Hybrid Systems to Enable High Penetration PV

Preprint

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Hybrid Systems to Enable High Penetration PV

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***Abstract*—A model for PV plus energy storage and fuel cells was developed in the System Advisor Model (SAM). This model was used to evaluate the ramp rate and interconnection capacity factor for a hypothetical utility-scale plant for several configuration options. For PV only, the plant experienced 3345 violations of a 10%/minute ramp up limitation and a interconnection capacity factor of 17.6%. Adding a battery reduced the violations to 154 per year and the magnitude of the average violation to 2%. Adding a fuel cell to the PV system increased the capacity factor to 78% without improving ramp violations. Using a combined PV plus storage plus fuel cell arrangement maintained the improved capacity factor while reducing ramp up violations to 23, illustrating the potential to operate a hybrid system both to enable grid integration requirements and increase utilization of the interconnection.**

***Index Terms*—solar plus storage, fuel cell, SAM**

I. Introduction

As photovoltaic (PV) penetration increases, utilities face increasing challenges to integrate the variable generation onto their systems [1]. In certain regions, PV penetration has increased to a level where grid integration issues have become a primary concern, leading to more restrictive interconnection policies such as limiting plant ramp rates [2].

Reducing variability and shifting PV generation to times when the grid can accept it has become an important consideration in some highly penetrated markets, leading to a strong interest in the coupling of energy storage. Other devices such as fuel cells have been proposed as mechanisms for levelizing site output and work in conjunction with PV and storage devices to facilitate grid integration [3].

Considering a hybrid system presents challenges including answering whether fuel cells can be effectively combined with PV plus storage systems to reduce the variability of PV output and simultaneously increase the capacity factor of the utility interconnection.

The authors have developed a new hybrid system model in NREL's open-source System Advisor Model (SAM) [4] in collaboration with laboratory and utility PV, battery, and fuel cell modeling experts [5] to answer these questions [1], and more broadly examine how these technologies can work in concert to improve grid-integration in regions with high-penetrations of PV.

II. Methods

An AC-connected fuel cell model was developed to consider the case where the PV array and battery system can integrate with a fuel cell connected to a common AC circuit.

[1]Models are open-source at github.com/NREL/ssc and will be released in official SAM version at sam.nrel.gov in Fall 2019

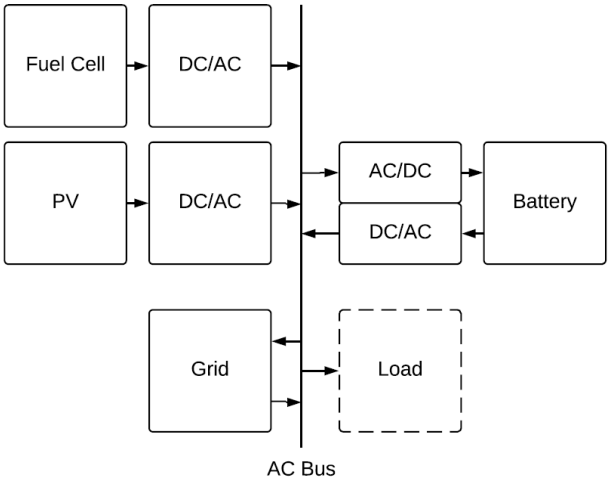

Fig. 1. PV plus Fuel Cell and AC-connected battery system diagram.

The model uses the PVWatts model coupled with SAM's detailed battery model.

A. System Configuration

The system is configured so the battery system integrates with the PV array on the AC side, as illustrated in Fig. 1. The dashed line around the load block indicates that this is an optional quantity that may not be present on utility scale plants. The grid block also is assumed to contain necessary power electronics (transformers) to step up the site voltage to the required interconnection voltage. In this configuration, the PV array and fuel cell produce DC electricity which is converted to AC power which can either meet the electric load, charge the battery, or export to the grid.

B. Hybrid System Model

The model follows the following steps, as outlined in Fig. 2. The fuel cell directly integrates with the PV and battery model, but can also operate without either system.

- Calculate PV generation using PVWatts [6], pass to fuel cell model.
- Calculate power to request from fuel cell based on dispatch strategy, PV generation and electric load
- Run fuel cell. Limit power based on fuel-cell dynamic response properties, minimum and maximum power delivery limits, and fuel available.
- Pass net system generation to battery model
- Calculate power to request from battery based on battery dispatch strategy, net generation, and electric load

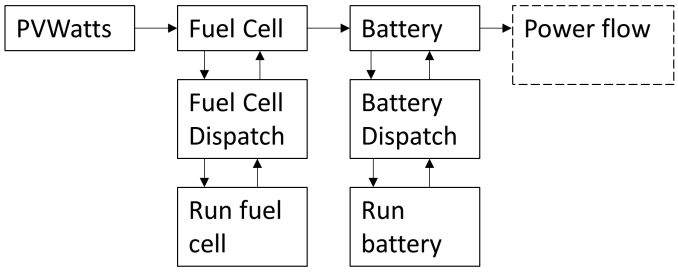

Fig. 2. Model flow

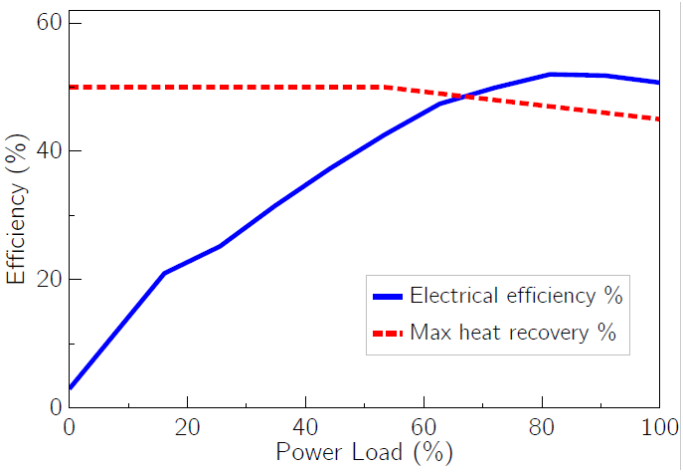

Fig. 3. Fuel cell efficiency

- Run battery. Limit power based on state-of-charge, electrical constraints.
- Calculate final power flow quantities, including how much of each component went to the load, grid or battery.

Steps for fuel cell dispatch and fuel cell operation will be elaborated in the following sections.

C. Fuel cell representation

The fuel cell model is a linear model which requires inputs of the electrical efficiency and heat recovery as a function of power load as shown in Fig. 3. Through this representation, the model can represent multiple types of generators, including Solid Oxide, Molten Carbonate, Phosphoric Acid, or Proton Exchange Membrane fuel cells. The electrical efficiency governs how much fuel has to be used to provide the desired power. The model is flexible enough to consider many of the complexities of fuel cell operation, including dynamic ramping up/down limitations, startup and shutdown limits and operational degradation.

D. Fuel cell dispatch

To choose how to operate the fuel cell, several dispatch options were devised. The power of the fuel cell P_t is calculated at each time step according to the strategies specified below:

1) Fixed output: This strategy operates the fuel cell with a constant power output indefinitely, according to the nameplate P_{max} capacity, and percentage at which to operate p_{fixed}, as in Eq. (1).

$$P_t = P_{max} * p_{fixed} \tag{1}$$

2) Follow electric load: Ramps the fuel cell to offset the electric load P_l, considering the PV generation P_{pv}, as in Eq. (2).

$$P_t = max(0, P_l - P_{pv}) \tag{2}$$

3) Manual dispatch: Allows specification of what power level to operate at different times. At each time, the model checks for a boolean value of whether the fuel cell can operate b_d, and if so, at what power percent p_d, to calculate the power in Eq. (3).

$$P_t = b_d * p_d * P_{max} \tag{3}$$

4) Input dispatch: Allows a custom power signal input P_i, derived from other sources, as in Eq. (4).

$$P_t = P_i \tag{4}$$

E. Operational Contraints

While the electric power in each step is set by the dispatch strategy in Eq. (1 - 4), the fuel cell is constrained based on chemistry, such that the power delivered in any time step is restricted to meet physical limitations in the device. The fuel cell power is first limited by the startup time t_s. Whether the fuel cell is started is represented by boolean b_s. The target power is modfied in Eq. (5).

$$P_t* = b_s \tag{5}$$

Dynamic response limits, ramping up and down, are also considered. The ramp rate dP_t is calculated with current and former power level P_t, P_{t-1}, and the time step dt in Eq. (6). The power level is modified to satisfy the ramp rate limit dP_{max}, in Eq. (7):

$$dP_t = \frac{P_t - P_{t-1}}{dt} \tag{6}$$

$$P_t = min(abs(dP_t), dP_{max}) \tag{7}$$

Fuel cells and other types of generators have minimum levels at which they can operate P_{min}. If a fuel cell is not in the process of shutting down, the power signal is contrained this minimum turn-down level in Eq. (8). Similarly, if the power output is higher than the maximum power level, it is contrained by Eq. (9).

$$P_t = max(Pt, P_{min}) \tag{8}$$

$$P_t = min(Pt, P_{max}) \tag{9}$$

The fuel cell model considers degradation of the stack as it operates which translates to a reduction in maximum power output. To consider the effect of degradation on the power target, the degraded max power $P_{max,deg}$ is initialized to P_{max} at the beginning of the simulation and updated at every time step considering a fixed degradation rate per hour of operation P_d, as in Eq. (10). The fuel cell power is updated to ensure that it is not operating above this maximum, in Eq. (11).

$$P_{max,deg} = P_{max,deg} - P_d \tag{10}$$

$$P_t = min(Pt, P_{max,deg}) \tag{11}$$

F. Heat and Fuel Consumption

The fuel cell operates as a combined heat and power device. The heat P_h generated by the fuel cell at any timestep is calculated using the heat recovery percentage $p_h r$ as a function of power load p_l, from Fig. 3. The heat is calculated in Eq. (12).

$$P_h = P_{max,deg} * p_{hr} \tag{12}$$

The fuel consumption fc at any time step is calculated in Eq. (13) using the electrical efficiency p_e as a function of power load, from Fig. 3 as well as the ratio of higher heating value HHV to lower heating value LHV.

$$fc = \frac{p_l P_{max}}{p_e \frac{HHV}{LHV}} \tag{13}$$

III. Results

A. Ramp rate control scenario

To illustrate the utility of the hybrid-system model, a hypothetical small utility scale plant was developed near Los Angeles, CA using 1-minute irradiance data. For this case-study, it was assumed that there was an interconnection requirement limiting ramps of 10% of the PV system capacity per minute (90 kW/min). Four scenarios were considered.

1) PV only: The PV system installed was assumed to be 900 kW with a 1.2 DC/AC ratio.

2) PV plus storage: A 500 kW / 1000 kWh lithium-ion storage system was added to the PV system and programmed to charge and discharge to reduce PV ramping up and down events.

3) PV plus fuel cell: 900 kW of Solid-Oxide fuel cells were added to the PV array with the strategy of discharging at full capacity in hours where there was no PV generation, and turning down during PV production hours. The primary goal of installing the fuel cell was to increase the capacity factor of the site while staying under a fixed interconnection limit. The fuel cells were assumed to have a ramp limit of 250%/hr of nameplate capacity, 37.5 kW/min.

4) PV plus fuel cell plus storage: The PV, storage, and fuel systems were combined into one plant, with the goal of providing a high capacity factor resource with ramp rate control.

B. System Operation

The maximum system ramp rate up/down in kW/min was calculated in 14.

$$RR_{max} = P_{pv,nameplate} * 0.10 \tag{14}$$

$$RR(i) = |\frac{dP}{dt}(i)| = |\frac{P(i) - P(i-1)}{t(i) - t(i-1)}| \tag{15}$$

$$P_{battery} = RR_{max} - RR(i) \tag{16}$$

$$P_{battery} = -RR(i) - RR_{max} \tag{17}$$

A simple ramp rate smoothing strategy was adopted from established sources [7]. The system ramp rate was calculated as in 15. In the event that $RR(i) > RR_{max}$, the battery was scheduled to charge according to 16, using the convention that negative power implies charging, while positive power implies discharging. If $RR(i) < -RR_{max}$ the battery was scheduled to discharge according to 17. This simple strategy does not result in perfect smoothing and is limited by the power capacity and state-of-charge limitations of the battery. Additional work could be completed to integrate a forecast and selectively operate the battery to maintain the capacity required to charge or discharge during ramp violation events.

C. Interconnection Capacity Factor

For a hybrid system, one of the presumed benefits is increasing the utilization of a fixed grid interconnection point. To quantify this utilization, the capacity factor of the interconnection is given in 18, where N are the total time steps in an annual simulation, Δt is the time step in hours, $P_{interconnect}$ is the interconnection limit and $P(i)$ is the power produced by the hybrid system during a time step. Excess production above $P_{interconnect}$ is assumed to be curtailed.

$$CF_{interconnect} = \frac{\sum_{i=1}^{N} P(i)\Delta t}{P_{interconnect} N \Delta t} \tag{18}$$

IV. Discussion

A high variability solar day was chosen to illustrate ramp rate challenges at a PV plant. Fig. 4 shows the raw PV system output and the system output where ramps violating the interconnection requirement are smoothed by a storage system.

The addition of a fuel cell to the PV system with and without storage is illustrated in Fig. 5. The fuel cell provides a constant output at night and ramps down as PV production begins to pick up in the early morning hours. Adding storage results in a smoothed signal.

Table I shows the key results. The PV-only scenario shows a low capacity factor accompanied by multiple ramping

TABLE 1

ANALYSIS RESULTS

Variable	PV Only	PV+Storage	PV+Fuel Cell	PV+Fuel Cell+Storage
Year 1 Capacity Factor	17.61%	17.60%	78.10%	77.36%
Year 1 Ramp Up Violations	3345	154	3341	20
Average up violation	73.4 kW/min	1.84 kW/min	73.4 kW/min	7.02 kW/min
Average up violation %	81.5%	2.04 %	81.6 %	7.80 %
Year 1 Ramp Down Violations	3195	519	3199	95
Average down violation	-72.6 kW/min	-2.71 kW/min	-72.7 kW/min	-2.26 kW/min
Average down violation %	-80.7%	-3.01 %	-80.7 %	-2.50 %

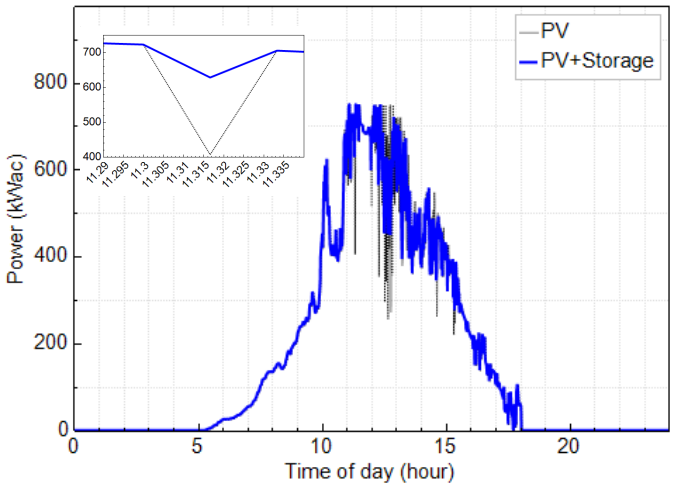

Fig. 4. June 19 system production. Inset: Zoomed in view of ramp down event

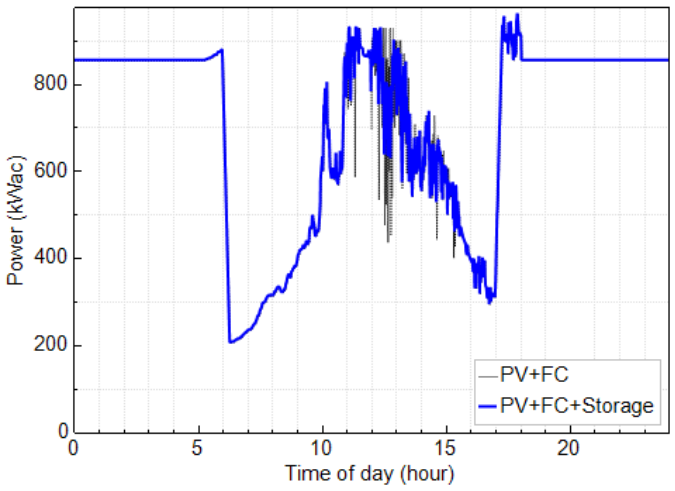

Fig. 5. June 19 system production with fuel cell added

violations, where each violation averages about 80% above the desired limit. Adding a battery reduces these violations significantly, and reduces the average violation to about 2% above the desired limit. This illustrates that the ramp rate smoothing control implemented for this study works well, but not perfectly. Violations result due to limitations in battery state-of-charge to provide charge or discharge at a desired time step.

Adding a fuel cell to the PV system results in a significant boost to the interconnection capacity factor, but does not affect ramping violations under this strategy. Adding a battery to the PV plus fuel cell system reduces ramp violations while maintaining the higher plant capacity factor.

This example case study illustrates that combining a PV plus storage system with a rudimentary ramp-rate control algorithm can significantly reduce the number and magnitude of ramping violations for a system under interconnection restrictions. The analysis also shows that adding a fuel cell to the PV system can significantly increase utilization of the interconnection. Adding a fuel cell to the PV system shows no impact on the ramp rate violations in this case, though additional work could be done to study integration of PV with fuel cells designed with fast dynamic response capabilities and develop more sophisticated methods to operate the hybrid system. Adding a battery to the PV plus fuel cell system illustrates the potential to derive multiple benefits, achieving both a higher plant capacity factor and limiting ramp rate violations and their magnitude.

V. SUMMARY

The work presents a model for PV plus fuel cells plus batteries within an open-source tool, enabling complex hybrid system modeling in support of grid-integration analysis. This model was used to examine the plant capacity factor and ramp rate violations for four scenarios. Adding a fuel cell was found to increase the capacity factor, while adding a battery with or without a fuel cell was required to mitigate ramping violations, indicating that different hybrid system components may be used for different goals in a grid integration scenario.

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