RAMP RATE CONTROL FOR PV PLANT INTEGRATION: EXPERIENCE FROM KARRATHA AIRPORT'S HYBRID POWER STATION

George Dickeson[1], Lachlan McLeod[1], Anthony Dobb[2], Lyndon Frearson[1], Bert Herteleer[1,3], Dione Scheltus[2]
[1] Ekistica, george.dickeson@ekistica.com.au,
PO Box 8044 (Desert Knowledge Precinct), Alice Springs Northern Territory 0871, Australia
[2]Australian Renewable Energy Agency (ARENA), Australia
[3] Research Group Energy & Automation, KU Leuven, Gebroeders De Smetstraat 1, 9000 Gent, Belgium

ABSTRACT: We present the operational characteristics of a ramp rate control system on a 1 MW PV array located at Karratha Airport in Western Australia. The control system utilises cloud-prediction technology (CPT) to facilitate pre-emptive curtailment of the array, as well as a smoothing battery energy storage system (BESS), in order to meet ramp rate constraints required by Horizon Power, the local network operator. This project received funding under the Australian Renewable Energy Agency's (ARENA) Regional Australia's Renewables (RAR) initiative for the purposes of seeking to improve the competitiveness of renewable energy systems on the North-West Interconnected System (NWIS), and generating and sharing knowledge that will assist network operators and decision makers to better understand the economic value and technical viability of connecting distributed renewable energy generation on remote, stretched grids. Among the results shown are the observed reduction in ramp rates, the lost yield due to both curtailment and BESS losses, and the degree to which the BESS's available power and energy capacity have been utilised. In addition, we present some of the key lessons learned during the commissioning process.
Keywords: Battery Storage and Control, Evaluation, Grid Stability, Hybrid, National Programme, Performance, Plant Control, R&D and Demonstration Programmes, Reliability.

1 INTRODUCTION

Increased investor confidence and continued cost reductions have led to a boom in the development of utility-scale PV plants worldwide. This rapid rate of installation has brought into focus a central dilemma of grids experiencing high renewable power fractions: renewable generators relying on variable resources require reserve generation to be available to cover short-term loss of power, while, those reserves become increasingly uneconomical as more renewable generation is installed.

Some utilities in Australia [1] [2], as well as in Germany, Ireland, Puerto Rico, and elsewhere [3], have opted to confront the issue of PV variability by introducing limits on the rate of change of power, or ramp rate. By imposing clear boundaries on ramp rates, a network can allow higher fractions of renewables with significantly reduced reserve requirements. Many different approaches to ramp rate control have been proposed, both in Australia and internationally:

- PV inverters can be used for smoothing ramp rates through Maximum Power Point Tracking, but have limited capability to do so. They are also able to limit the upward ramp rate in the event of a fast increase in resource(s) [3].
- Battery energy storage systems (BESSs) can charge and discharge in response to changes in PV power, allowing the net exported power to be kept within ramp rate constraints [4] [5] [6].
- Cloud predictive technology (CPT) can be used to trigger pre-emptive curtailment [3], [4], [7] and/or allow for more optimal selection of thermal generators.
- Many hybrid approaches have been proposed which utilise more than one of the above technologies [3], [4].

Ramp rate control systems are receiving increasing attention in the industry and many simulated results have been published. However, there is currently limited literature available for developers that show empirical

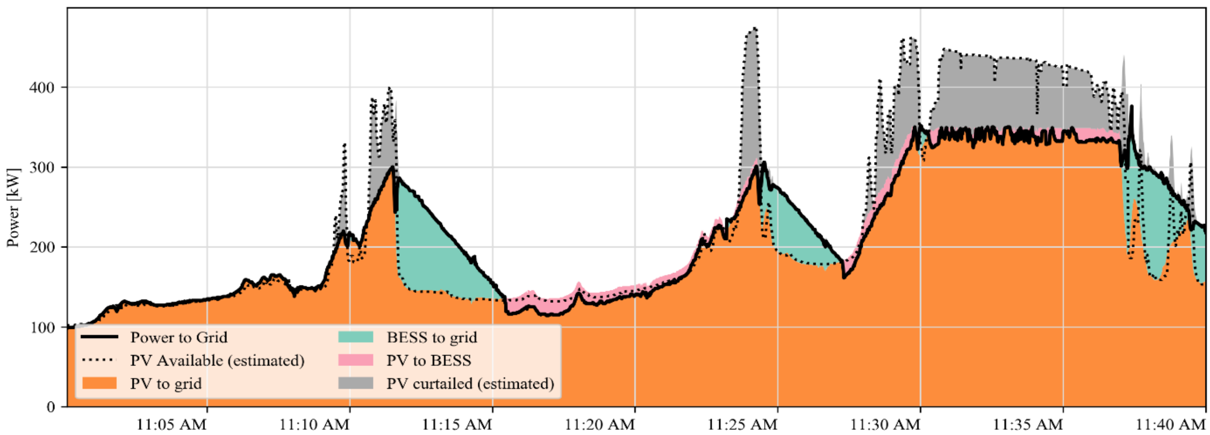

Figure 1. Example of the Karratha Airport ramp rate control system, for a 500 kW_{AC} block, operating over a forty-minute period. Upward ramp control is facilitated by curtailment at the PV inverters, while downward ramp control is facilitated by discharging the BESS. From 11:30 AM, the PV array is pre-emptive curtailed at a set point of approcimately 340 kW. This curtailment is necessary to ensure that the BESS will be capable of fully compensating for the imminent drop in available PV power.

characteristics of an operating ramp control solution [8]. In this paper, we present performance characteristics and lessons learned in the first three years of operation of a hybrid BESS and CPT ramp rate control system for a 1 MW_{AC} PV array, located at Karratha Airport in Western Australia.

1.1 Description of the technical constraint

The Karratha Airport hybrid power station connects into the North-West Interconnected System (NWIS), in the remote Pilbara region of Western Australia. The NWIS is operated by Horizon Power and serves approximately 500 GWh of annual load.

Horizon Power's technical requirements for renewable energy systems [1] place restrictions on both the upward (positive) and downward (negative) ramp rate, as measured at the output of the renewable energy system. These constraints are defined with respect to the nominal AC rating of the PV inverters (P_{nom}): A maximum positive ramp rate (rr_{max}) equivalent to a rise of 100% of nominal power over 6 minutes, and a minimum negative ramp rate (rr_{min}) equivalent to a drop of 100% of nominal power over 12 minutes (or, 16.7% and 8.3% and per minute, respectively.)

This constraint is captured by the inequality (1). The instantaneous ramp rate ($\dot{p}$) is defined as the time derivative of the AC power, shown here in kilowatts per minute.

$$rr_{min} = -0.083 \le \frac{\dot{p}}{p_{nom}} \le 0.167 = rr_{max} \qquad (1)$$

Table 1. Definitions applying to (1)

Symbol	*Definition*	*Units*
rr_{min}	Minimum p.u. ramp rate	-/minute
rr_{max}	Maximum p.u. ramp rate	-/minute
$\dot{p}$	PV ramp rate, i.e. time derivative of PV AC power.	kW/minute
p_{nom}	PV nominal AC power rating	kW

Since constraint (1) refers to the *instantaneous* ramp rate, meeting this constraint at arbitrarily short time scales would be both impractical from a control perspective, as well as unnecessary to the goal of maintaining grid stability. Horizon Power defines a "non-linearity" band that allows for temporary exceedances of up to 10% of p_{nom} for positive and negative ramps.

One consequence of the non-linearity band is that a complete assessment of compliance cannot be determined on the basis of individual ramp rate measurements, but must consider the ramping behaviour of the power station over each rolling twelve-minute window. An example is shown in Figure 2, with compliance being tested specifically from 11:36 am. The blue bounded region represents the constraint described by (1), while the red bounded region extends the blue region to include the non-linearity band, and is the actual constraint required by Horizon Power.

An example is shown in Figure 2, with compliance being tested specifically from 11:35:30 am. The soft constraint regions represent the power levels permissible under inequality (1), while the hard constraint (shown in red) extends this region to allow for short-term excedences of up to 10% of P_{nom}.

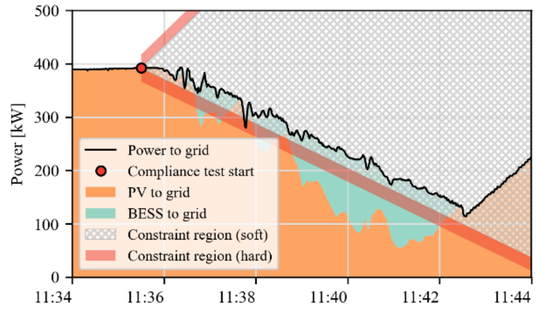

Figure 2. Demonstration of Horizon Power's ramp rate constraint using a ten-minute example of operational data.

1.2 Karratha Airport Hybrid Power Station

The hybrid power station consists of a 1 MW_{AC} PV array located at Karratha Airport and connected to the NWIS. The PV array and ramp rate control system were designed and constructed by CPS National, with technology partner MPower, and is owned by IIG Solar Income Fund. The cloud camera is Fulcrum3D technology.

The PV array is comprised of two independent 500 kW_{AC} blocks, each with identical but independently functioning ramp rate control systems (the results presented in this paper typically describe the behaviour of one of the two blocks.) Each ramp rate control system consists of an on-site cloud camera and cloud prediction system, as well as a 234 kW / 367.2 kWh valve-regulated lead-acid (VRLA) BESS [9]. Figure 3 shows the layout of the site at Karratha Airport.

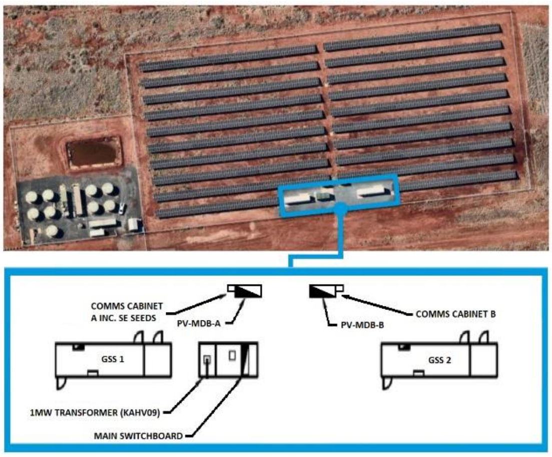

Figure 3. Aerial photo of Karratha Airport's hybrid power station, including a schematic of the ramp rate control system, comms, transformer, and switchboard (bottom). The site is divided into two PV blocks, each with an independently operating BESS, CPT, and control system.

Under normal operating conditions, when the CPT does not forecast any irradiance occlusion events (such as cloud cover), the PV runs uncurtailed. However, if the probability of an impending occlusion event rises above a threshold each PV block is curtailed at a fixed set point. When an occlusion event occurs, the BESS responds independent of the CPT. The measured power drop results in the BESS discharging at a level sufficient to comply with the ramp rate constraint (as long as the impact of an occlusion event is less than 234 kW, which is the capacity of the BESS inverter). An example of the control system operating over a forty-minute period can be seen in Figure 1.

The maximum discharge power of each BESS (234 kW) is considerably lower than the nominal power of each corresponding PV block (500 kW). For the BESS to be capable of compensating for large drops in solar resource, the PV must run curtailed when occlusion events are likely. A function of the CPT is, therefore, to ensure that the PV is not curtailed unnecessarily during clear sky periods. This behaviour can be seen clearly in Figure 2, from 11:34 to 11:44 am.

1.3 Approach to the presentation of results

The performance characteristics of any ramp rate control system are highly dependent on local climate; cloudier days call for more intervention than clear-sky days. In order to make the results presented here more readily transferable to other locations we have aimed to demonstrate performance characteristics independent of local conditions. To this end we have presented, where possible, performance characteristics alongside the daily variability index (VI) [10]. Days with a higher VI typically require more intervention from the control system.

The VI is defined in terms of the daily irradiance arc-length, $L(g)$ (Equation (2)). Here g_i is the i^{th} irradiance sample of the day, and Δt is the time in minutes between samples.

$$L(\boldsymbol{g}) = \sum_{i=1}^{N} \sqrt{(g_{i-1} - g_i)^2 + \Delta t^2} \qquad (2)$$

The VI is then defined as the ratio of the arc-length of the observed irradiance and the arc-length of the corresponding clear-sky irradiance, g_{clear}, calculated algorithmically. We utilise the Ineichen/Perez clear sky model made available in pvLib [11].

$$VI = \frac{L(\boldsymbol{g})}{L(\boldsymbol{g_{clear}})} \qquad (3)$$

In general, calculating the VI at different time resolutions, results in different values[1]. Throughout this paper the VI is calculated over 5-minute averaged irradiance.

Table 2. Definitions applying to (2) and (3)

Symbol	*Definition*	*Units*
$L(g)$	Daily irradiance arc-length	-
g_i	i^{th} irradiance sample of the day	W/m^2
Δt	Time between samples	minutes
VI	Daily variability index	-
$\boldsymbol{g}$	Measured irradiance samples	W/m^2
$\boldsymbol{g_{clear}}$	Calculated clear sky irradiance	W/m^2

2 ANALYSIS OF OPERATIONAL DATA

2.1 Description of the dataset

The dataset under study consists of three years of SCADA measurements from Karratha Airport's hybrid power station, logged at 1-second temporal resolution. The logged quantities include the real power of the PV array and the BESS, the battery state of charge, and the global horizontal irradiance. Days with significant missing data, as well as periods of abnormal operation, have been excluded.

In addition, a 1-second resolution simulation of the PV array has been used to provide an estimate of the available (pre-curtailment) PV power, given the measured irradiance. In order to account for the area smoothing effect of the PV array, the simulation output has been modified using the first order low-pass filter technique described in [12].

2.2 Impact on ramp rates

Overall, interventions from the ramp rate control system have resulted in significant reduction in the occurrence of ramp rates in excess of constraint (1). Figure 4 demonstrates this impact for both upward and downward ramp rates. The red line represents the estimated available (pre-curtailment) PV power, while the black line shows the observed power to grid. The dashed green lines indicate the ramp rate constraints defined by (1), while the solid green line depicts the maximum ramp rate over 1-minute allowed by the non-linearity band.[2] The period examined included occasions during which ramp rates exceeded the constraints listed in section 1.1.

The impact can be most clearly seen at ramp rates close to the lower constraint, where the intervention from

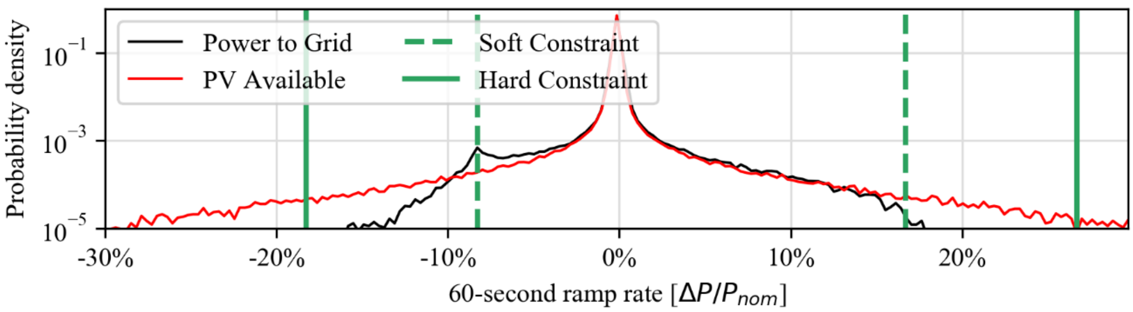

Figure 4. Distribution of measured ramp rates for PV block 1, measured over 60-second time periods. The "PV Available" line shows the distribution of ramp rates for the simulated PV array using measured on-site irradiance as input, and has been filtered [12] to account for the area smoothing effect. The "Power to Grid" line shows the distribution of measured ramp rates after the impact of PV curtailment and BESS charging and discharging.

[1] The variability index manifests a *coastline paradox*; it tends to be greater when measured at higher temporal resolution.

[2] While Figure 4 demonstrates the operational impact of the control system upon ramp rates, it cannot be used to evaluate the level of compliance with the grid requirement for observations lying between the soft and hard constraints due to the definition of the non-linearity band.

the BESS results in a visible peak in the distribution, demonstrating how the BESS is successfully supporting the power station in reducing ramp rates.

2.3 Losses

Compared to a PV array with no active power control, Karratha Airport's PV array incurs losses for two primary reasons: a) round trip inefficiencies and parasitic consumption of the BESS and control system, and b) curtailment of the PV array, including both pre-emptive curtailment triggered by the CPT, as well as curtailment to facilitate controlled upward ramping.

2.3.1 BESS Losses

Despite the relatively low round-trip efficiency of the VRLA technology, losses due to the BESS were found to be minor. Over the period examined, less than 2% of all PV-generated energy flowed through the BESS. Combined losses and parasitic loads of the BESS accounted for just 0.92% of generated energy.

Figure 5 shows the cumulative distribution of daily total energy discharged from the BESS, as well as the corresponding daily variability index. On almost half of the days examined, the BESS was not called upon at all. Even on days scoring a very high variability index, rarely was more than 100 kWh of energy required from the BESS.

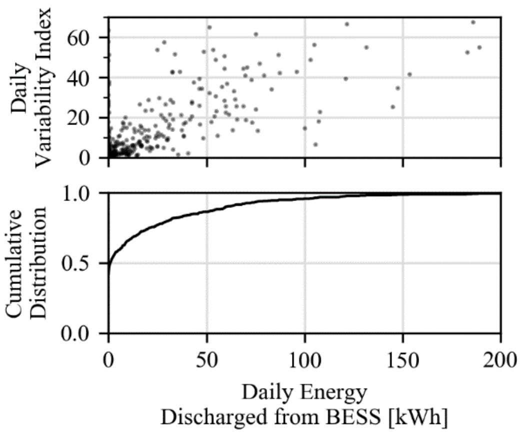

Figure 5. Daily total energy discharged from the BESS versus the daily variability index for PV block 1.

2.3.2 Curtailment Losses

In order to estimate the level of loss due to curtailment, we have compared the measured PV power to a simulation of an equivalent PV array using the global horizontal irradiance measurements from an on-site pyranometer. Based on this estimate, energy losses from curtailment account for 1.93% of available yield over the entire period examined but reached up to 10% on some days, as can be seen in Figure 6.

Perhaps counterintuitively, the amount of energy lost due to curtailment is not highly correlated with the variability index. This is because the threshold at which the CPT triggers pre-emptive curtailment must be set conservatively in order to ensure that the BESS is capable of compensating for a power drop. Some of the most significant curtailment therefore occurs on relatively clear days when the CPT nonetheless predicts an occlusion event with probability above the threshold. If a small number of non-technically compliant events were allowed each year by the network operator, the CPT trigger could be adjusted to reduce the number of false positives while admitting occasional false negatives.

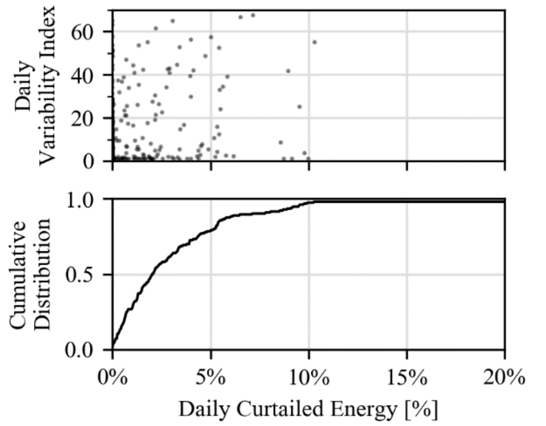

Figure 6. Estimated daily curtailed energy as a percentage of total available energy for PV block 1.

2.4 BESS utilization

The BESS energy capacity was designed to support three worst-case downward ramps consecutively, with no intervening opportunity to charge. Results to date confirm that this sizing was conservative, and that a significantly smaller energy capacity could be utilised with little impact on either the level of curtailment or the ability of the power station to meet the ramp rate constraint. However, it should be considered that a reduced capacity would result in an increase in the effective number of annual cycles, thus reducing the expected operational life of the BESS.

Figure 7 shows the distribution of daily maximum depth of discharge (DOD). Depth of discharge is a measure of the BESS's state of charge, with 100% DOD meaning 'empty', and 0% DOD meaning 'full'. During the period examined, Karratha Airport's two independent BESSs rarely exceeded a DOD of 40%.

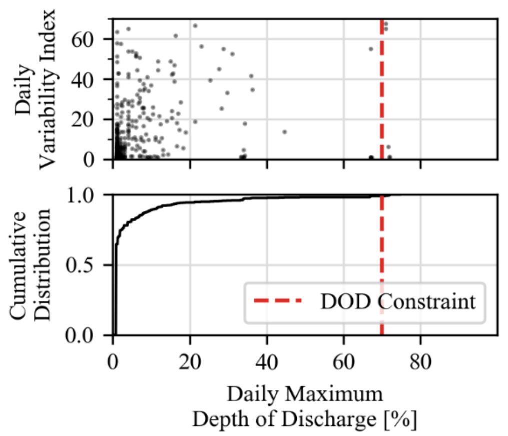

Figure 7. Daily maximum depth of discharge of the BESS for PV block 1.

The BESS power capacity (i.e. the battery inverter AC rating) of 234 kW was found to be a constraining factor on several occasions in the period examined. This sizing, which represents 47% of the nominal power of each PV block's AC rated power, was chosen in order to meet the level of drop in available power typical of the most severe occlusion events, assuming that the PV array would already be curtailed by the CPT.

Figure 8 shows the distribution of the maximum daily discharge power for block 1, along with the corresponding daily variability index. The sharp rise on the right end of the distribution indicates that the BESS was discharged at its maximum power on a number of days, and on some of these occasions the BESS's power limitation resulted in small exceedances of the ramp rate constraint.

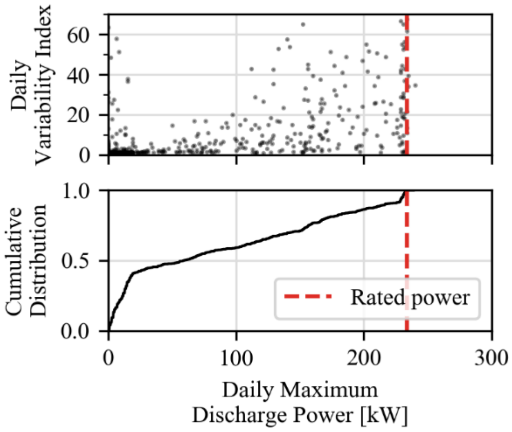

Figure 8. Daily maximum discharge power of the BESS for PV block 1.

The rate of these occurrences, and minimum level of curtailment needed in order to avoid them, is the subject of on-going review by operators of this renewable energy system.

3 LESSONS FROM COMMISSIONING AND OPERATION

3.1 CPT forecast uncertainty

Existing studies exploring simulations of CPT-enabled ramp rate control typically assume "perfect" forecasting capability. Under this assumption, the PV array can be curtailed pre-emptively for the minimum duration, and consequentially, spill the minimum amount of energy, while still meeting the ramp rate constraint (if the BESS design is appropriate). In contrast, real-world CPT systems have inherent forecasting uncertainty, and the control system designer must weigh the balance of both false positive predictions (i.e. predicted occlusion events that do not come to pass) and false negative predictions (i.e. occlusion events that the CPT failed to predict).

When applied to the specific application of ramp rate control, CPT false negatives may result in non-compliance with network technical requirements, while false positives merely result in temporary curtailment. Therefore, a designer will tend to prefer a conservative integration of the CPT, resulting in a considerable number of false positives being admitted.

Overall, Karratha Airport's CPT triggered curtailment of the PV array at least once on 65% of all days examined. On relatively clear days, with variability index between 0.8 and 1.2, the curtailment was triggered on 54% of the days, while on comparatively cloudy days, with variability index of 2.0 or above, curtailment was triggered on 80% of the days. An element of contingency has been provided for in the control algorithms to minimise unnecessary curtailment. Over time, as more performance data becomes available, this level of contingency is constantly reviewed and may potentially be reduced.

3.2 Determination of the curtailment set-point

When the CPT predicts an occlusion event, the PV array is curtailed to a fixed set point. The appropriate level of this set point is influenced by the interaction of many factors, including the CPT forecast window length, forecast uncertainty, the BESS's rated power and energy capacity, as well as the maximum likely drop in power during an occlusion event.

Of these concerns, one central trade-off has dominated decisions of the set point value to be used at Karratha Airport: If the curtailment set point is too high, the BESS may not have sufficient power to compensate for an imminent drop in power, while if the curtailment set point is too low, the frequent false positive predictions of the CPT will result in untenable amounts of lost yield.

Initially, the ramp down limit setpoint was set to 386 kW (with some dither around this nominal level) per PV block. In June 2018, this was lowered to 366 kW. In January 2019, it was adjusted to include a 2-minute delay at the ramp down limit before being allowed to ramp up. The set point value continues to be adjusted as operators become more familiar with the operation of the power station and its technical compliance.

Given these, the specific terms of technical compliance have considerable impact upon the scope for CPT integration, and consequentially, the required cost of the ramp rate solution. If a small number of exceedances per year were allowed, the CPT trigger could be adjusted to reduce the number of false positives while admitting occasional false negatives. This adjustment would allow for more heavy curtailment, but on fewer days.

3.3 Control mode transitions

To ensure that the BESS remains charged with sufficient energy to support downward ramping, the control system employs a state of charge control mechanism. When the BESS is not currently in use to support the controlled downward ramps, PV power is used to charge the BESS at a rate proportional to the deviation from a target level.

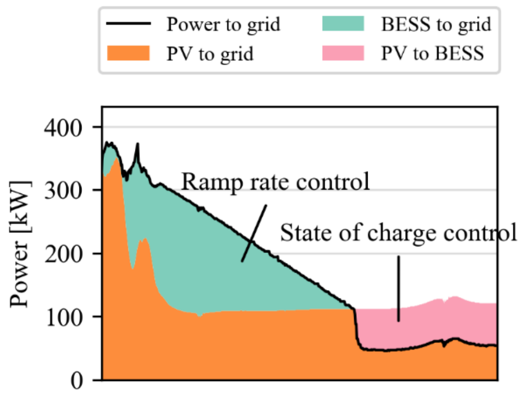

Figure 9. Example showing the impact of control mode transitions upon the effective ramp rate of the power station.

When the control system completes a controlled downward ramp, the transition from ramp rate control to state of charge control can result in an abrupt change in BESS power, and can cause fast ramp events. The resulting change is exacerbated if the BESS's energy is depleted and therefore charged at a faster rate. An example of this behaviour can be seen in Figure 9.

Although this phenomenon can result in unexpected deviations from the target ramp rate, these occasions were found to remain within or near the non-linearity bounds over the period examined. Nonetheless, the impact upon ramp rates due to the charging power level, and the method of state of charge control, should be given careful consideration by renewable energy system designers.

3.4 Operations and Maintenance

The ability of CPT to effectively detect and respond to occlusion events is influenced by the clarity with which data is processed via the cloud camera and processing unit. The CPT tower provides a ledge where animals, such as birds, can rest. This may result in a build-up of excrement and dust on the camera lens, which reduces the ability for effective detection and response. This has proven to be an issue and should be considered when deploying into geographically remote and/or isolated areas.

4 CONCLUSIONS

Notwithstanding occasional exceedances, the ramp rate control system at Karratha Airport has been successful in removing fast ramp events throughout its three-year operation, while keeping the total yield within 3% of estimated available power.

Based on analysis conducted on data from approximately three years of operation, adjustments to the control system have resulted in the cloud prediction technology having a reduced role providing the support required to ensure that the downward ramps are kept within the constraints outlined in Horizon Power's technical requirements. These adjustments have placed greater responsibility upon the BESS, resulting in the BESS discharging nearer to its maximum power rating.

Nonetheless, less than 2% of all PV-generated energy flowed through the two independent BESSs, and the depth of discharge rarely exceeded 40%. The BESS inverter's maximum power was found to be a limiting factor on multiple occasions, indicating that some fine-tuning of the curtailment set point is required in order to avoid constraint exceedances.

Developers seeking to incorporate cloud prediction technology into ramp rate control systems should carefully weigh the risks and costs associated with false negative predictions when determining the appropriate sizing. While hybrid approach can provide a cost benefit over BESS-only solutions, the degree of this benefit depends heavily on the forecast reliability, and upon the frequency of false-negative predictions that can be admitted within the network rules.

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