulation Market threshold is below 40% - this is a rolling average of the actual hourly performance score for the last 100 hours a resource has operated. The Precision Score is calculated according to Equation 2 and Equation 3:

Equation 2:

$$Error = Avg\ of\ Abs\left|\frac{Response - Regulation\ Signal}{Hourly\ Average\ Regulation\ Signal}\right|$$

Equation 3:

$$Precision\ Score = 1 - \frac{1}{n}\sum Abs(Error)$$

A smaller hourly average regulation signal in the denominator yields a larger error, which, in turn, yields a lower Precision Score. This phenomenon is observed in the present work because the signal crosses zero often. In this work the issue was overcome by using the regulation signal rather than the hourly average regulation signal.

CAISO normally measures the accuracy of response to the AGC signal during 15-minute intervals by calculating the ratio between the sum of the total 4-second set point deviations and the sum of the AGC set points, according to Equation 4:[24]

Equation 4:

$$PS_{CAISO} = \left[1 - \frac{\sum_{T=1}^{T}|s[T] - y[t]|}{\sum_{T=1}^{T} s[t]}\right]$$

Where PS_{CAISO} is the performance score in CAISO and at each time slot T of length four seconds, $s[T]$ and $y[T]$ denote the AGC setpoint and the mechanical output of the regulation resource. The fraction in Equation 4 is a normalized measure of performance inaccuracy in following the AGC setpoints. Thus, 1 minus the fraction is used to obtain a performance accuracy measure. In the current study, five second intervals were used as AGC signals.

6.4.1 BESS

6.4.1.1 Overview

To demonstrate the capabilities of WEICan's BESS to follow an external signal, a standard frequency regulation duty cycle, adjusted for the battery specifications was followed for 24 hours. Discharges ranged from -115 kW to 115 kW in five second steps. The file is read into a python program which writes the input value to a Modbus Server setup to receive the input signal on WEICan's second RTAC. The code on the RTAC does some basic logic points to determine the validity of the input signal:

- is the input between -115 kW and +115 kW?
- is the wind park producing >300 kW?
- is the state of charge of the BESS within the limits of 20 and 90%?

If so, the input signal is sent to the BESS, else it is set to 0.

This duty cycle was run twice, once with the battery heater on and once with the battery heater off. Although WEICan does not have access to BESS temperatures, external temperatures ranged from -12.8°C to -5.9°C during the test with the heater off and from -4.8°C to -2.4°C during the test with the heater on. The BESS starts to curtail charge power and discharge power when its temperature falls below 15°C and -5°C, respectively. The heater thermally preconditions the cells at cold ambient temperature.

6.4.1.2 Results

Figure 13 shows the ability of WEICan's BESS to follow five second setpoints from a standard frequency duty cycle for 24 hours with the battery heater off and Figure 14 shows results from the same test with the battery heater on. The BESS was able to follow the signals more closely when the battery heater was on due to the heater being required for the battery to charge at its full range. This can be seen more clearly in Figure 15, which looks at the time from 15.70 h to 15.90 h where the BESS is clearly able to follow the signal more closely when the heater is on than when it is off. While the BESS could perform the test better when the heater was on, it still did not reach 100% of the setpoint values.

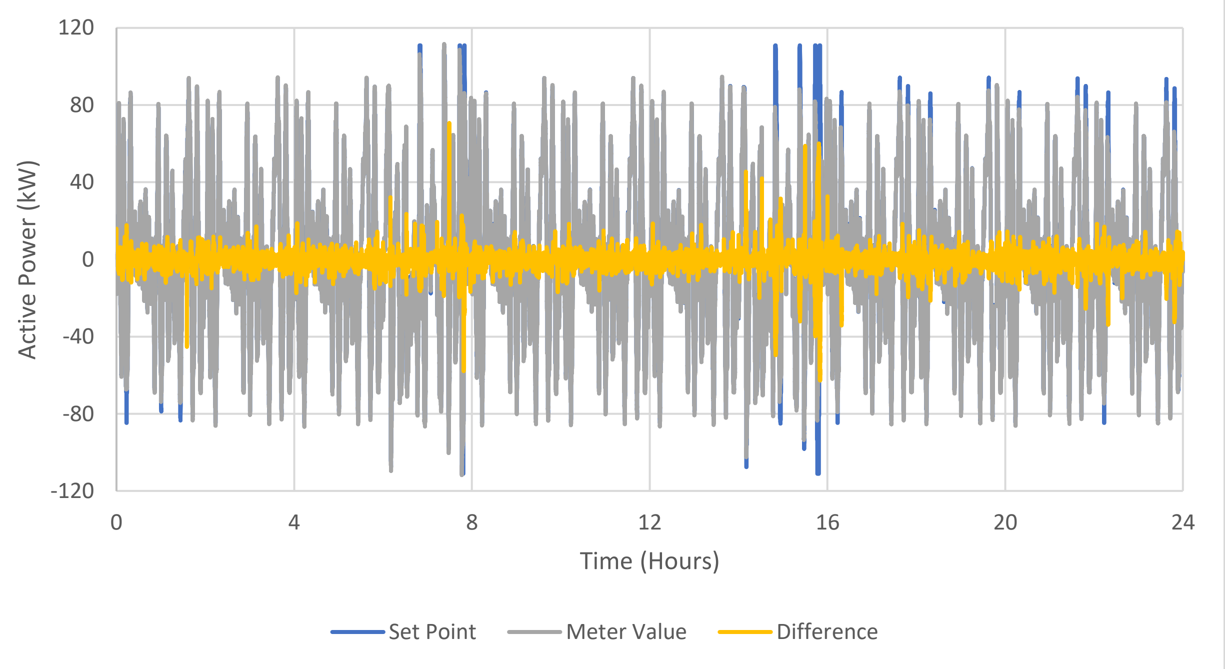

Figure 13. BESS following a standard frequency regulation duty cycle with the heater off

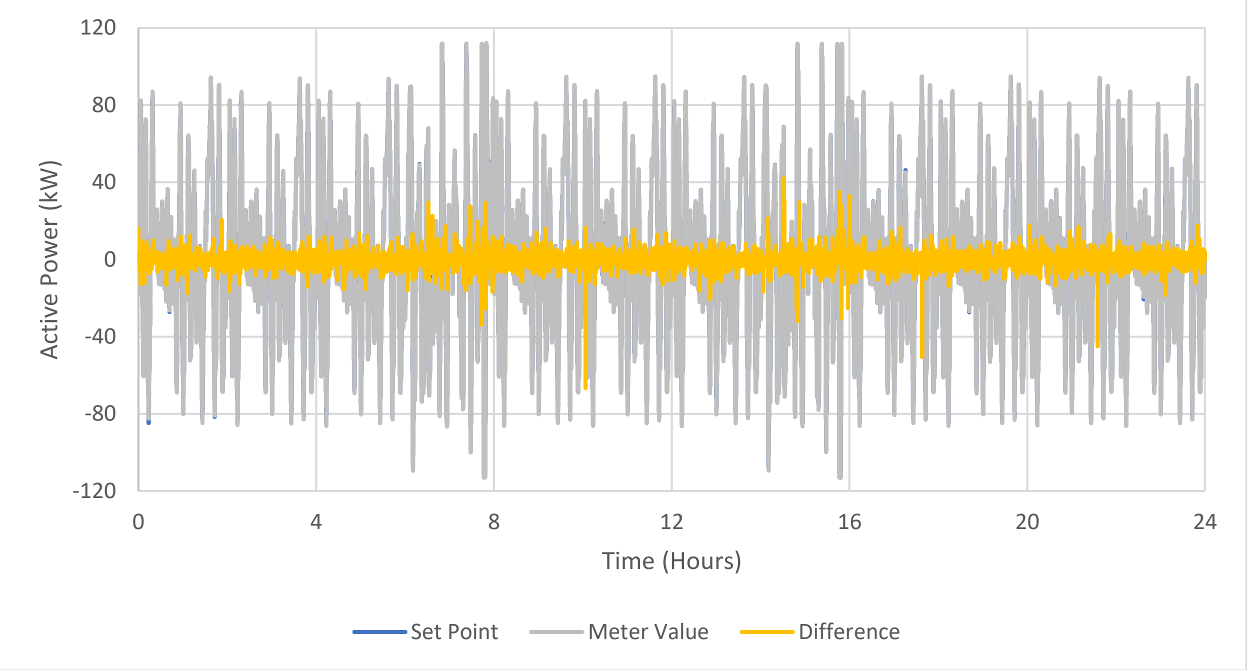

Figure 14. BESS following a standard frequency regulation duty cycle with the heater off

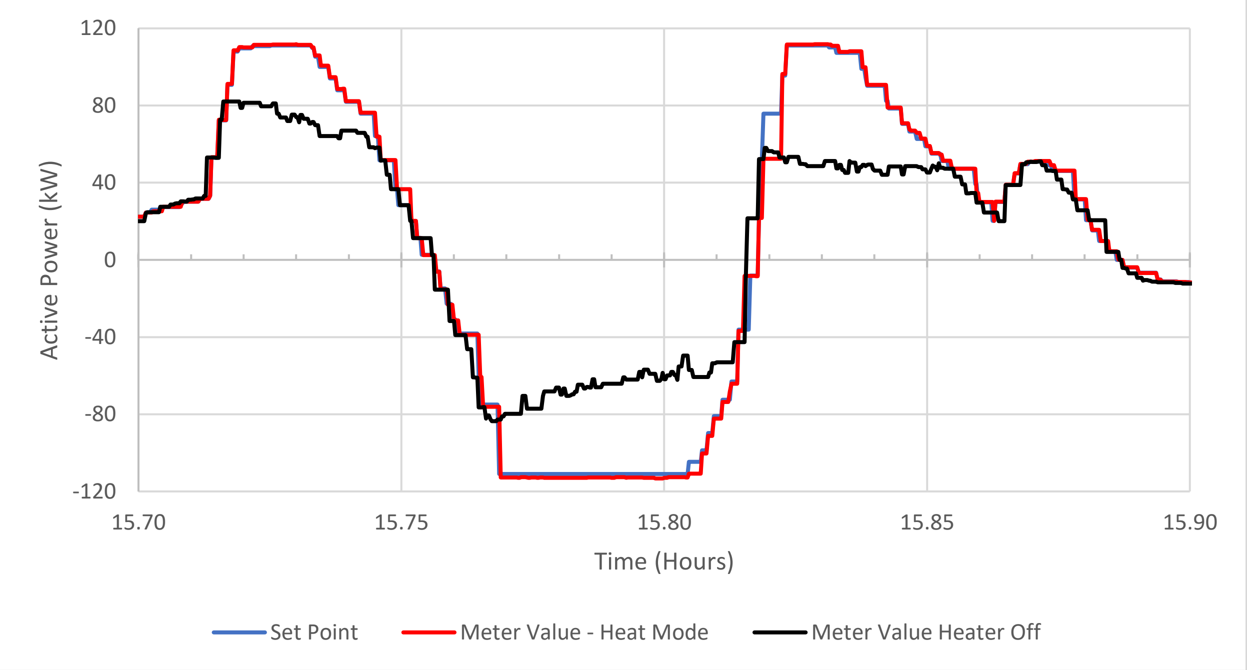

Figure 15. BESS following standard frequency duty cycle with and without the heater on

The state of charge (SOC) of the BESS over the 24-hour test were normalized to have the starting point of 50% by subtracting the starting point value from all SOC values in each test. Figure 16 shows that the normalized SOC of the BESS decreased throughout the tests. The test with the heater on resulted in a lower SOC by the end of the test because energy from the battery was used to power the heater throughout the test.

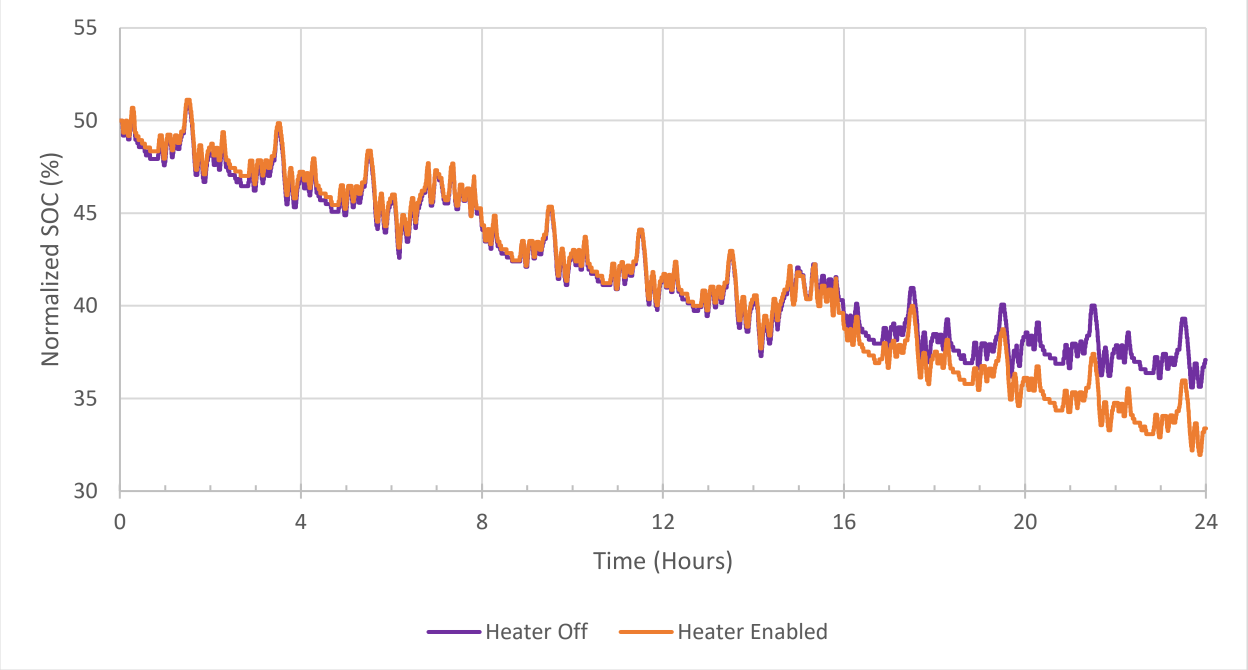

Figure 16. Normalized state of charge over the 24 hour test

In this work, the Precision Score for the BESS, calculated according to the PJM method described above, was 91.8% without the heater and 92.2% with the heater. Being above 40%, these numbers mean the battery would be able to participate in the regulation market in both cases. These numbers are equivalent to numbers reported by PJM for energy storage (90% to 93%).[25]

The Accuracy Score for the BESS, calculated according to the CAISO method described above, was 96.2% without the heater and 97.8% with the heater.

It could be worth considering the value of having the BESS heater on during a test of this type. The improvement in the Precision and Accuracy Scores were minimal (0.4% and 1.6%, respectively) with the heater on, and the state of charge was about 3% lower by the end of the test with the heater on, compared to that of the test with the heater off. These differences would be more significant at colder temperatures.

6.4.2 PV

6.4.2.1 Overview

To demonstrate the capabilities of the inverter on WEICan's PV array to follow an external signal, a standard frequency regulation duty cycle, adjusted for the PV and inverter specifications was followed for twenty minutes. A twenty-minute section of the same frequency regulation duty cycle that was used for the BESS input was chosen that maximized the difference between two adjacent setpoint values. The frequency response signal was adjusted from -115 kW to 115 kW to provide a multiplier from -1000 to 1000. This was important so that more decimal places could be used, as Modbus uses integer values. The input signal is divided by 1000 later to produce a -1 to 1 range signal.

All data is from a single SMA inverter as WEICan's second PV inverter was not functioning during the test.

PV setpoints are set via a percentage of the maximum capacity of the inverter. For example, 1% = 62.5 kW*0.01 = 0.625 kW. The system uses whole number values for the setpoint with no rounding. For example, a setpoint of 30.54 kW = 48.86% (30.54 kW/62.5 kW*100%) ≥ 48% = 30 kW (48%/100%*62.5 kW).

The twenty-minute file was sent to the RTAC in the same method as the BESS input signal described in Section 3.3.2 BESS. Python code read the file and then wrote the signal value to the Modbus register on a Modbus server set up on the RTAC. The Modbus signal was then used to calculate the PV setpoint. Since the inverter cannot produce negative real power, the signal was used to modulate a flat set power value.

6.4.2.2 Results

To determine the impact of setpoint variation and ramp rate, three PV following tests were run:

- At a lower setpoint variation ((Modbus Input signal)/1000*10 kW + 10 kW) with 20%/s ramp rate.
- At a higher setpoint variation ((Modbus Input signal)/1000*25 kW + 25 kW) with 20%/s ramp rate.
- At a higher setpoint variation ((Modbus Input signal)/1000*25 kW + 25 kW) with 1000%/s ramp rate.

A representative plot showing the input signal setpoint and PV active power is shown in Figure 17. The difference between the two values is also plotted. The higher and lower setpoint variations are plotted in Figure 18 and using 20% and 1000% ramp rates is shown in Figure 19. In Figure 18, differences are observed due to the 0.625 kW output step sized based upon the 1% steps. In all cases, the PV inverter was able to follow the signal quite well and setpoint variations and ramp rates did not have a large impact on results. The PJM Precision Scores were found to be:

- 96.3% for the lower variation setpoint test at 20%/s ramp rate
- 98.7% for the higher variation setpoint test at 20%/s ramp rate
- 98.6% for the higher variation setpoint test at 1000%/s ramp rate

These values are higher than that found for the battery and would also render the PV eligible to participate in the regulation market in the PJM jurisdiction. Similarly, the Accuracy Scores for the PV, calculated according to the CAISO method described above, were found to be:

- 96.9% for the lower variation setpoint test at 20%/s ramp rate
- 98.9% for the higher variation setpoint test at 20%/s ramp rate
- 98.8% for the higher variation setpoint test at 1000%/s ramp rate

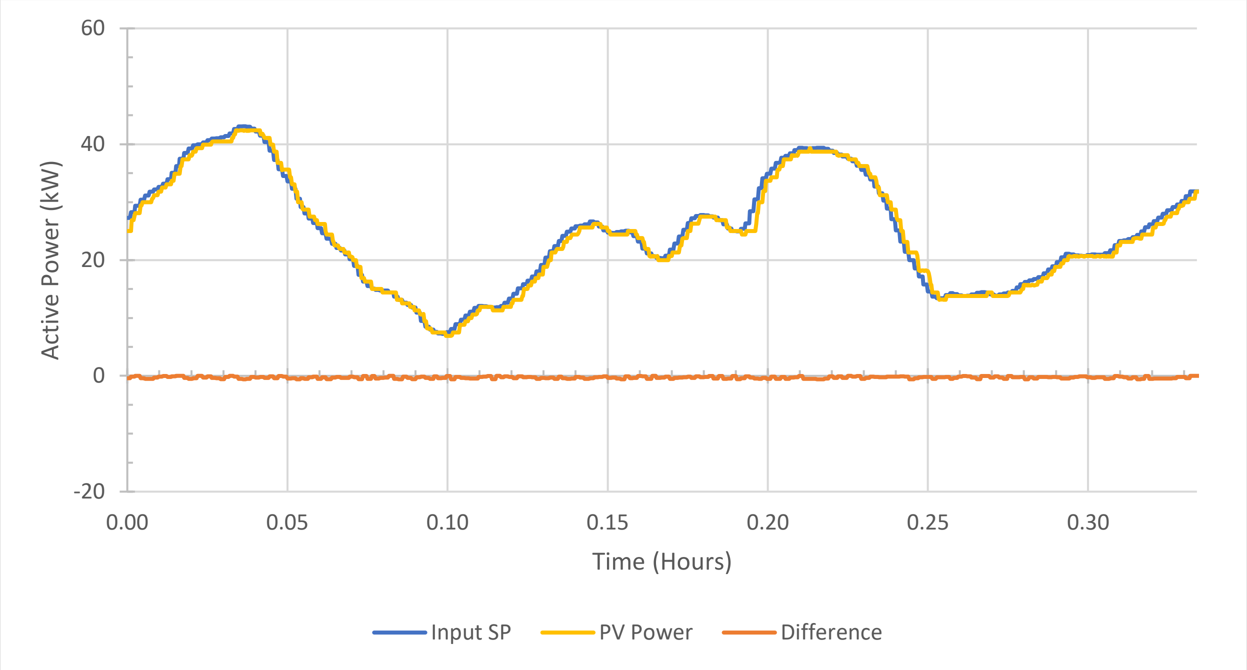

Figure 17. Input signal setpoint and PV active power for the higher setpoint variation and 20%/s ramp rate

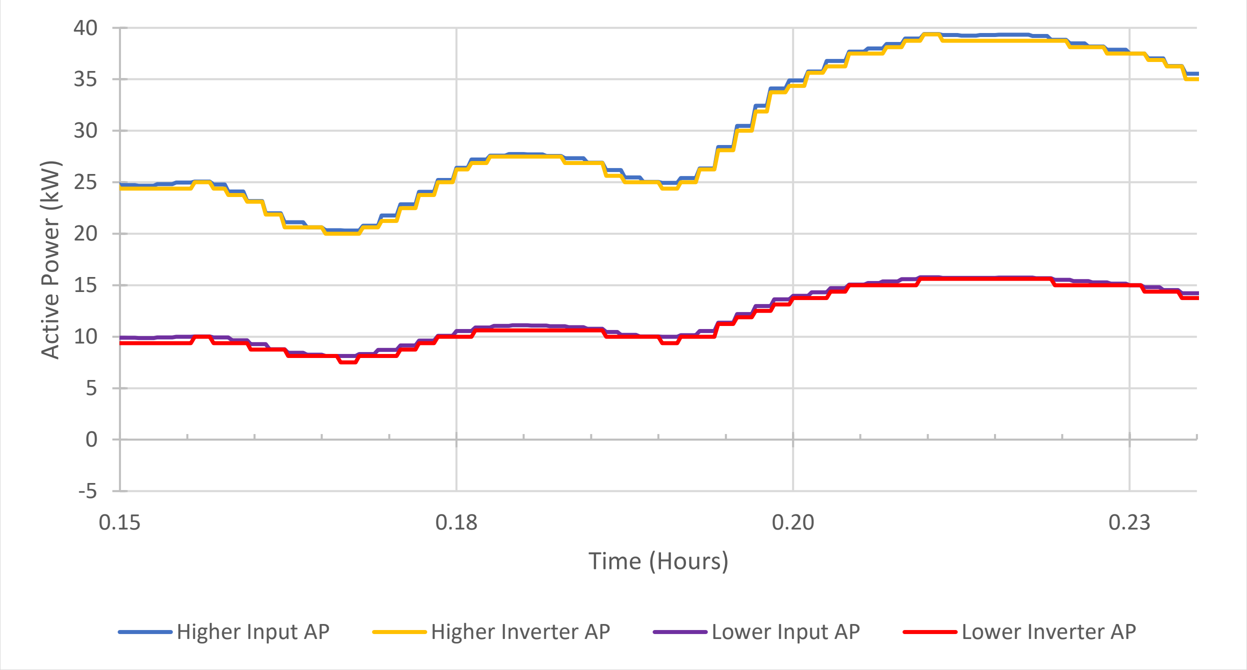

Figure 18. Input signal setpoint and PV active power for higher and lower setpoint variation at 20%/s ramp rate.

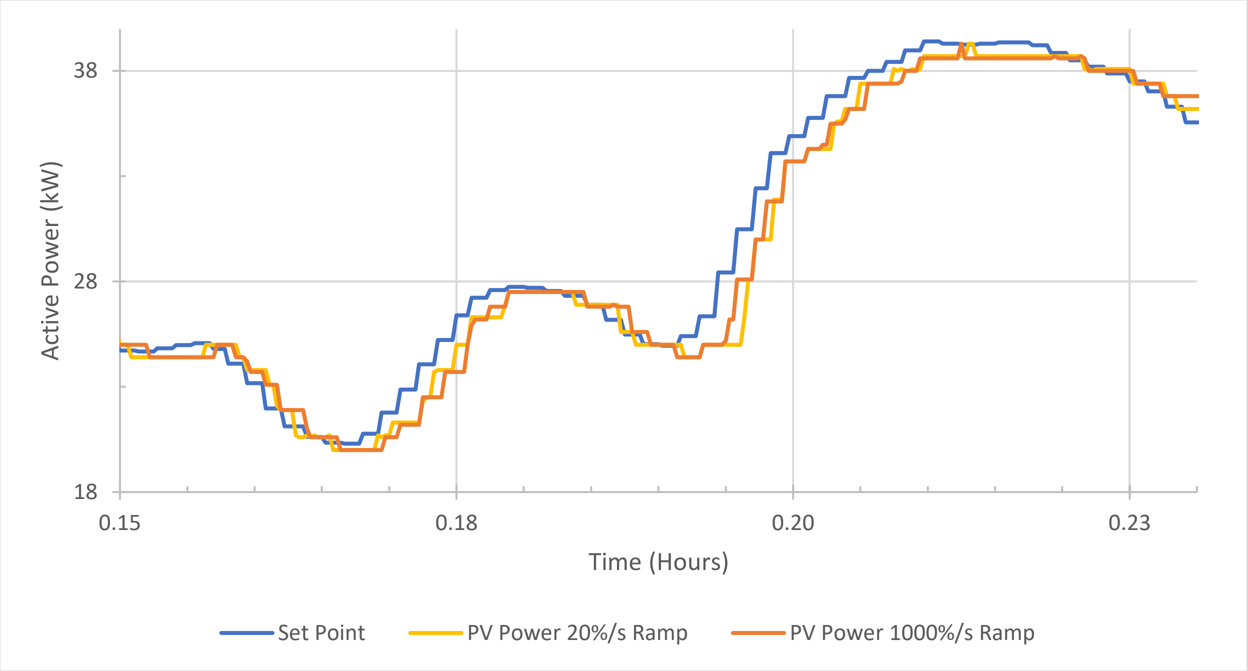

Figure 19. Input signal and PV active power at 20%/s and 1000%/s ramp rates

It should be noted that the battery demonstrations were 24 hours while the PV demonstrations were 20 minutes. A longer time period that had more irradiance fluctuation would likely have resulted in lower PV precision and accuracy values. In a similar study, First Solar, NREL, and CAISO[3] carried out AGC by following historical four second signals at a 300 MW solar power plant. Tests were conducted for 20 minutes at three different solar resource intensity time frames: (1) sunrise, (2) middle of the day (noon-2 pm) and (3) sunset. The CAISO Accuracy Scores of the solar plant were 93.7% at sunrise, 87.1% in the middle of the day, and 87.4% at sunset. Their numbers were similar, but lower than those found in the present demonstration. While these few short tests allow some preliminary conclusions on the abilities of these generators to provide AGC services, longer testing with different cloud conditions is necessary to collect sufficient statistics.

For comparison, typical regulation-up accuracies for CAISO's conventional generators are as follows:[3]

- Combined cycle - 46.88%
- Gas turbine - 63.08%
- Hydro - 46.67%
- Limited energy battery resource - 61.35%
- Pump storage turbine - 45.31%
- Steam turbine - 40%

In all cases, both the PV array and the battery had significantly higher accuracy than conventional generators.

7 Summary and Conclusions

This work demonstrated the capabilities of a solar PV-BESS power plant to provide a range of reliability services to the grid. Together this work demonstrated:

1. Role and ability of storage in reducing morning and evening power ramps from solar PV, i.e. charge/discharge storage to reduce MW ramp rate.
2. Ability of solar and storage each to provide AGC following.
3. Ability of the combined system to provide firm capacity (i.e. MW), depending on the market requirements.
4. Reactive power support from PV and BESS, which is important in voltage regulation of the grid.

Simple controls and algorithms were used in this work. Results could improve if forecasts and more complex algorithms are incorporated. Periods with different cloud conditions for the PV and longer demonstration periods for both the battery and the PV are required to gain a deeper understand the capabilities of PV and batteries in providing these services. However, the results from this demonstration serve as a proof-of-concept that can show transmission-connected equipment owners the capabilities of the technology.

Procurement of ancillary services from inverter-based energy sources is still relatively rare in Canada. Most jurisdictions do not offer compensation for the benefits that solar PV and energy storage can offer. Data from real world demonstrations such as that carried out in this work help utilities and system operators realize the capabilities of the inverter-based energy sources to provide ancillary services and will help them in the creation of markets for such services.

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