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Storage requirements for PV power ramp-rate control

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Abstract

Short-term variability in the power generated by large grid-connected photovoltaic (PV) plants can negatively affect power quality and the network reliability. New grid-codes require combining the PV generator with some form of energy storage technology in order to reduce short-term PV power fluctuation. This paper proposes an effective method in order to calculate, for any PV plant size and maximum allowable ramp-rate, the maximum power and the minimum energy storage requirements alike. The general validity of this method is corroborated with extensive simulation exercises performed with real 5-s one year data of 500 kW inverters at the 38.5 MW Amaraleja (Portugal) PV plant and two other PV plants located in Navarra (Spain), at a distance of more than 660 km from Amaraleja.

Keywords: Grid-connected PV plants; Power fluctuations smoothing; Ramp-rate control; Energy storage sizing

1. Introduction

Concerns about the potential of PV output fluctuations caused by transient clouds were expressed more than 25 years ago (Jewell and Ramakumar, 1987; Jewell and Unruh, 1990) and are now attracting widespread interest and attention, as a result of growing PV penetration rates. As the PV power share in the grid increases, such fluctuations may adversely affect power quality and reliability (Marcos et al., 2011a). In particular, power fluctuations of less than 10 min are typically absorbed by the grid as frequency fluctuations. This issue is of special importance in relatively small grids, such as islands, with high penetration rates, because the smoothing effect from the aggregation of geographically dispersed PV plants is intrinsically limited (Marcos et al., 2011b; Perpiñán et al., 2013). It was precisely an island grid operator, The Puerto Rico Electric Power Authority, that recently opened the door for PV power variability regulations, by imposing a 10% per minute rate (based on nameplate capacity) limitation on the PV plants being connected to its grid (PREPA, 2012).

Standard (without storage) PV plants exhibit power variations far beyond this limitation. For example, up to 90% and 70% per minute variations have been recorded, respectively, at 1 MW and 10 MW PV plants (Marcos et al., 2010). Hence, compliance with such regulations requires combining the PV generator with some form of energy storage technology, to either add or subtract power to or from the PV output in order to smooth out the high frequency components of the PV power. Fuel cells (Rahman and Tam, 1988), electric-double layer capacitors (Kakimoto et al., 2009) and, mainly, batteries (Hund et al., 2010; Byrne et al., 2012; Ellis et al., 2012; Leitermann, 2012; Xiangjun et al., 2013) have been proposed. Smoothing algorithms can be found (Kakimoto et al., 2009; Hund

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et al., 2010; Xiangjun et al., 2013; Loc Nguyen et al., 2010; Beltran et al., 2011). However, storage requirements have been scarcely addressed. Power and energy storage capacity have only been derived from some rather simple and intuitive considerations regarding PV output profiles: sudden drops from full power to 0, which is obviously the maximum conceivable fluctuation, were assumed in Kakimoto et al. (2009) in order to determine the size of the required capacitor. Somewhat more realistically, a drop from full power to 10% in 2 s was assumed in Hund et al. (2010) to conclude that relatively small batteries suffice. Although detailed observations and studies on irradiance fluctuation are also available (Mills et al., 2009; Kuszamaul et al., 2010; Mills and Wiser, 2010; Perez et al., 2012; Lave et al., 2012), these have not yet led to specific engineering rules in order to determine the storage system size to PV output smoothing.

This paper presents a method to calculate, for any PV plant size and maximum allowable ramp-rate, the maximum power and the minimum energy storage requirements alike. The solutions based on the observed relationship between PV output fluctuations and PV generator land size. 5 s power measurements were recorded at the output of 500 kW inverters at the 38.5 MW Amaraleja (Portugal) PV plant. Combining several inverters, any PV plant power size from 0.5 to 38.5 MW can be considered. First, extensive simulation exercises, performed with one year data made it possible to deduce power and energy storage characteristics for different PV plant sizes, different allowable ramp-rates and different state of charge (SOC) control algorithms. We then go onto propose a general model for the worst fluctuation case. Compared to the allowable ramp-rate this model makes it possible to deduce analytical equations for the maximum power and the minimum energy storage requirements alike. The general validity of this method is corroborated with power fluctuation data from two other PV plants located in Navarra (Spain), at a distance of more than 660 km from Amaraleja.

2. Experimental data

The experimental data for this work is taken mainly from the Amaraleja (South Portugal) PV plant. This plant occupies an area of 250 ha and includes 2520 solar trackers with a rated output of 17.7–18.8 kWp, up to a total peak power of 45.6 MWp. The corresponding inverter power, P^*, is 38.5 MW and the ground cover ratio (GCR) is 0.162. The trackers are one-vertical axis models, with the receiving surface tilted 45° from the horizontal. The plant is divided into 70 units, each comprising 36 tracking systems connected to a 550 kW DC/AC inverter. The minimum and maximum distances between the units, are 220 m and 2.5 km respectively. Thanks to extensive monitoring, 5 s synchronized records of the output power of all the inverters are available from May 2010. From this work, data was taken not only of the entire PV plant but also of 5 sections with P^* between 0.55 kW and 11.5 MW (Fig. 1), making it possible to study the dependence between the storage requirements and the size of the PV power plant.

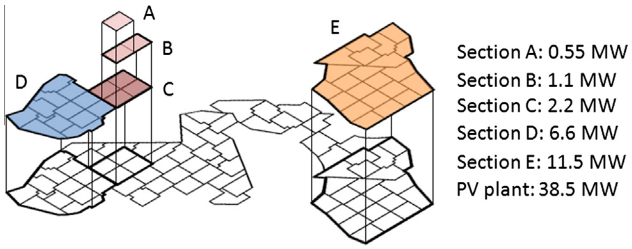

Fig. 1. Field distribution of the Amaraleja PV plant sections considered in this work.

Furthermore, the geographic independence of the method proposed herein was checked against an entire year (2009) with 1 s data from two PV plants located more than 660 km from Amaraleja: Rada and Castejón (South of Navarra, Spain), with P^* of 1.4 MW and 2 MW respectively. Further details can be found in Marcos et al. (2011a).

3. PV power fluctuations without storage

Given a power time series $P(t)$, recorded with a certain sampling period, Δt, power fluctuation at time t, $\Delta P_{\Delta t}(t)$ is defined as the difference between two consecutive samples of power, normalized to the inverter power P^*. That is:

$$\Delta P_{\Delta t}(t) = \frac{[P(t) - P(t - \Delta t)]}{P^*} \times 100\ (\%) \tag{1}$$

It is then possible to compare the time series of $\Delta P_{\Delta t}(t)$ with a given ramp value, r, and count the time the fluctuations exceed the ramp ($abs\ [\Delta P_{\Delta t}(t)] > r$). Fig. 2 shows the results for a full year (July 2010–June 2011) and for the different Amaraleja PV sections described above. As expected, the occurrence of fluctuations decreases with r and with P^*. For $r = 1\%$/min and $P^* = 550$ kW, power fluctuation exceed the ramp for 40% of the time. For the same ramp, increasing the PV size to $P^* = 38.5$ MW

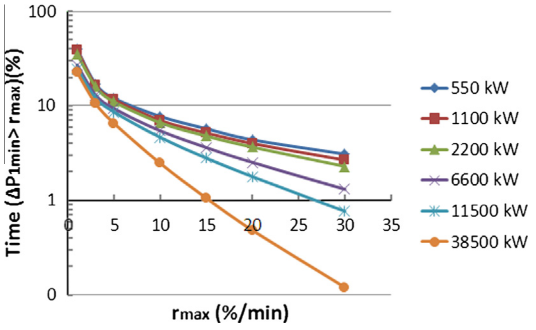

Fig. 2. Frequency over one year (July 2010–June 2011) of PV power fluctuations calculated in 1-min time window, $\Delta P_{1\min}(t)$, are superior to a given ramp r (%/min). The frequency value is given in relative terms to the total production time (4380 h).