Grid-Tied PV System Energy Smoothing

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ABSTRACT

Grid-tied PV energy smoothing was implemented by using a valve regulated lead-acid (VRLA) battery as a temporary energy storage device to both charge and discharge as required to smooth the inverter energy output from the PV array. Inverter output was controlled by the average solar irradiance over the previous 1h time interval. On a clear day the solar irradiance power curve is offset by about 1h, while on a variable cloudy day the inverter output power curve will be smoothed based on the average solar irradiance. Test results demonstrate that this smoothing algorithm works very well. Battery state of charge was more difficult to manage because of the variable system inefficiencies. Testing continued for 30-days and established consistent operational performance for extended periods of time under a wide variety of resource conditions. Both battery technologies from Exide (Absolyte) and East Penn (Advanced Valve Regulated Lead-Acid) proved to cycle well at a partial state of charge over the time interval tested.

INTRODUCTION

The PV output from a grid connected array can change rapidly because of the movement of overhead clouds. In some cases, for example when a large PV system is connected to a relatively small grid or at the end of a weak feeder, rapid output power change can make it difficult to regulate voltage and frequency. The response time of steam turbines and other forms of generation can be too slow to mitigate the power fluctuations. It is possible to locally mitigate the effects of PV output variability using onsite energy storage. Effective PV energy smoothing requires an energy storage system that is integrated into the inverter and control system that will source and sink energy as the PV array power fluctuates according to the available solar resource. This mode of operation requires the energy storage system to operate at a partial state of charge (PSOC). The PV energy smoothing system described in this paper and shown in Figure 1 uses the battery at about 50% state of charge (SOC) and the energy in and out of the battery is determined by the average solar irradiance over a 1h time interval. On a clear day the solar power sold to the grid will be offset by about 1h. On a variably cloudy day the power curve will be smoothed based on the average solar irradiance and the battery capacity will be returned to the same state of charge at the end of the day as at the beginning of the day. Because battery energy is only used to smooth the PV array output, battery capacity can be relatively small. In this case model calculations indicate that battery capacity can be as low as 143 Ah at 48 volts for 3.5 kW of PV assuming a maximum DOD of 25%.

The intent of the energy smoothing algorithm is to reduce the rate and amount of fluctuations from the output PV power to meet utility requirements. Specifications for the 1.2 MW PV system at Lana'i in Hawaii require ramp rates of less than 6 to 60 kW/s depending on the time of day [1]. Modeling and Laboratory testing at Sandia National Laboratories Distributed Energy Technologies Laboratory (DETL) has shown that the ramp rates can easily exceed these values.

Figure 1: Grid-tied PV energy smoothing system.

The PSOC mode of battery operation is potentially very damaging to conventional valve regulated lead-acid (VRLA) batteries because of the formation of hard sulfation on the battery plates. In this test two battery types, the Absolyte from Exide and the carbon enhanced advanced VRLA from East Penn were used to evaluate their performance. The carbon enhanced VRLA technology has only recently been made available as a result of the Advanced Lead-Acid Battery Consortium (ALABC) development work directed at designing lead-acid batteries for use in hybrid electric vehicles [2,3]. The ALABC battery technology is now available through East Penn Manufacturing in a large industrial VRLA format [4]. The Absolyte battery technology has a long history in cycling solar and utility applications [5].

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Laboratory testing at Sandia National Laboratories Distributed Energy Technologies Laboratory (DETL) has demonstrated that the new carbon enhanced advanced VRLA battery technology can tolerate the PSOC cycle operation more than ten times that of conventional float service VRLA batteries. Thus, the cost of energy storage for grid-tied PV systems can be significantly less because of the improved cycle-life.

The main challenge for the future will be to integrate all of the control functionality into the inverter to average irradiance, use the average irradiance to calculate inverter output, compensate for efficiency losses and manage the battery when the required recovery and discharge to 50% SOC is necessary.

ENERGY SMOOTHING ALGORITHM

The primary variable to determine how much energy to sell is the running average of the solar irradiance. This value is then multiplied by a scale factor and used to set the sell energy from the inverter. This delays and smoothes the output power and prevents fast power spikes to the grid. The longer the running average, the smoother the energy delivered, but it also requires more battery storage capacity. If the scale factors are set properly, the inverter will sell approximately the same amount of electricity back to the grid as without the smoothing control.

The second control variable is based on the battery capacity and the state of charge. Using irradiance alone does not guarantee the battery will remain in any particular state of charge, if the scale factor settings are too high or low the battery will tend to fully charge or discharge and thereby no longer be capable of delivering or absorbing power for smoothing. To keep the battery SOC centered, the charge level is calculated by the data acquisition system. A proportional gain is applied to the difference between the 50% charge point and the current charge level and added to the irradiance power output to obtain the current sell power. The proportional gain means that if the battery is close to 50% charged, then only the running average irradiance is significant for controlling the inverter. When the battery is highly charged, it will sell extra energy and when it is low it will sell less energy than using just the running average irradiance as the control. This tends to slowly and smoothly help center the battery to the 50% charge level where it may either deliver or absorb any transient power spikes.

$$\textbf{Inverter Output Watts} = (I_r \times K_i) + (C_l - C_{50\%}) \times K_s$$

I_r = Running Average Irradiance in W/m^2
K_i = Constant (Irradiance Scale Factor)
C_l = Measured Battery Charge Level in Wh
$C_{50\%}$ = Battery Charge at 50% in Wh
K_s = Constant (Battery Charge Scale Factor)

Finally, battery voltages are monitored by both the inverter and the Data Acquisition System. If any voltages go out of bounds the system is safely shut down by removing the contactors to the inverter with the problem and prompts the user to remedy the issue before proceeding. This prevents failures or unforeseen situations from over or under charging the batteries during the experiments.

SYSTEM DESIGN

To demonstrate the power smoothing capability two systems were implemented and controlled with a virtual energy management system (EMS) that was programmed in LabView. The EMS controls the output to the utility by averaging the irradiance value and will subsequently smooth out the fast variations that are experienced during cloudy conditions. Each of the two battery based grid-tied PV energy smoothing systems consisted of the same equipment except for the batteries. The two PV grid-tied systems have 3.2 kW_{STC} of Shell Solar SQ80 modules, a Xantrex XW6000 inverter, a 3kW Xantrex charge controller, a Xanbus link with Ethernet bridge, and LabView EMS with data acquisition that is used to monitor and control the performance of each system according to the power smoothing algorithm setpoints. The only system differences are the 300 Ah Absolyte Exide battery and the 300 Ah carbon enhanced advanced VRLA battery from East Penn.

TEST PROCEDURE

Prior to conducting the power smoothing tests a detailed laboratory characterization of both VRLA batteries was conducted. Each VRLA battery had an initial capacity characterization evaluation performed before undergoing a month's worth of energy smoothing operation. After the capacity test, the batteries were received at a full state of charge; therefore the first operation required the batteries to be discharged to 50% state of charge. Once the batteries were discharged the power smoothing cycling begins. During this operation the batteries are subjected to PSOC-cycling that corresponds to the irradiance conditions for that day. The LabView based virtual energy management system will only sell enough PV power to the utility to keep the batteries at the desired PSOC. At night the inverters are a load on the batteries so for the next day of operation a small amount of extra charging of the batteries is required.

During the month long operation monitoring the state of charge is essential to the performance of the system and the health of the battery. A properly set power smoothing algorithm should maintain the 50% PSOC through the entire cycling period but an adjustment was made to maintain the desired level, which is an indication that system inefficiencies were not properly compensated for.

TEST RESULTS

A common assumption about battery based utility interconnected PV inverters is that the system will help alleviate the intermittency issue associated with cloud cover, but this is not the case and the following data shows that prior to implementing the power smoothing the output power from these battery based systems is directly correlated to the irradiance level. The battery based utility interconnected PV inverter's output is dependant on irradiance and temperature conditions. The inverter output tracks the output of the photovoltaic array as can be seen in Figure 2. The high ramp rates that result can lead to stability concerns in weak grids or in high penetration regions.

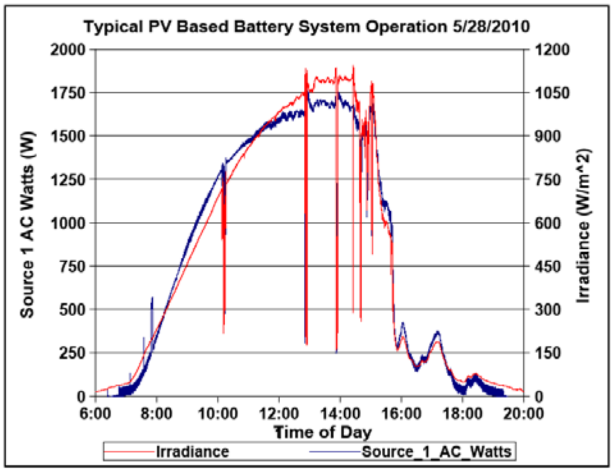

Figure 2: Battery based utility interconnected PV inverter operation during cloud cover.

Initial energy smoothing work based on computer modeling indicated that battery size could be relatively small to achieve significant energy smoothing. The model was based on an irradiance profile generated from a sine function and adjusted as required by output factors from 0.1 to 1. This number was then multiplied by the array size in watts to achieve the simulated power output. The time interval was 2 seconds with the assumption that the array did have the ability to go from full power to 10% power in that time interval. Battery energy requirements and power rate of change in W/s were calculated as a function of the change in time and power. The results are in Table 1 and show that dramatic smoothing can be achieved with a 15 min irradiance averaging interval and a small 37 Ah battery. Because of the power limitations of the battery, the practical size of the battery needs to be sized so that it does not exceed the 1h discharge rate of the battery. This size limitation is to prevent over heating and in this case a 3.5 kW PV array at 48V would require about 73 Ah of battery capacity. At the 1h irradiance smoothing interval the ramp rate at 0.875 W/s is about $1/4^{th}$ that of a 15 min. smoothing interval. The minimum battery size for the 1h interval is 143 Ah based on a maximum daily DOD of 25% of the total battery Wh capacity.

Both batteries underwent an initial and final capacity test at Sandia National Laboratories Power Sources Technology group using programmable battery testers designed for large industrial batteries. In Table 2 are the battery specifications and initial and final capacity measurements. The results show that both batteries increased in capacity slightly by about 5 to 13%. This is very encouraging and indicates that with proper battery management battery life should be good.

Table 1: PV energy smoothing model results for a 3.5 kW PV array.

Irradiance Smoothing Interval (h)	Minimum Battery Size (Wh)	Minimum Battery Size (Ah @ 48V)	Max Power Ramp Rate (W/s)
1.00	6,840	143	0.875
0.50	3,488	73	1.75
0.25	1,756	37	3.5
0.00	NA	NA	1,575

Table 2: Battery specifications and test results.

Battery	Cell#	Specification Ah @ 8h rate (43A & 48A)	Capacity Initial Ah @ 100A rate	Temp °C	Capacity Final Ah @ 100A rate	Temp °C
Absolyte Type GP #90G09	1 to 12	344	274	31	288	31
	13 to 24	344	272	31	296	31
East Penn ALABC Advanced #95-09	1 to 12	380	307	28	326	32
	13 to 24	380	291	28	330	33

Implementing the power smoothing algorithm can have a beneficial effect by energy shifting the output from the PV system and providing power during a more peak load time of the day. The following plot in Figure 3 shows the inverter output and the irradiance during a full day of operation. The results verify that the battery is operating close to a 50% SOC Wh capacity and selling PV power to the utility.

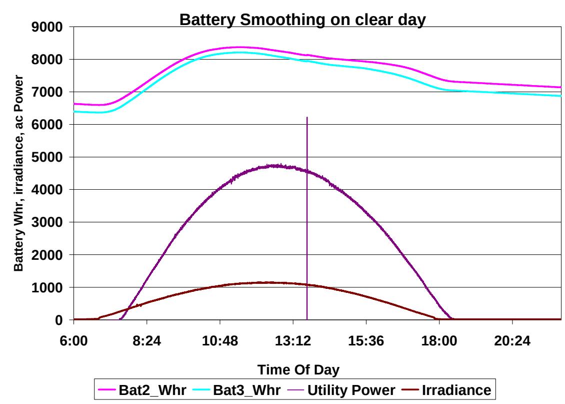

Figure 3: Power smoothing algorithm operation during clear day.

During a cloudy day, the smoothing algorithm will reduce the rapid energy variations as shown in Figure 4. The energy sold to the utility in Figure 4 is dramatically smoothed during the dynamic irradiance conditions. Notice the rate of change is low and the utility interaction during this type of variation would be minimal as compared to the stability of a high penetration situation without smoothing.

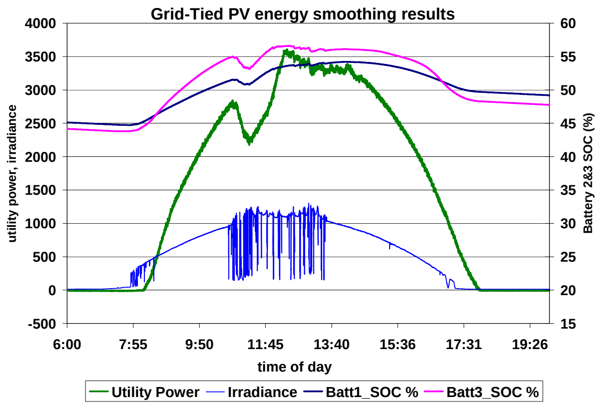

Figure 4: Energy smoothing algorithm operation during cloudy day.

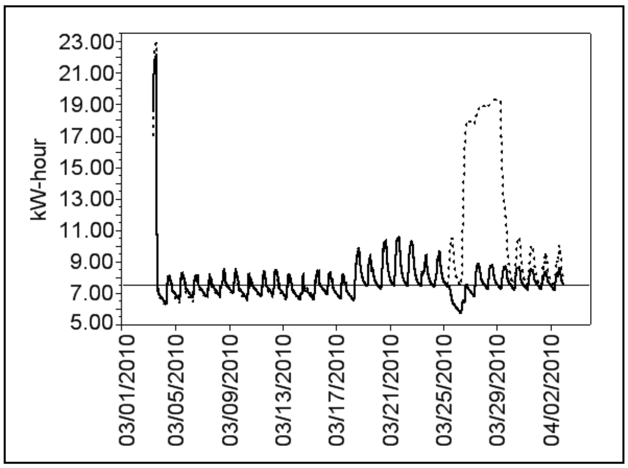

Figure 5: Battery Wh capacity over 30-day test period for both batteries.

The energy smoothing algorithm requires the battery to be at a PSOC so energy can flow in and out of the battery as needed during dynamic irradiance conditions. Operating the battery at a PSOC does present the system with the challenge of maintaining the battery at 50% SOC over repeated cycles. To accomplish this task it is necessary to keep accurate energy or Ah measurements and to include compensation factors in the control algorithm to accommodate small inefficiencies in the inverter and battery.

In Figure 5 and 6 are 30-day energy (Wh) and capacity (Ah) measurements. The results show that under constant energy (Wh) control, the Ah capacity was slowly drifting downward as a result of the higher inefficiencies that are inherent in controlling battery capacity using Wh vs. Ah control. The solution to this problem would be to control the battery SOC using Ah counting, thus the battery would stay much closer to the intended 50% Ah SOC. Also shown in Figure 5 and 6 is a full charge on one of the batteries near the end of March. This was caused by a system fault and the battery was promptly returned to 50% SOC.

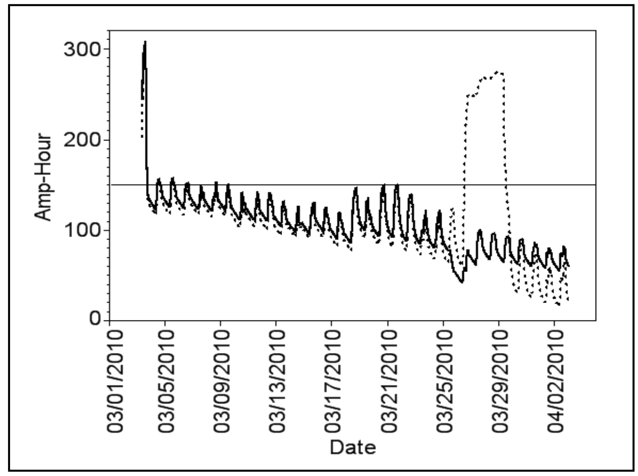

Figure 6: Battery Ah capacity over 30-day test period for both batteries.

Based on the daily maximum Ah DOD, which was measured at between 30 and 50 Ah, the minimum battery capacity should be between 120 and 200 Ah. This agrees reasonably well with the modeled capacity requirement of 143 Ah.

SUMMARY

The work presented in this paper has demonstrated that all of the basic components of a grid-tied PV energy smoothing system are available and can be implemented to construct the system. The biggest obstacle to overcome will be the integration of the energy control algorithm into the inverter and the battery management functions required to operate the energy smoothing system.

Test and model results have shown that the irradiance averaging algorithm has worked well and requires only a relatively small battery to accomplish its function. In addition, the new cycling VRLA batteries from East Penn and Exide have proven to both cycle well with a slight capacity gain based on one month of operation. This is an indication that battery life may be good for many years. Based on the above initial results, PV grid-tied energy smoothing looks to be very achievable and at a reasonable cost.

ACKNOWLEDGMENTS

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