An analysis of storage requirements and benefits of short-term forecasting for PV ramp rate mitigation

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***Abstract*— As renewable energy penetration on the grid increases, requirements are being placed on PV owners and operators to limit power ramp rates. PV power ramping is an issue for grid stability since generation-load balance must be continually met, and when a large PV resource significantly increases or decreases, another resource must compensate to ensure matching. Traditional dispatchable resources have a limited ability to respond quickly. Therefore, to aid in grid stability, ramp rate limitations are imposed on PV plants. This work addresses the question of how much fast-responding storage is needed to mitigate high ramp rates of PV plants, and how much benefit is there from short-term power forecasting in terms of reducing the storage requirement. The results provide a baseline estimate for system planners and designers. Furthermore, the storage controller design and optimization is given, along with the open-source code, such that others can tailor the simulation to their specific plant and weather profile. Results from studying 100 MW PV plant power production profile show a reduction in ramp-rate violations from 10% of yearly intervals to below 1% with a storage rating of 12 minutes. With forecasting, the same level of smoothing can be achieved with a 5-minute storage device. Additionally, a sensitivity analysis shows how the storage requirements vary with different constraints, such as storage power rating, PV system size, forecast window length, and ramp-rate limit magnitude.**

Keywords—PV, ramp rate, control, storage, battery, forecasting

I. Introduction

PV power ramping is an issue for grid stability since generation-load balance must always be met and when a large PV resource significantly increases or decreases, another resource must compensate to ensure matching. Traditional dispatchable resources have a limited ability to respond quickly. Therefore, to address the concern, ramp rate limitations can be imposed on PV plants [1]. This work addresses the question of how much fast-responding storage is needed to mitigate high ramp rates of PV plants, and how much benefit is there from short-term power forecasting in terms of reducing the storage requirement.

The objective of the energy storage in this study is to provide smoothing, rather than firming. In smoothing, the storage limits the rate of change of power in order to buy time for the larger power system to respond In firming applications, the objective is to hold the power steady to a pre-defined value for specific periods of time, like 30 minutes to an hour. Firming is a more storage intensive objective than smoothing. In smoothing, short-term power forecasting on the order of 15 to 30 minutes can make an impact on the storage requirement by allowing the controller to anticipate and prepare for ramping events. In firming applications, longer-term forecasting, on the order of hours to a day, plays a significant role.

The objective of this work is to provide a baseline estimate of storage requirements for system planners and designers. Furthermore, the controller presented here is straightforward to understand and implement by planners and designers in their own simulations when different system constraints and weather patterns are considered. The code is posted publicly [2] and the controller is documented here. This fills an industry need as controllers designed and used by commercial storage providers are proprietary. While sophisticated commercial controllers will be able to achieve higher performance, the controller presented here is a reasonable baseline for PV system and grid designers to use.

II. Main Results

A. Problem Setup

The primary question addressed in this work is: how much storage is needed (in terms of energy and power) to smooth PV production and how much does forecasting reduce the storage requirement? To answer the question, a series of simulations are performed using data from a PV plant and simulating an energy storage system along with a controller. In each simulation, the controller utilizes the storage system to smooth the PV power, subject to the system constraints. When the storage system is unable to limit the PV power to stay within the ramp rate limitation, a violation occurs. The total number of violations over the simulation period is the metric used to measure storage effectiveness.

Ramp rates are defined in terms of the change in power from one interval to the next. In this study, intervals are 10 minutes. The ramp rate is calculated based on the discrete average of each interval, rather than a rolling average. Constraints that limit the storage device's ability to smooth are its energy capacity and power capacity. It has a finite energy capacity, and its energy state is represented by the state of charge. While we start off with a base case power capacity of the storage equal to that of the PV system, the power capacity is later reduced to assess the impact. The combined PV plus storage power cannot exceed the PV nameplate rating and cannot go negative (draw power from the grid). Finally, in the base case, PV power curtailment is not used as a method to limit up-ramps. Up-ramp curtailment is considered in the sensitivity analysis.

B. Controller Design

In designing a storage controller, the goal is to provide a reasonably effective, yet straightforward controller that can serve as a baseline for estimating the storage requirement for a given power profile. This controller is not necessarily optimal, yet it provides a useful baseline to which other controllers can be compared. The controller responds to incoming signals or measurements of the PV system power and the storage state of charge (SOC). Additionally, with the forecast option, the controller has knowledge of future PV power, 30 minutes ahead in the base case.

A proportional plus integral (PI) feedback controller is utilized to accomplish the control objectives. The controller seeks to track the PV power without exceeding the ramp rate limitation, while simultaneously bringing the SOC of the storage back to a nominal, resting value. By successfully tracking the PV power, the controller minimizes the amount of power sent into or out of the storage. By returning the storage back to a nominal SOC, the controller avoids unnecessarily operating the storage at near empty or near full, such that it is ready to respond to future ramps in either direction. Figure 1 shows a smoothing example from a variable day.

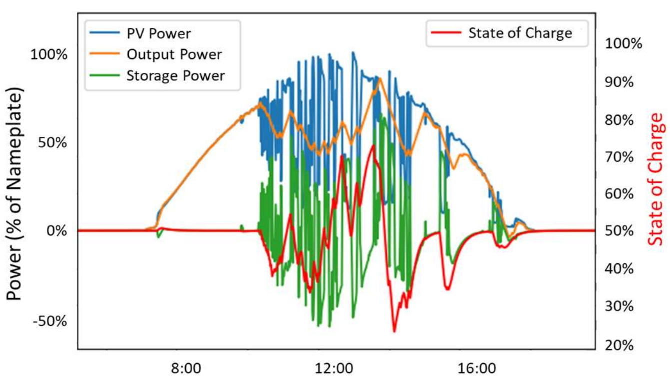

Figure 1. Example PV Power and Smoothing Profile for a Highly Variable Day

The output power tracks the PV power, but is limited in its rate of change. The state of charge is included with the corresponding secondary Y-axis. The SOC deviates from the resting state of charge of 50% throughout the day. Figure 2 demonstrates the influence of the integrator term. In this PV profile, smoothing in the morning causes the SOC to rise. Then while the PV returns to a smooth profile, the controller seeks to return the state of charge to the resting value.

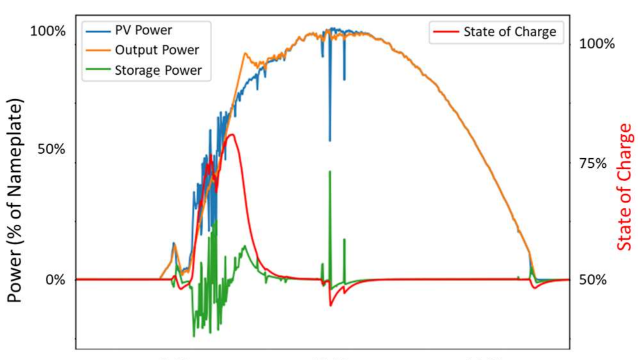

Figure 2. Example of State-of-Charge Recovery by Output Power Overshoot

This is accomplished as the output power overshoots the PV power for a short period to discharge the storage. To balance the proportional and integral terms, an optimization is performed on set of training data from the plant.

Short-term forecasting can improve the performance of a smoothing controller. If ramping is anticipated, the controller can begin to smooth before PV power changes by beginning to ramp the output power in the same direction as the anticipated PV power ramp. This is demonstrated in Figure 3. On the top, without forecasting, storage begins discharging at the point when PV begins to drop. The energy the storage expends to slow down the power drop is proportional to the shaded area, and the maximum power required by the storage is proportional to the vertical line. On the bottom, with forecasting, the controller can begin reducing output power by pre-charging the storage before the PV power drops. Once the PV power drops and crosses over the output power, the controller switches to discharging the storage to maintain the desired output power slope. At the end of the ramping event, the SOC is roughly the same as it was before since the storage both charged and discharged. The energy capacity requirement is proportional to one of the shaded triangles, and the power requirement is proportional to one of the vertical lines, whichever is larger in both cases.

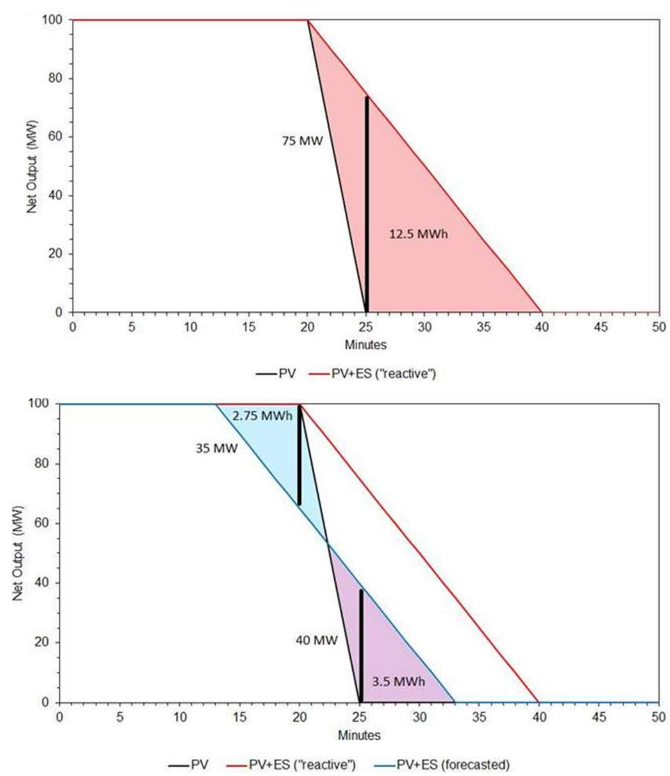

Figure 3. Example Showing Storage Energy and Power Utilization without Forecasting (top) and with Forecasting (bottom)

Forecasting is incorporated into the controller by adding a forecasting term in addition to the proportional and integral terms. The forecast accumulated error is another integral term, as it is proportional to the energy difference between the current output trajectory and the power forecast.

The four parameters in the controller (proportional, integral, forecast, and resting SOC) are system and location specific for optimal performance. A binary-search parameter optimization was implemented to find the best parameters for each simulation condition. The parameter optimization algorithm is included along with the full controller in the public repository, and both will be explained in greater detail in the full paper.

C. Results

In the following analyses, data was used from a 100 MW PV plant covering the span of a year. The results are specific to this PV system, weather patterns, and controller design. However, by providing the controller design and implementation code, others can perform the analysis on their own systems, locations, and grid requirements. Yearly violations are presented as a percentage of the total intervals for the year. Figure 4 shows the yearly violations for the "Base" controller and the "Base Forecast" controller as storage energy capacity increases. The forecast controller shows significantly improved performance over the base controller. Without forecasting, violations are nearly eliminated with 0.3 hours of storage (18 minutes).

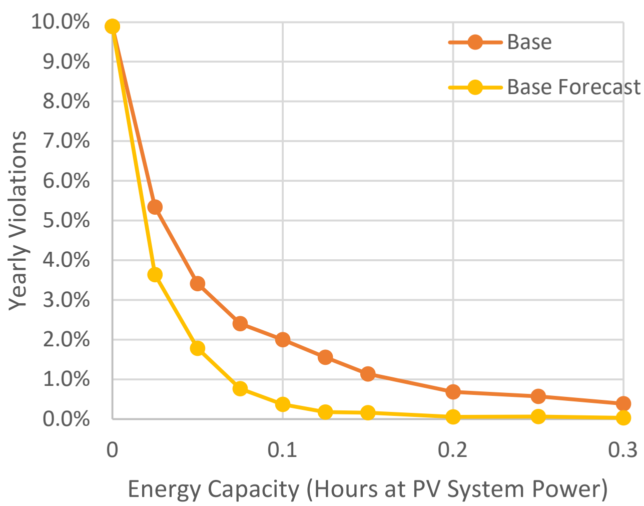

Figure 4. Ramp Rate Violations as a Function of Storage Energy Capacity

Figure 5 shows the effects of reducing the storage power rating from 100% of the PV system capacity down to 10%. There are minimal impacts until the storage power drops below around 20% of the PV system capacity.

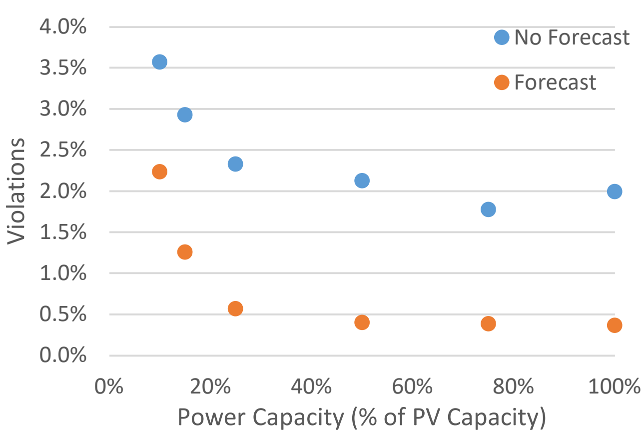

Figure 5. Effects of Varying Storage Power Capacity (0.1 hour energy rating)

Lastly, Figure 6 shows the impact of a varying ramp rate slope requirement. The number of violations increases nearly linearly as the ramp rate slope requirement is changed from 10% to 2.5% per interval.

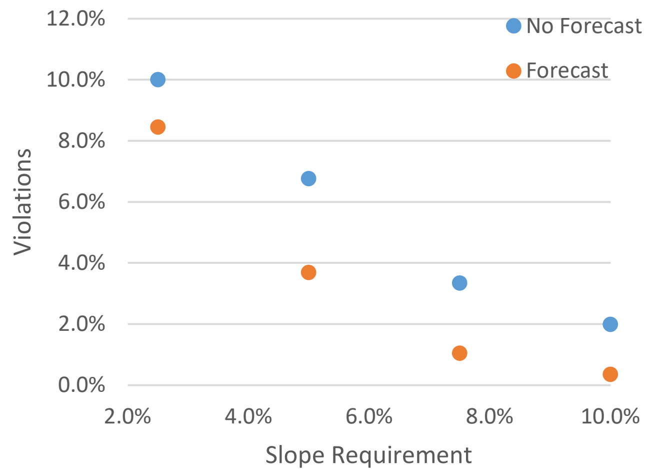

Figure 6. Effects of Varying Ramp Rate Slope Limit (0.1 hour energy rating)

Results from the full sensitivity analysis will be included in the full paper including the effects of a varying forecast window length, geographic smoothing, as in [3], and relaxation of the grid-charging and curtailment restrictions. The results corroborate what others have found that forecasting combined with up-ramp curtailment can nearly eliminate the need for storage altogether as in [4] and [5]

III. Summary

These results demonstrate that a relatively small amount of storage is necessary to achieve power smoothing compared to the storage requirement for other applications like firming and time-of-day shifting. Furthermore, short-term forecasting provides a substantial benefit for ramp rate mitigation.

This presented approach provides a baseline approximation for the storage requirements of ramp rate mitigation. This baseline is useful for system planners and designers. For this reason, the controller presented here is presently being incorporated into NREL's System Advisor Model

References

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