

# 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

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## 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

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 Wisser, 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

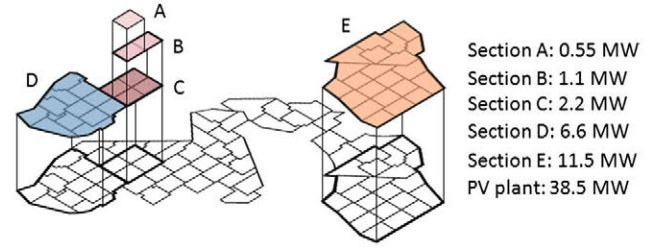


Fig. 1. Field distribution of the Amaraleja PV plant sections considered in this work.

(Fig. 1), making it possible to study the dependence between the storage requirements and the size of the PV power plant.

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,  $\Delta t$ , 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:

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

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

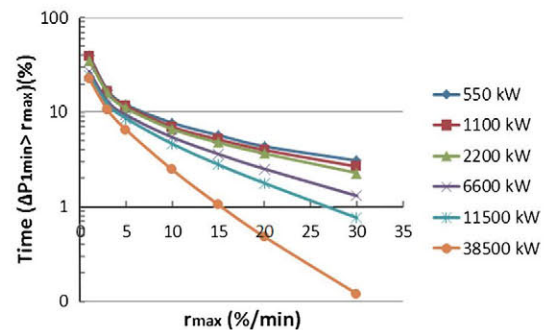


Fig. 2. Frequency over one year (July 2010–June 2011) of PV power fluctuations calculated in 1-min time window,  $\Delta P_{1min}(t)$ , are superior to a given ramp  $r$  (%/min). The frequency value is given in relative terms to the total production time (4380 h).



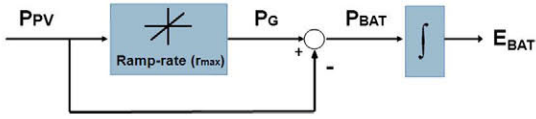


Fig. 3. Ramp-rate control model for a given  $P_{PV}(t)$  time series. Looking for simplicity, battery and associate electronic converter losses are ignored.

reduces the time the ramp is exceeded to 23%, whilst for a much less stringent ramp,  $r = 30\%/min$ , these values drop to 3% and 0.1%, respectively. These examples show that imposing power ramp limits (typically around  $10\%/min$ ) makes it necessary to resort to an Energy Storage System (ESS) even when large PV plants are concerned. In this paper we will assume that our ESS is a battery, just to make the presentation easier, although all the analyses shown are equally valid for any other storage technology.

## 4. Smoothing of power fluctuations by energy storage

### 4.1. Ramp-rate control

Let us consider a maximum permissible ramp rate value of the power injected into the grid,  $r_{MAX}$  ( $\%/min$ ). Fig. 3 shows a basic model of the corresponding ramp-rate control.  $P_{PV}(t)$ ,  $P_G(t)$  and  $P_{BAT}(t)$  are, respectively, the power from the inverter, the power to the grid and the power to the battery. Obviously:

$$P_{BAT}(t) = P_G(t) - P_{PV}(t) \quad (2)$$

Initially, the inverter tries to inject all its power into the grid,  $P_G(t) = P_{PV}(t)$ . The control is activated when the maximum allowable ramp condition is broken. That is, if:

$$|\Delta P_{G,1min}(t)| > r_{MAX} \quad (3)$$

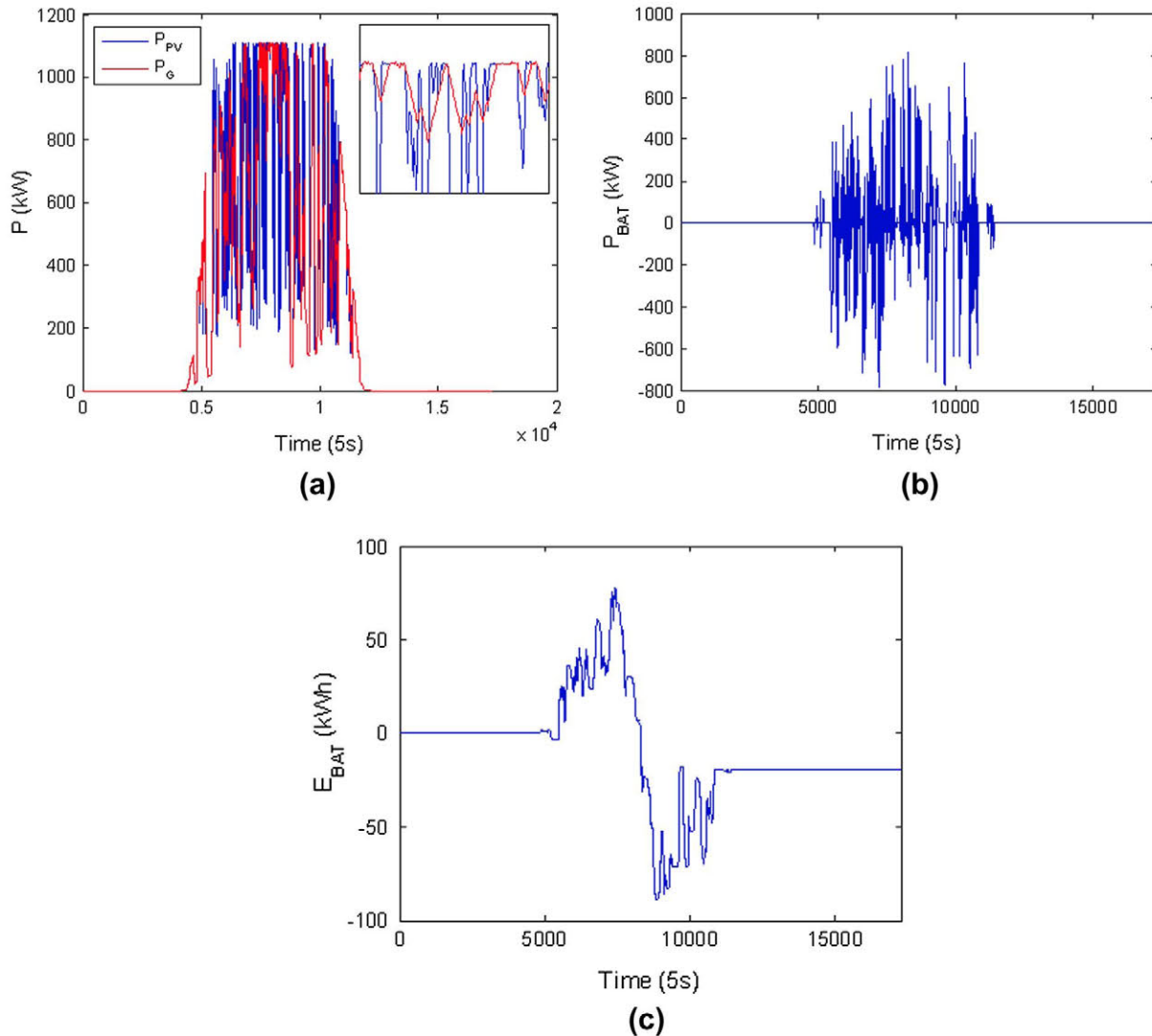


Fig. 4. (a) Evolution of the generated power,  $P_{PV}(t)$  by Section B (1.1 MW) on 31th October 2010 and the simulated power which would be injected to the grid  $P_G(t)$  in the case of disposing a battery which limits fluctuations to  $r_{MAX}$  of  $10\%/min$  ( $0.833\%/5s$ ). (b) Battery power,  $P_{BAT}$ . (c) Battery energy,  $E_{BAT}$ .

Then, the corresponding power excess or shortage is either taken from ( $P_{BAT}(t) > 0$ ) or stored into ( $P_{BAT}(t) < 0$ ) the battery. The energy stored at the battery,  $E_{BAT}(t)$ , is given by the integral of  $P_{BAT}(t)$  over time. In this way, the behavior of the whole system can be easily simulated for any time series of  $P_{PV}(t)$ . For the sake of simplicity, any potential battery and associated electronic converter losses are disregarded here.

As a representative example, Fig. 4 shows, for  $r_{MAX} = 10\%/min$ , the 1.1 MW Amaraleja PV section on an extremely fluctuating day (31th October, 2010), the resulting evolution of  $P_{PV}(t)$  and  $P_G(t)$  (Fig. 4a),  $P_{BAT}(t)$  (Fig. 4b) and  $E_{BAT}(t)$  (Fig. 4c). Battery requirements for this day derive from the corresponding maximum power and energy values. In this example, the required battery power is  $P_{BAT,MAX} = 873$  kW (or  $P_{BAT,MAX} = 0.79P^*$ ) and the required battery capacity is  $C_{BAT} = E_{BAT,MAX} - E_{BAT,MIN} = 175$  kW h (or 10 min of capacity, equivalent to 0.16 h of PV plant production at  $P^*$ ). It is worth mentioning that the daily battery energy balance is negative ( $-20$  kW h). At first glance, this may appear counter-intuitive, because the PV power fluctuation distribution is essentially symmetrical (clouds reaching and leaving the PV field). However, this can be understood by carefully observing the battery charge and discharge dynamic. Note that the area of upper regions (charging) is larger than the area of lower ones (discharging).

Fig. 5 shows the result of extending the simulation exercise to an entire year (July 2010–June 2011), to all the Amaraleja PV sections, and for  $r_{MAX} = 10\%/min$ . The State of Charge (SOC) of the battery at the end of a day has been concatenated with the SOC at the beginning of the next day. As the example shown in Fig. 4, the tendency of the battery to discharge continuously affects the entire one year period. An important initial conclusion can be drawn: instead of distributing the storage systems for single power plants or sections within a power plant, it seems wiser to add multiple sections or power plants to a single storage system. On the other hand, the battery discharging tendency leads to excessive battery capacity requirements, in the order of some hours. More practical alternatives are obtained when adding charge to the battery at different

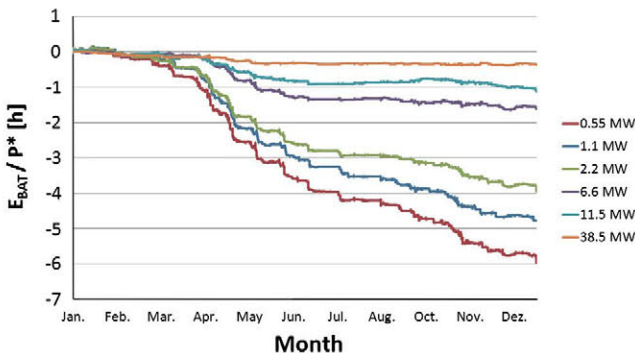


Fig. 5. Evolution of storage time,  $E_{BAT}/P^*$  (h), in the battery during one year (July 2010–June 2011), limiting the ramps to a maximum of 10%/min in different PV systems.

times throughout the year, as will be seen below. Nevertheless, an important conclusion can be reached from Fig. 5: the energy that must be managed through the storage systems is very low, only about 0.3% of the total energy production for limiting the power ramps of a 0.5 MW plant at a maximum of 10%/min (for this case, as Fig. 2 showed, the battery time of use is equal to 8%). Thus, efficiency related aspects are scarcely relevant.

#### 4.2. Overnight battery recharging

Overnight battery recharging from the grid makes sense because electricity demand usually drops at night. Fig. 6 presents the results of a simulation exercise similar to Fig. 5, except that this time, if required, energy at the battery is restored each night. That is:

$$E_{BAT,end\ day_{i-1}} < 0 \Rightarrow E_{BAT,beginning\ day_i} = 0 \quad (4)$$

In this way the tendency of the battery to discharge continuously does not affect the entire period of one year, but is limited to one day and therefore significantly reduces the required battery size, which is now in the order of some minutes. For example, battery requirements for  $r_{MAX} = 10\%/min$  in the 1.1 MW Amaraleja PV section are now  $P_{BAT,MAX} = 890$  kW (or  $P_{BAT,MAX} = 0.81 \cdot P^*$ ) and  $E_{BAT,MAX} = 451$  kW h (or 25 min of capacity, equivalent to 0.41 h of PV plant production at  $P^*$ ). The comparison of these figures with the above mentioned results for 31th October 2010, reveals that power battery requirements, which are obviously imposed by the worst individual fluctuation, tend to be constant throughout the analysis period. However, the same is not true for the battery energy requirements, which are imposed by the fluctuation distribution throughout the worst day.

#### 4.3. Daytime battery recharging controlled by state of charge

Another interesting battery recharging possibility, not requiring energy to be supplied from the grid, consists in establishing a reference value for the energy stored in the

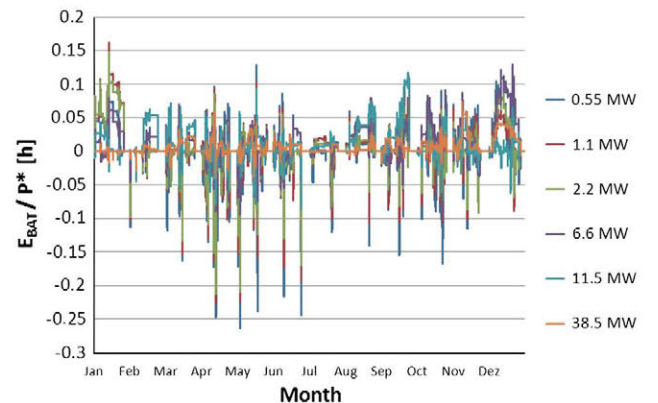


Fig. 6. Evolution of storage time,  $E_{BAT}/P^*$  (h), in the battery during one year (July 2010–June 2011), limiting the ramps to a maximum of 10%/min in different PV systems with overnight recharge.



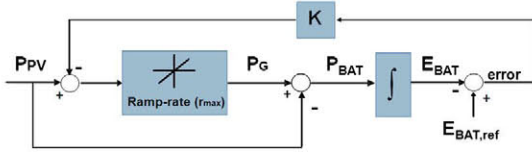
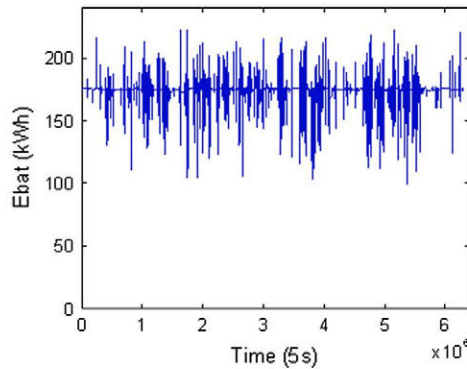


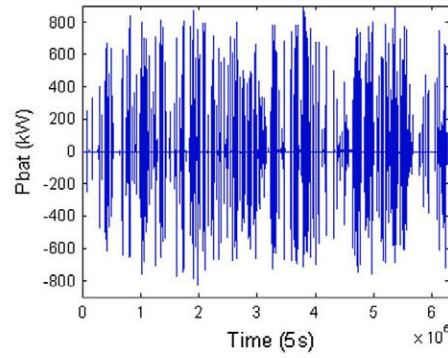
Fig. 7. Ramp-rate control model modified with additional SOC control. Notice that the SOC control action is also smoothed by the ramp-limiter in order to guarantee that power fluctuations are always below  $r_{MAX}$ .

battery,  $E_{BAT,REF}$  and in implementing a control loop that continuously tries to return  $E_{BAT}(t)$  to this reference, providing the ramp-rate limit is observed and energy is never taken from the grid (nighttime charging forbidden). Fig. 7 presents the corresponding model. The control will be faster or slower depending on the value of  $K$ . For example, a value of  $K=1$  means that if  $E_{BAT}(t) - E_{BAT,REF} = 1$  kWh the control would request 1 kW from the battery. Obviously, once the battery capacity is defined,  $E_{BAT}$  control is equivalent to SOC control.

In this way the battery tendency to continuously discharge has no effect on the entire one year period or on the entire one day period, but only on the short period the control requires to restore  $E_{BAT,REF}$ . This therefore further reduces the required battery size. Fig. 8 shows the results of a simulation exercise again for the 1.1 MW Amaraleja PV section and for a one year period (July 2010–June 2011).  $E_{BAT,REF}$  and  $K$  have been arbitrarily set to 175 kWh and 6, respectively. The latter allows for a good compromise between system stability and fast battery recharging. Now, corresponding battery requirements are  $P_{BAT,MAX} = 890$  kW (or  $P_{BAT,MAX} = 0.81 \cdot P^*$ ) and  $C_{BAT} = E_{BAT,MAX} - E_{BAT,MIN} = 124$  kWh (or 6.7 min of capacity, equivalent to 0.11 h of PV plant production at  $P^*$ ). Thus, the required battery capacity is significantly lower than that corresponding to nighttime recharging. In fact, this  $K$  value is large enough to almost restore  $E_{BAT,REF}$  just after each fluctuation. Thus the impacts of successive fluctuations become independent of each other and battery



(a)



(b)

Fig. 8. Evolution along July 2010–June 2011 of  $E_{BAT}$  (a) and  $P_{BAT}$  (b) for section B (1.1 MW), a  $r_{MAX}$  of 10%/min and with SOC control.  $E_{BAT,REF}$  and  $K$  have been arbitrarily set to 175 kWh and 6, respectively.

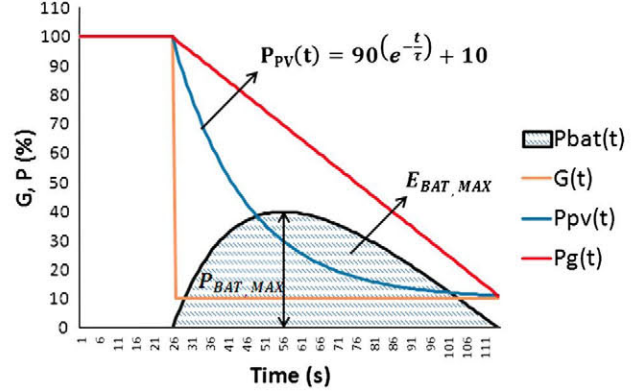


Fig. 9. Worst fluctuation model. The blue line represents the  $P_{PV}(t)$  response to an irradiance fluctuation (yellow line) and the red one is the power injected to the grid  $P_G$  with a ramp-rate control. The difference between  $P_G$  and  $P_{PV}$  is  $P_{BAT}$ , the maximum difference corresponds to  $P_{BAT,MAX}$  and the defined integral of  $P_{BAT}$  corresponds to  $E_{BAT,MAX}$ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

requirements become essentially linked to the “worst fluctuation”, i.e. the individual fluctuation requiring the highest energy demand.

## 5. The worst fluctuation model

Careful study of real worst fluctuations observed at Amaraleja lead us to postulate that the worst fluctuation is properly described (Fig. 9) by a power exponential decay from  $P^*$  to  $0.1P^*$  (or an exponential rise from  $0.1P^*$  to  $P^*$ ) with a time constant,  $\tau$  (s), which is empirically correlated (Fig. 10) with the shortest dimension of the perimeter of the PV plant,  $l$  (m), by an expression such as:

$$\tau = a \cdot l + b \quad (5)$$

where  $a = 0.042$  (s/m) and  $b = -0.5$  s. Table 1 presents the real  $\tau$  values observed at the different PV Amaraleja sections and Fig. 10 shows that they are in good agreement with Eq. (5).

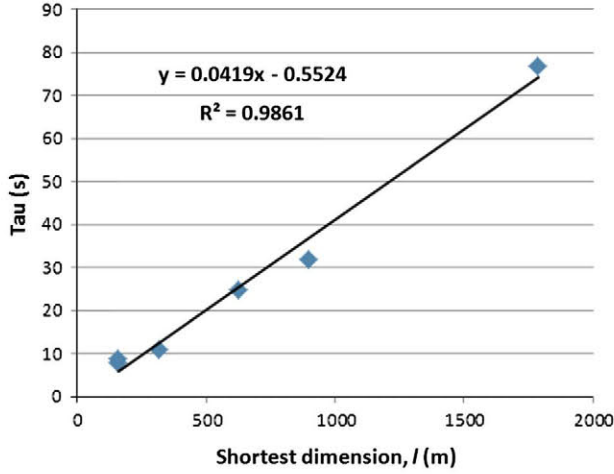


Fig. 10. Adjustment of observed time constant values  $\tau$  vs. shortest perimeter dimension  $l$ , Eq. (5). The general expression of this equation is  $y = mx + n$ , where  $m$  gives the coherency to the units. In our case,  $m = 0.042$  (s/m).

Table 1  
Characteristic power  $P^*$ , shortest perimeter dimension  $l$  and time constant  $\tau$  of the observed worst fluctuation at the different Amaraleja PV sections.

Power, $P^*$ (MW)	Short dimension, $l$ (m)	Tau, $\tau$ (s)
0.55	158	8
1.1	158	9
2.2	318	11
6.6	626	25
11.5	896	32
38.5	1786	77

Battery requirements for ramp-rate limitation are easily derived from the model showed in Fig. 9. We can see the response of  $P_{PV}(t)$  and  $P_G(t)$  to a negative irradiance  $G(t)$  fluctuation.  $P_{PV}(t)$  evolution corresponds to a first order system with a time constant  $\tau$ , while  $P_G$  decreases with a

rhythm being set by  $r_{MAX}$ . The power demanded to the battery  $P_{BAT}(t)$  corresponds with the difference between  $P_G(t)$  and  $P_{PV}(t)$ , Eq. (2). Therefore,  $P_{BAT}(t)$  along the worst fluctuation time is given by:

$$P_{BAT}(t) = \frac{P^*}{100} [90(1 - \exp(-t/\tau)) - t \cdot r_{MAX}] \quad (6)$$

where  $r_{MAX}$  is expressed as % per time. This expression gets a maximum for

$$t_{P_{BAT,MAX}} = \tau \cdot \ln \frac{90}{\tau \cdot r_{MAX}} \quad (7)$$

Thus, the required battery power is given by:

$$P_{BAT,MAX}(t) = \frac{P^*}{100} \left[ 90 - \tau \cdot r_{MAX} \left( 1 + \ln \frac{90}{\tau \cdot r_{MAX}} \right) \right] \quad (8)$$

where  $P^*$ ,  $P_{BAT,MAX}$  is expressed in (kW),  $r_{MAX}$  in (%/s) and  $\tau$  in (s). On the other hand, the battery discharging process lasts until the time the power ramp reaches  $0.1P^*$ . Corresponding time span,  $T_R$ , is:

$$T_R = \frac{90}{r_{MAX}} \quad (9)$$

Thus, the required battery energy is given by:

$$\begin{aligned} E_{BAT,MAX} &= \int_0^{T_R} P_{BAT}(t) dt \\ &= \frac{0.9P^*}{3600} \left[ \frac{90}{2 \cdot r_{MAX}} - \tau \cdot \left( 1 - \exp \left( -\frac{90}{\tau \cdot r_{MAX}} \right) \right) \right] \\ &\approx \frac{0.9P^*}{3600} \left[ \frac{90}{2 \cdot r_{MAX}} - \tau \right] \end{aligned} \quad (10)$$

where  $P^*$  is expressed in (kW),  $r_{MAX}$  in (%/s),  $\tau$  in (s) and  $E_{BAT,MAX}$  in (kW h). As the sign of the first fluctuation is unknown, a double capacity battery is required to absorb both the upwards and downwards fluctuation:

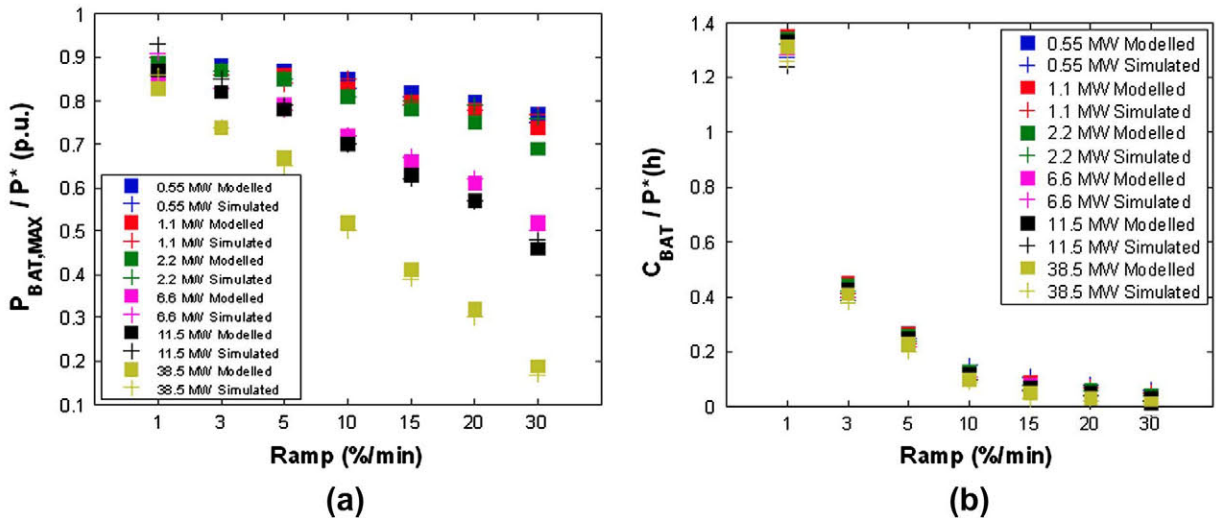


Fig. 11. Storage requirements for ramp-rate control: (a) battery power  $P_{BAT,MAX}$ , normalized to inverter power  $P^*$  and (b) storage time  $C_{BAT}/P^*$ , in hours. Results derived from the worst fluctuation model show good agreement with the ones derived from detailed simulation based on 5 s real data recorded at different Amaraleja PV sections.



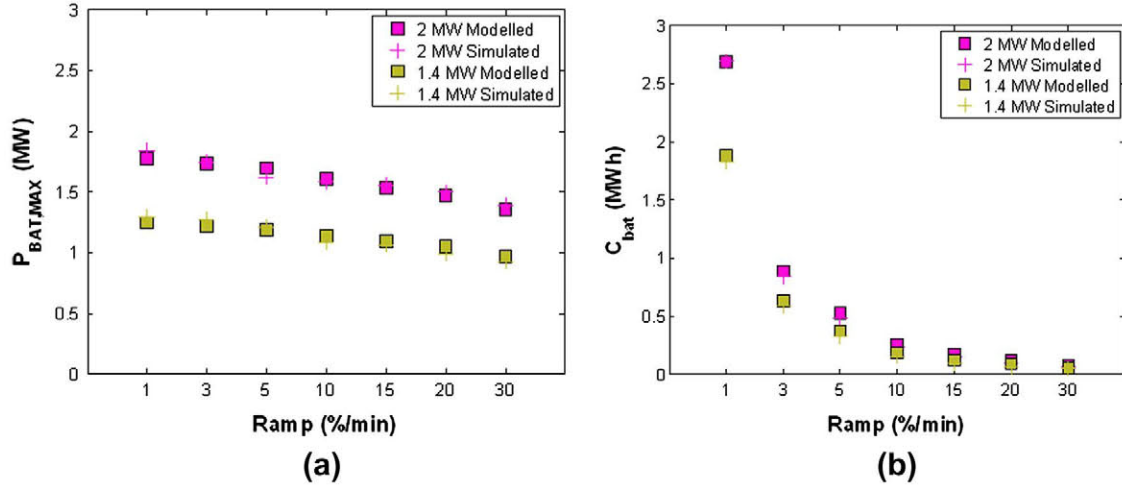


Fig. 12. Worst fluctuation model validation compared to data from two other PV plants, at a distance of 660 km from Amaraleja PV plant: (a) battery power  $P_{BAT,MAX}$  in MW and (b) battery capacity  $C_{BAT}$  in MWh.

$$C_{BAT} = 2 \cdot E_{BAT,MAX} = \frac{1.8P^*}{3600} \left[ \frac{90}{2 \cdot r_{MAX}} - \tau \right] \quad (11)$$

For example, for  $P^* = 1.1$  MW and  $l = 158$  m, Eq. (5) leads to  $\tau = 6.14$  s, and battery requirements for limiting the ramp-rate to  $r_{MAX} = 10\%/min$  are, from Eq. (8),  $P_{BAT,MAX} = 0.84 \cdot P^* = 928$  kW and, from Eq. (11),  $C_{BAT} = P^* \cdot 0.132$  h = 145 kW h. For  $P^* = 38.5$  MW and  $l = 1786$  m, corresponding results are  $\tau = 74.51$  s,  $P_{BAT,MAX} = 0.53P^* = 20.4$  MW and  $C_{BAT} = P^* \cdot 0.098$  h = 3773 kW h.

Fig. 11 compares the battery requirements for the different PV Amaraleja sections and for different ramp-rate limits, as deduced from simulation based on a year of observed 5 s data and as given by Eqs. (8) and (11). Good agreement is clearly observed. Furthermore, in order to check the general validity of the worst fluctuation model, we performed a similar exercise for two different PV plants located at a distance of about 660 km from Amaraleja, at Rada ( $P^* = 1.4$  MW;  $l = 260$  m;  $\tau = 10$  s) and Castejon ( $P^* = 2$  MW;  $l = 310$  m;  $\tau = 12$  s), both in the South of Navarra (Spain). Fig. 12 presents the corresponding results which, again, show very good agreement between modelled and simulation-derived data.

## 6. Conclusions and outlook

This paper has dealt with storage requirements for smoothing short term PV power fluctuations, studying the relationship between PV plant size and ramp-rate limits, and the required power and capacity of the battery. We propose 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.

Extensive simulations based on observed 5 s power measurements recorded at different peak power PV sections, ranging from 0.5 MW to 38.5 MW, at the Amaraleja PV plant were performed, considering three battery recharging possibilities: at the end of the year, each night and

continuous SOC controlled recharging throughout the day. Relevant conclusions are that the energy managed through the storage system is in practice very low, and that PV peak power aggregation reduces battery power and capacity requirements alike.

When SOC controlled battery recharging is applied, which probably represents the most practical alternative, battery requirements are essentially imposed by the “worst fluctuation”. An analytical theoretical model for this fluctuation case has been proposed and validated, by comparing the corresponding battery requirements with the ones derived from detailed simulations based on real power data.

Ramp-rate control is not the only method for smoothing fluctuations; therefore, there is a need to study new ways with smarter SOC controls that may result in a better use of the ESS. Finally, the results presented in this paper indicate that the time during which fluctuations exceed the maximum allowable ramp is very short. Consequently, it would be necessary to analyze possible auxiliary functions to be performed by the ESS (such as frequency regulation or time shifting) to maximize its value.

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