Solar Energy 169 (2018) 242–248

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Brief Note

Dealing with the implementation of ramp-rate control strategies – Challenges and solutions to enable PV plants with energy storage systems to operate correctly

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ARTICLE INFO

Keywords:
Smoothing
Power fluctuation smoothing
Ramp-rate control
Energy storage sizing
Experimental validation

ABSTRACT

Energy storage systems (ESS) have been widely proposed as a solution for smoothing out photovoltaic (PV) power fluctuations and complying with new regulations that limit the maximum fluctuation over a given period, typically 10%/min, evaluated over a shorter period of time, such as one second. Although ramp-rate control is one of the most used strategies it does require symmetric charge-discharge power capabilities, which most commercially available batteries do not have. This can lead to non-compliance with the regulations and is a problem that has not yet been sufficiently studied. Furthermore, delays in the communication system between the measurement of the actual PV power, the PLC calculation time and the battery converter response time can lead to a failure to comply with the maximum ramp rate limit, bringing to light the need for faster systems. These two problems are addressed herein, and solutions are presented and validated with 1 s experimental data from a 122.4 kWp PV array section coupled to a 100 kW/56 kWh lithium-ion battery within a 1.18 MWp PV plant in northern Spain.

1. Introduction

The short-term variability of the power produced by PV plants due to the intermittent nature of the solar resource together with the growing demand for the installation of new PV plants, pose one of the greatest challenges to those responsible for PV integration into power networks with conventional generators. Consequently, some transmission system operators (TSO) have issued new grid codes to address this matter, including new criteria to make it easier for the TSO to react appropriately against harmful power fluctuations, i.e., fluctuations with a time scale of less than 10 min (CRE, 2014; NERSA, 2012; PREPA, 2012). Such criteria include setting power variation maximum ramps for the power being fed into the network by intermittent generation plants. For instance, the target specified in Puerto Rico (PREPA, 2012) is 10%/min. It is thereby ensured that the rest of the system, if provided with sufficient control capacity, can respond to any rapid power changes at the intermittent power generation plants. Given the fact that PV power fluctuations are greater than the restrictions imposed, some type of ESS is required in order to comply with regulations. Different strategies have been presented in the literature (de la Parra et al., 2015; Hund et al., 2010; Kakimoto et al., 2009; Kinjo et al., 2006; Marcos et al., 2014a, 2014b; Monai et al., 2004; Rahman and Tam, 1988; Traube et al., 2013) in order to adequately smooth out PV power fluctuations and comply with a maximum ramp-rate restriction imposed by a given regulation. In this way, one of the most used strategies is the ramp-rate control (Alam et al., 2014; Kakimoto et al., 2009; Khanh et al., 2010), hereinafter called ($RR_{classic}$). In a recent study (de la Parra et al., 2015), we proposed a new ramp-rate control strategy that halves the ESS requirements of the $RR_{classic.}$ The control is based on the two PV plant output limits: the maximum PV plant power occurring under clear sky conditions ($P_{PV,Max}(t)$) and the minimum PV plant power occurring with complete cloud cover ($P_{PV,Min}(t)$). Therefore, as a function of the instantaneous PV power, it is then possible to obtain the state of charge (SOC) of the ESS needed to smooth out any potential fluctuations.

As shown in de la Parra et al., 2015, battery requirements for both strategies are easily derived from what is termed the *worst fluctuation model* which is an effective method to calculate, for any PV plant size and maximum allowable ramp-rate (r_{MAX}), the maximum power and the minimum energy storage requirements alike. It is based on the worst fluctuation that could take place at a PV plant and is a function of the shortest measurement of the PV plant perimeter and the maximum cloud speed.

According to this method, battery requirements for ramp-rate

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https://doi.org/10.1016/j.solener.2018.04.054
Received 19 March 2018; Received in revised form 24 April 2018; Accepted 25 April 2018

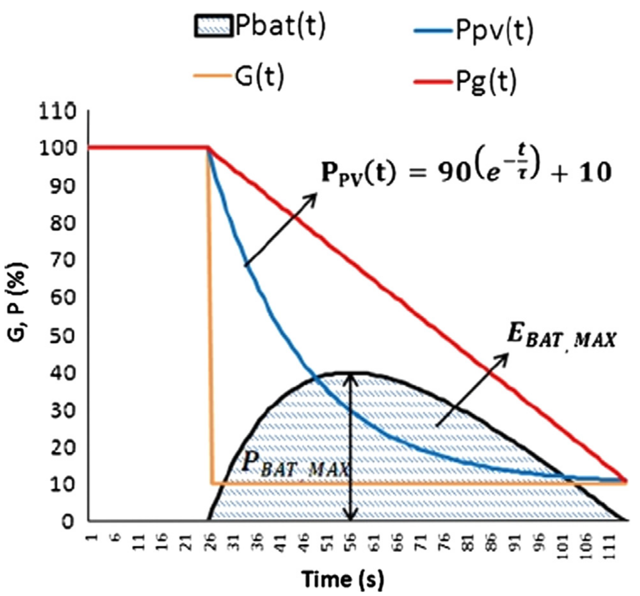

Fig. 1. *Worst fluctuation model.* The blue line represents the generated PV power $P_{PV}(t)$ response to an irradiance fluctuation (orange line) while the red line is the power injected into the grid $P_g(t)$ with a ramp-rate control. The difference between $P_g(t)$ and $P_{PV}(t)$ is $P_{bat}(t)$, the maximum difference corresponds to $P_{BAT,MAX}$ and the defined integral of $P_{bat}(t)$ corresponds to the energy to be provided by the ESS, $E_{BAT,MAX}$. (Marcos et al., 2014b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

limitation are easily derived from the worst fluctuation observed at the Amareleja PV plant (see Fig. 1). This is properly described as an exponential decay from the nameplate power, P_N, to $0.1P_N$ (or an exponential increase from $0.1P_N$ to P_N) which means that the beam irradiance disappears and only the diffuse light remains, with a time constant, τ [s], which is empirically correlated with the shortest dimension of the PV plant perimeter of the l [m], by Eq. (1) (Marcos et al., 2014b):

$$\tau = a \cdot l + b, \tag{1}$$

where $a = 0.042$ (s/m) and $b = -0.5$ s.

Battery requirements are easily derived from Fig. 1 and are given by Eq. (2) (Marcos et al., 2014b):

$$E_{BAT,MAX} \approx \frac{0.9P_N}{3600}\left[\frac{90}{2 \cdot r_{MAX}} - \tau\right], \tag{2}$$

where P_N is expressed in [kW], r_{MAX} in [%/s], τ in [s] and $E_{BAT,MAX}$ in [kWh]. However, as the sign of the fluctuations is unknown, in the $RR_{classic}$ a double capacity battery is required to absorb both the potential upward and downward fluctuations. So the minimum battery required (C_{BAT}) is given by Eq. (3) (Marcos et al., 2014b):

$$C_{BAT} = 2 \cdot E_{BAT,MAX} = \frac{1.8P_N}{3600}\left[\frac{90}{2 \cdot r_{MAX}} - \tau\right], \tag{3}$$

and the required battery power is given by Eq. (4) (Marcos et al., 2014b):

$$P_{BAT,MAX}(t) = \frac{P_N}{100}\left[90 - \tau.\ r_{MAX}\left(1 + \ln\frac{90}{\tau \cdot r_{MAX}}\right)\right]. \tag{4}$$

It is worth noting that $P_{BAT,MAX}(t)$ is the same for both a downward and upward fluctuation, in other words, the EES must have symmetric charge and discharge powers.

On the other hand, de la Parra et al. (2015) proposes the $RR_{clear\text{-}sky}$ strategy, consisting in the implementation of a SOC control based on the actual power given by the PV plant and its production limits. Despite the variable nature of solar radiation, advantage can be taken of the fact that its limits are well known. The instantaneous PV plant power generated, $P_{PV}(t)$, for specific values of irradiance, $G(t)$, and cell temperature, $T_c(t)$, can be easily estimated with a parametric model of the PV plant under consideration. It is possible to estimate the PV plant production limits at each moment in time: the PV plant power under clear sky conditions, $P_{PV,Max}(t)$, and the PV plant power under full cloud cover conditions in which only diffuse light reaches the PV arrays, $P_{PV,Min}(t)$. These values respectively represent the maximum and minimum power outputs that can occur at the PV plant at that moment in time. In this way, it is possible to calculate the maximum power variation that can take place, either positive or negative, from the instant power generated by the PV plant, $P_{PV}(t)$. Thus, as a function of the actual PV power, it is then possible to obtain the state of charge needed in order to either absorb or supply the energy required, depending on the nature of the fluctuation, either upward or downward respectively. The logic of this SOC control can be found in de la Parra et al. (2015). Applying this control, it is again possible to operate with half the capacity required in Eq. (3), that is calculated as Eq. (5) (de la Parra et al., 2015)

$$C_{BAT} = \frac{0.9P_N}{3600}\left[\frac{90}{2 \cdot r_{MAX}} - \tau\right]. \tag{5}$$

However, none of these papers have addressed the problem that most commercially available batteries have different maximum charge and discharge powers (Saft, 2018) that may be insufficient for correct operation. The most common drawback is that, as the charge power is lower than the discharge power (typically 33/100), at a given moment in time the battery may be unable to absorb all the power required to comply with a ramp rate limitation in the event of an upward fluctuation. There are previous studies that limit the ramping-up events with the inverters (de la Parra et al., 2016, 2015; Ruifeng and Saha, 2010; van Haaren, 2013, 2015). However, in this paper the inverters only limit during ramping-up moments in which the battery is not able to absorb the power required. The solution is validated on a real PV power plant with 122.4 kWp PV array and a 100 kW/56 kWh battery. Furthermore, this solution was simulated with 1 s power measurements which were recorded at the output of the 100 kW inverter for a maximum allowable ramp-rate value (r_{MAX}) of 10%/min.

Another problem that has been scarcely addressed in the literature is how the results obtained could be affected by the different communication and calculation delays, and also by the response time of the converter coupled to the battery. Logically, when a PV power fluctuation occurs, during the time taken for the system to react, this fluctuation will pass directly to the power grid. Abdollahy et al. (2013) and Kim and Parkhideh (2017) claim that a delay in power measurement and transmission may cause significant error which may not only generate a less smooth output but also may act in reverse direction and add even more fluctuation (oscillations) to the aggregate output. In Bullich-Massagué et al. (2017) a filter in the active power measured at the point of common connection (PCC) is proposed to mitigate the oscillations. All these studies are verified through simulations. This paper shows for the first time in a commercial PV plant the effect of these delays and proposes an easier solution in which the filter is not necessary. It is also shown how a total delay of 3 s leads to non-compliance with the ramp rate limitation and how, by reducing this time to around 1 s, the strategy functions correctly.

2. Experimental data

The database used in this study is taken from the "Montes del Cierzo" PV plant, located in Tudela (Spain) which is one of the first PV plants to exceed a power output of 1 MW. It was connected to the grid in 2002 with a total nameplate power of 1.18 MWp with 400 azimuthal trackers with 12,062 PV modules in two different zones. The zone used