Low-cost solar micro-forecasts for improving the efficiency of PV farm output smoothing.

Andrea Mammoli, *Member, IEEE*, Anthony Menicucci, Abraham Ellis *Member, IEEE*,Thomas Caudell, Steve Willard, and John Simmins, *Member, IEEE*

DISTRIBUTION-LEVEL photovoltaic (PV) farms are becoming increasingly attractive for utilities to meet renewable portfolio standards. These installations, typically with peak power ranging from 0.5 MW to 2 MW, are generally cost-effective, and can be deployed in a matter of months, without lengthy transmission interconnection delays. Siting PV at a single location provides economies of scale in comparison to residential PV, and allows the utility to control and maintain the resource more effectively. However, because the PV array is contained within a small geographic area, it is more susceptible to cloud-driven intermittency than either large ($>$ 100 MW) installations, or residential roof mounted installations of equivalent capacity. Batteries are sometimes deployed to offset power quality problems due to cloud-driven intermittency. The present work is based on the experience from the deployment of a 500 kW PV farm with 1.5 MWh total smoothing and shifting batteries, located in Albuquerque, New Mexico [1]. An aerial view of the plant is shown in fig. 1.

Fig. 1. Aerial view of the 0.5 MW Prosperity PV plant with battery storage. The plant occupies approximately four acres (16,000 m^2). The shifting and smoothing batteries are in the white containers.

This work was supported by the Electric Power Research Institute under contract number EP-P32412/C1504.

A. Mammoli is with the Center for Emerging Energy Technologies at the University of New Mexico, Albuquerque, NM 87131 USA e-mail: mammoli@unm.edu

A. Menicucci is with the Department of Mechanical Engineering at the University of New Mexico, Albuquerque, NM 87131 USA

A. Ellis is Sandia National Laboratories, Albuquerque, NM 87131 USA

T. Caudell is with the Department of Electrical and Computer Engineering at the University of New Mexico, Albuquerque, NM 87131 USA

S. Willard is with PNM Resources, Alvarado Square, Albuquerque, NM 87158 USA

J. Simmins is with the Electric Power Research Institute, 942 Corridor Park Blvd., Knoxville, TN 37932

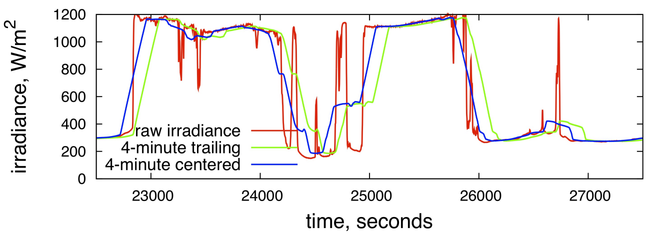

Fig. 2. Solar irradiance signal sampled at 1-second interval (red), and smoothed with a trailing window (green) and with a centered window (blue) using a 4-minute window.

A 500 kWh subset of the battery system, capable of delivering up to 500 kW of power, is used to offset cloud-driven variability, by delivering power when clouds suddenly occlude the sun, and by absorbing power when the sun re-emerges. The magnitude of the power delivered or absorbed by the batteries is based on the difference between the instantaneous power produced by the PV farm, and an underlying ‘smooth’ power. The smooth signal is calculated either by using a moving average of the the real-time power production [2], or by a low-pass filter. The size of the moving average generally ranges from one minute to approximately thirty minutes. The raw signal, and moving averages obtained with a sliding windows of 4 minutes are shown in Fig. 2.

The moving averages are calculated using a window trailing the real-time signal, and using a window of the same size, but centered on the real-time signal. The trailing window signal lags the centered window signal by a time equal to half the size of the window, but is otherwise identical. To ensure that sufficiently smooth power is delivered to the grid, the power corresponding to the difference between the real-time irradiance and the averaged irradiance must be supplied by the batteries. It is evident from inspection of the plots that the difference between real-time irradiance and average irradiance is generally smaller for the case of the centered sliding window. Thus, using a centered sliding window, the requirement on the batteries would be smaller.

While the batteries are designed for this duty cycle, their lifetime is nevertheless a function of the total energy absorbed or delivered. If it were possible to used a centered window, the lifetime of the smoothing batteries could be extended substantially. This is illustrated in Fig. 3. While the power delivered by the batteries using a centered 4-minute window comparable to the power delivered by batteries using a trailing window, the energy drawn or stored is approximately 100

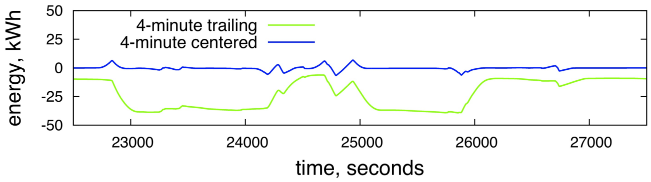

Fig. 3. Energy balance for a smoothing battery using a trailing (green) and centered (blue) moving average as a reference signal.

Fig. 4. Typical near-infrared image of clouds surrounding the sun. Note that the solar disk is well-defined, as are the edges of the surrounding clouds.

times smaller, corresponding to a longer lifetime.

The problem is that, in the field, only data for past events are available, so that only a trailing sliding window can be used. The object of the study reported here is to provide a short-term prediction for the future (a micro-forecast), at very low cost, making it possible to use a centered window.

The importance of short-term cloud predictions, as well as means to obtain them, have been reported on elsewhere [3]. Because of the emphasis on minimal cost, here it is assumed that a simple, shadowband-less fixed camera using Si-based charge-coupled device (CCD) technology is used to obtain the prediction. Forward-looking infrared (FLIR) imaging was considered as an option, but is very expensive. Si-based CCDs are sensitive to near-IR, an in fact a short-pass filter is commonly placed in front of the CCD to only allow visible-range photons. When taking images centered around the sun, without a shadowband, there is intense glare from the sun, the sun's image bleeds through to the pixels around the sun's disk, and in addition, there is atmospheric scattering around the solar disk, making it very difficult to clearly see clouds that are approaching the sun.

By using a long-pass filter, it is possible to eliminate the visible range entirely from the image projected onto the camera's CCD, along with some of its undesirable side-effects, including glare and atmospheric scattering. It is in fact possible to obtain clear images of the solar disk and of neighboring clouds. An example of such an image is shown in Fig. 4.

If the sun is not occluded, approaching clouds can be distinguished. Similarly, in a field of dark clouds, an opening in the cloud cover can be seen before it reaches the sun. To illustrate the principle, the pixel intensity along a line in the direction of cloud motion passing through the sun was obtained for a series of images spaced ten seconds apart.

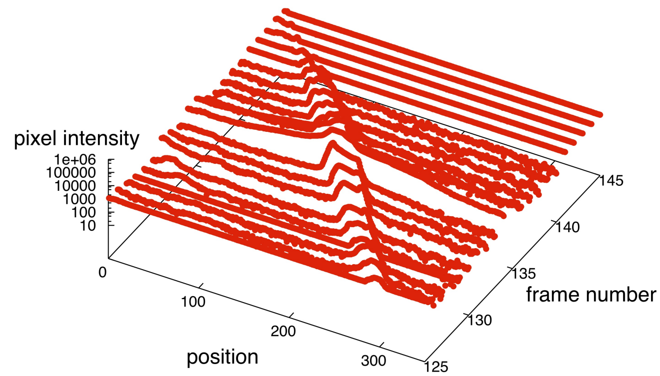

Fig. 5. Pixel intensity along a line in the direction of cloud motion passing through the sun, for a series of 20 frames spaced 10 seconds apart. An opening in the cloud cover approaching the sun can be seen moving from left to right, coinciding with the sun around frame 135, position 180. The opening can be seen receding after this.

This is plotted in Fig. 5. The movement of an opening in the cloud cover can clearly be seen, first approaching the sun, then receding. The approaching and receding break in cloud cover can be observed at least 60 second before and after its coincidence with the location of the sun.

Having established the possibility of detecting changes in cloud cover, it becomes necessary to develop a tool to interpret the images and provide a forecast, possibly associated with a measure of reliability. In keeping with the stated requirement of cost-effectiveness, the image processing must be carried out with relatively small processing power, such as might be available, for example, in a camera-equipped 'smart phone'. To this end, a neural network based on Adaptive Resonance Theory was applied to associate a particular cloud pattern with an irradiance value 60 seconds later [4]. This class of networks is know for its ability to learn quickly, as well as for its ability to refine its knowledge in the field [5]. After training, the computational cost of interpreting the input, which could be a large data set, is minimal, and suitable for deployment on a small portable device. As a proof of concept, a Lateral Priming Adaptive Resonance Theory (LAPART) network was trained using a subset of 180 images from a total of 360, and tested using the remaining subset. Testing is illustrated in Fig. 6. It is evident that the network successfully predicts irradiance 60 seconds in advance of being exposed to an image. Based on these results, the possibility of obtaining predictions 120 to 180 seconds in advance, seems quite realistic.

References

[1] O. Lavrova, F. Cheng, S. Abdollahy, H. Barsun, A. Mammoli, D. Dreisigmayer, S. Willard, B. Arellano, and C. van Zeyl, "Analysis of battery storage utilization for load shifting and peak smoothing on a distribution feeder in New Mexico," in *Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES*. IEEE, 2012, pp. 1–6.

[2] F. Cheng, S. Willard, J. Hawkins, B. Arellano, O. Lavrova, and A. Mammoli, "Applying battery energy storage to enhance the benefits of photovoltaics," in *Energytech, 2012 IEEE*. IEEE, 2012, pp. 1–5.

[3] C. W. Chow, B. Urquhart, M. Lave, A. Dominguez, J. Kleissl, J. Shields, and B. Washom, "Intra-hour forecasting with a total sky imager at the UC San Diego solar energy testbed," *Solar Energy*, 2011.

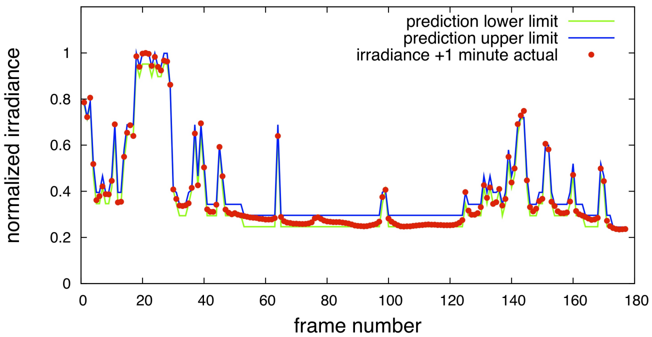

Fig. 6. Prediction band for the solar irradiance one minute after the image presented to the LAPART network, shown together with the actual measured value.

[4] T. P. Caudell and M. J. Healy, "Studies of inference rule creation using LAPART," in *Fuzzy Systems, 1996., Proceedings of the Fifth IEEE International Conference on*, vol. 3. IEEE, 1996, pp. ICNN1–ICNN6.

[5] M. J. Healy and T. P. Caudell, "Guaranteed two-pass convergence for supervised and inferential learning," *Neural Networks, IEEE Transactions on*, vol. 9, no. 1, pp. 195–204, 1998.