Control Measures for Smoothing PV Power Fluctuations in Madeira Power System

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***Abstract*— This paper describes an automatic control strategy that was designed to provide real-time control measures to mitigate photovoltaic (PV) power fluctuations in future scenarios of the power system of Madeira island, in Portugal. In this approach, the main concern is to avoid active power balance shortfalls. At the same time, the smoothing of short-term PV power fluctuations is obtained by this approach, for mitigation of frequency stability problems. Currently, PV power penetration is small in this power system and, therefore, PV facilities are usually allowed to inject into the grid all the available power. In a near future, this operational philosophy must change, since PV installed capacity is foreseen to increase considerably in this island. If the mitigation of the expected PV output fluctuations is done through the use of an energy storage system, this will require a large power capacity, since the storage system must be able to cope with high power fluctuations. To avoid this scenario, the presented control strategy combines the definition of limits to PV power production increases, by operating bellow the maximum power point tracking (MPPT) curve, with the use of a battery energy storage system with a relatively small power size. The storage system is used to reduce the PV energy curtailment caused by MPPT control and to directly control the ramp-rate of PV power drops. From a comprehensive analysis of historical data of PV power production, the presented results for the Madeira island illustrate the quality of this approach, namely, the ability to reduce the PV power fluctuations to acceptable values from the perspective of system security, without the need of a storage system with a large power capacity.**

Keywords- photovoltaic power fluctuations; energy storage; active power balancing; island systems.

I. INTRODUCTION

Together with wind, solar photovoltaic (PV) is becoming one of the preferred options for power generation through renewable energy sources. In particular, since 2016, solar PV has been one of the most used renewable power sources worldwide, with around 100 GW added in 2018 [1]. However, the power produced from PV directly depends on solar irradiance, making this an intermittent power source. Irradiance fluctuates not only daily, but also hourly and over shorter periods of time, like minutes and even seconds, caused by changes in cloud cover. This intermittent and variable nature may require new flexible operating strategies, depending on the penetration level [2] and the geographical dispersion of the PV power production [3]-[4]. Nowadays, due to the trend towards renewable energy penetration growing, the amount of required active power reserve, for seconds to minutes time intervals, is increasing for ensuring a proper active power balancing and frequency control [5]. According to [6], active power–frequency control is the most prominent factor affecting large-scale PV integration into power systems. This is particularly observed in isolated power systems, like in islands, due to the limited available resources for flexibility, when compared to interconnected systems [7].

To prevent excessive voltage and frequency deviations on the grid side, provoked by short-term sharped PV power fluctuations in the time interval of seconds, some power utilities operating in islands impose ramp-rate limits to the PV output power. These limits depend on the specific characteristics of the electric network and of the installed generation portfolio in the power system [8]. For instance, the Puerto Rico Electric Power Authority defined a ramp-rate limit of ±10% of the rated capacity per minute for PV power production [9]. In the 1.2 MW La Ola PV plant in Lanai, Hawaii, a 1.125 MW/0.5 MWh battery system was designed to limit the net output ramp-rate to 30% per minute [10].

Besides having high rate of change in the time interval of seconds, the magnitude of PV power fluctuations occurring in the time interval of minutes frequently reach even larger values. In fact, the larger the sampling time, the higher becomes the magnitude of PV fluctuations [10][11]. In the particular case of a large PV system, with a rating in the order of tens of megawatts, the registered PV power fluctuations can easily exceed ±30% of the rated capacity per 10 seconds, ±70% per minute and more than ±80% per 10 minutes [11]. Therefore, a very large penetration of PV power production may provoke large power generation variations, within a few minutes, that must be accounted by the active power reserves.

The containment of PV power fluctuations can be performed by limiting the magnitude and ramp-rate of PV power production increases. This can be performed using dump loads to dissipate the excess PV power or by controlling the maximum power point tracking (MPPT) [2]. These methods present a relatively low implementation cost, but the ramp-rate of PV power variations is solely contained by performing PV power curtailment. Therefore, these are not

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recommended methods to be used alone for large PV plants (i.e. in the order of megawatts), since these may limit largely the revenues of PV system owners. In [12], these two methods were tested alone to limit the power fluctuations of a 10 MW PV system to a certain range. According to the obtained results, the loss of revenues of PV system owners is smaller if the containment of PV power fluctuations is performed by operating the PV farm below the MPPT curve.

A direct control of PV power drops is only possible with the use of fast acting energy storage systems. In particular, battery energy storage systems (BESS) are the preferred for MW scale PV installations, like in [12] and [13], since they are able to provide suitable values for both power and energy densities [2]. The results presented in [12] show that operating the PV system bellow the MPPT curve combined with the use of a BESS is the most economical strategy to mitigate PV power fluctuations, in large PV systems, when compared with using only one of the two techniques.

The aim of the previous described works is to smooth short-term and sharp PV power fluctuations. No concerns exist on mitigating active power balance shortfalls in the time frame of several minutes. In Madeira power system future scenarios, a significative growth is expected for the installed PV power. If new control strategies are not adopted, this increase will be enough to create, not only undesirable large frequency excursions due to short-term power fluctuations, but also large active power balance shortfalls in the time frame of minutes. This paper describes a control strategy that was proposed to mitigate these expected large PV power fluctuations to acceptable values from the perspective of system security. The proposed control strategy combines the use of limits to the magnitude and ramp-rate of PV power production increases, by MPPT control, with the use of a BESS with a relatively small power size.

The general organization of this paper is as follows. First, section II explains the active power balancing constrains that are expected in the Madeira power system, from the foreseen connection of new PV facilities in a near future scenario. Then, the proposed control strategy is properly described in section III. Next, section IV describes the control measures found for the Madeira power system, from adopting the proposed control strategy, and presents the obtained results with the defined actions. The effectiveness of the proposed approach is also demonstrated by performing a battery cycle life evaluation for the Madeira use case. Finally, section V summarizes the main conclusions obtained from this research.

II. Expected Constrains from Connecting new PV Plants in Madeira Island

A. Future Scenario of PV Power Production

Currently, two main PV plants exist in Madeira power system, totalizing 15 MW of PV installed capacity and having a maximum power penetration around 15%. This is not a significant power penetration and, therefore, PV generation facilities are usually allowed to inject into the grid all the available power. However, in a near future this operational philosophy must change, since the PV installed capacity is foreseen to increase considerably in this island. In fact, an additional installed power of 60 MW is foreseen from the connection of new PV plants, totalizing 75 MW of PV installed capacity for a peak load not exceeding 140 MW.

In this work, to estimate the future PV power fluctuations in the Madeira island, the used input data was historical daily time series of PV power production, registered with a time resolution of 10 seconds, collected throughout the year 2016 from the two existing PV plants. For illustrative purposes, figure 1 presents the registered time series of the total PV power production for a disturbed day, in 2016, together with the expected time behavior of the total PV production for the near future scenario. In this analysis, a 30 MW increase of installed PV capacity is assumed in the vicinity of each of the two existing main PV plants. By doing so, the analysis includes the smoothing effect provided by the geographical dispersion of the existing plants.

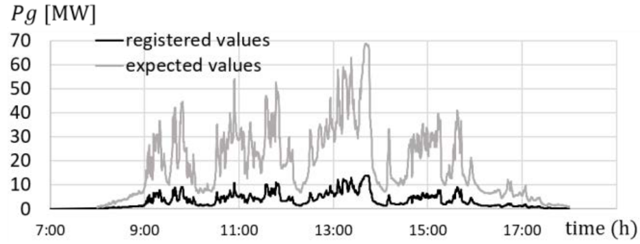


Figure 1. Daily time series of the total PV power production in a disturbed day (registered and expected values)

B. Expected Behavior of PV Power Ramp-Rates

In this study, (1) was used for the computation of the ramp-rates, for a given sampling time Δt, at any instant t.

$$\partial Pg(t)/\partial t_{\Delta t} \cong Pg(t) - Pg(t-\Delta t) \qquad (1)$$

The daily time series of PV power ramp-rates were computed by using (1) for all the instants t of the same day, i.e. by moving time t at the same rate as the raw data resolution (10 seconds in this case). Figure 2 presents the obtained 15-min ramp-rates (i.e., with a sampling time Δt of 15 minutes), for the daily time series of the PV power productions presented in figure 1.

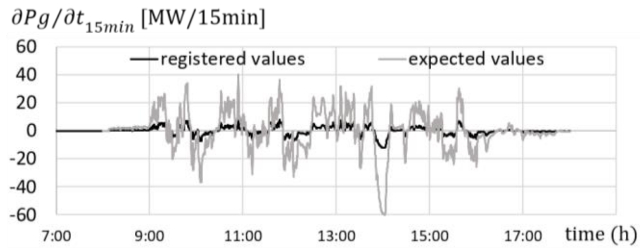
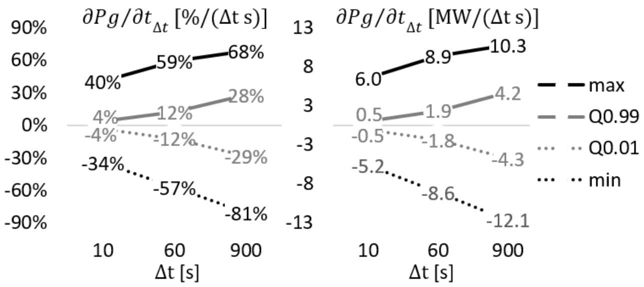


Figure 2. Daily time series of the 15-min ramp-rates for the total PV power in a disturbed day (registered and expected values)

Figure 3 provides a statistical characterization of the registered PV ramp-rates in year 2016, from applying (1) along the year with a sampling time, Δt, of 10 seconds, 1 minute and 15 minutes. Two graphics are presented with distinct units for PV power fluctuations: the one on the left, in percentage of the PV rated capacity per Δt seconds and the other in MW/Δt seconds. As observed in other real-case system analyses, namely in [10] and [11], the larger the sampling time, the larger are PV power fluctuations. As expected, the probability distributions of these PV fluctuations are approximately symmetrical, resulting from clouds passing. In the particular case of Madeira island, as presented in figure 3, the ramp-rate of total PV production can be as high as 60% of the rated capacity per minute (per 60 seconds) and 80% per 15 minutes (per 900 seconds).



Legend: max: maximum value; min: minimum value; Q_x: quantile x

Figure 3. Registered ramp-rate values for the total PV power production in year 2016 (statistical analysis)

Figure 4 provides a similar statistical characterization of PV ramp-rates, by comparing the registered behavior in year 2016 with the expected behavior for the future analyzed scenario. These results show that the magnitude of PV fluctuations is expected to largely increase after the connection of the new PV plants, which justifies the need to adopt new real-time control measures to mitigate PV power fluctuations in this power system. As shown in figure 4, quantiles 0.01 and 0.99 of PV ramp-rates are relatively far away from the extreme values, meaning that the probability for these extreme values is very low. However, a deeper analysis showed that the ramp-rates violating quantiles 0.01 and 0.99 are spread along many days of the year. This can be observed in figure 5 which presents the expected time series of 15-min ram-rates for the total PV power production during a full year. Therefore, for the sake of system security, even PV fluctuations outside quantiles 0.01 and 0.99 must be contained to acceptable values by some automatic procedure.

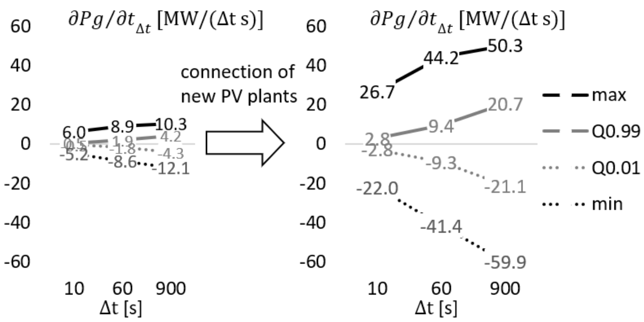


Figure 4. Expected ramp-rate values for the total PV power production along a year (statistical analysis)

C. Acceptable Limits for PV Fluctuations

In the particular case of the analyzed scenarios for the Madeira power system, and in order to prevent excessive frequency excursions, PV ramp-rates must not exceed about $\pm 11\text{MW}/10\text{s}$. These limits are imposed by the amount of frequency containment reserve that is planned for system operation. Moreover, ensuring a proper active power balancing control imposes the following constrains for the fluctuations of the total PV power production:

- A ceiling limit to power increases of 11 MW within each 15 minutes, i.e. when compared to the value of PV production in the beginning of each 15 minutes dispatch solution;
- A floor limit to power variations of -30 MW, within each 15 minutes, and with ramp-rate limits of $\pm 30\text{MW}/15\text{min}$.

The ceiling limit is defined by the adopted spinning reserve criteria to accommodate increases of power production in this power system. Therefore, it bounds upward PV power variations to secure values from an active power balance perspective.

For the secure accommodation of PV power production shortfalls, a dedicated automatic control is foreseen in this power system by regulating the production of a reversible hydro power plant, when in generation mode, being able to compensate, in about 11 minutes, an active power generation decrease of 30 MW. This was the reason to define, in this study, a floor limit to PV power variations of -30 MW, within each 15 minutes, with PV ramp-rate limited to $\pm 30\text{MW}/15\text{min}$. Moreover, PV power fluctuations violating these limits are accepted, provided that these variations do not exceed -40 MW, within each 15 minutes, with ramp-rate limited to $\pm 40\text{MW}/15\text{min}$. In fact, by assuming that these violations can be accurately forecasted and if occurring concentrated in a reduced number of days along a full year, these can be effectively managed via the implementation of preventive actions from system operators.

From the results of figure 4 and figure 5, it is evident that the expected PV fluctuations for the Madeira power system clearly violate the previously described acceptable limits. Therefore, without the adoption of new automatic control actions, the expected magnitude increase of PV power fluctuations may provoke operational security problems due to large frequency excursions and the lack of spinning reserve amount able to restore active power balance.

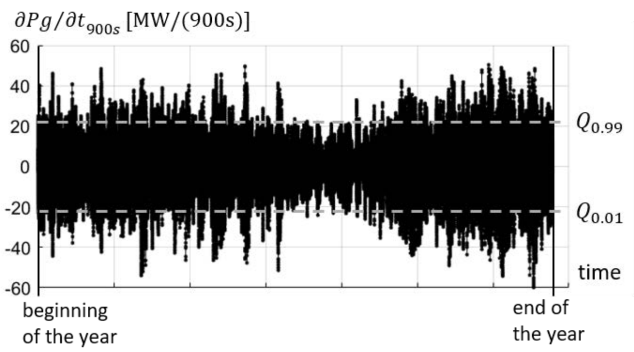


Figure 5. Annual time series of the 15-min ramp-rates for the expected total PV power production

III. Proposed Control Strategy to Mitigate PV Power Fluctuations

A. Rationale for the Proposed Control Strategy

In the presented work, a hybrid automatic control strategy is considered by combining MPPT control, together with the use of a BESS system. Upward PV power fluctuations are bounded to secure values by operating bellow the MPPT curve. The storage system is used to reduce the PV energy curtailment, caused by MPPT control, and to directly control PV power decays to acceptable values. A trade-off must be performed between the required power and energy rating for the BESS (resulting into investments costs) and the obtained annual PV energy curtailment (resulting into operational costs). At the same time, the control solution must be able to reduce PV power fluctuations to acceptable limits from the perspective of system security.

Among the available fast acting storage technologies, a battery was the preferred choice due to its good ratio between power and energy density, enabling charge/discharge power for long periods of time, and also for being a mature technology [14]. Using conventional thermal generation for balancing PV fluctuations was left to a last resort option of system operators, to maximize electricity production from renewable energy sources.

In the analyzed application, minimizing the BESS power rating is mandatory since the cost per unit power output may become an important factor of the BESS capital cost. In fact, a lower contribution of cell cost components can be expected as system size increases, since, for larger systems, power electronics converter costs become more relevant [15]. A detailed cost breakdown for BESS is often scarce or difficult to obtain due to confidentiality restrictions. However, from the literature review of recent developments for BESS, namely from the data presented in [14] and [16] for lithium-ion (Li-ion) batteries, the estimated capital cost for power converter (in \$/kW) may exceed the one estimated for energy (in \$/kWh). Therefore, aiming to minimize the BESS capital cost, the proposed approach was designed to minimize, mainly, the required power capacity of the BESS.

The control strategy was assumed to have a single centralized BESS, since a smoothing of PV power fluctuations is expected as a result of the geographical dispersion of PV plants [3]-[4], providing a filtering effect on the PV power fluctuations to be compensated by the BESS.

B. High-Level Architecture of the Control System

The high-level architecture assumed for the control system is illustrated in figure 6.

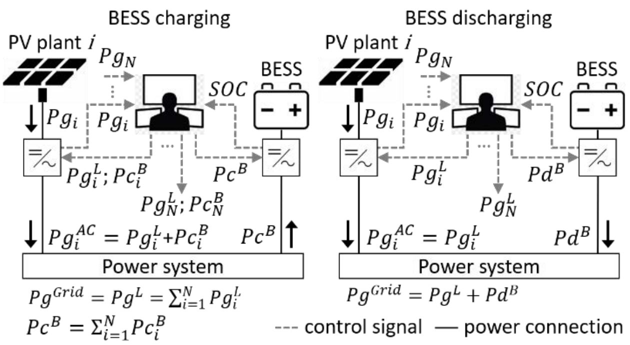


Figure 6. High-level architecture of the control system

In this figure, a distinction is performed between battery charging and discharging situations during daylight. The presented operating conditions are:

- N: number of connected PV power plants;
- Pg_i: active power provided by solar irradiance in PV power plant i;
- Pg_i^{AC}: active power production at the AC side of PV power plant i;
- Pg_i^L: the part of Pg_i^{AC} that results from applying, to Pg_i, the limits to power production increases;
- Pc_i^B: the remaining part of Pg_i^{AC}, used to charge the BESS;
- Pc^B: charging power at the AC side of the BESS;
- Pd^B: discharging power at the AC side of the BESS;
- SOC: battery state of charge.

With these values, the following operating conditions can be obtained at the control center:

- $Pg = \sum_{i=1}^{N} Pg_i$: total PV active power provided by solar irradiance;
- $Pg^{AC} = \sum_{i=1}^{N} Pg_i^{AC}$: total PV active power production at the AC side of PV power plants;
- $Pg^L = \sum_{i=1}^{N} Pg_i^L$: the part of Pg^{AC} that results from applying, to Pg, the limits to PV power increases;
- Pg^{Grid}: net value of the total PV active power production, being equal to Pg^L during battery charging and to $Pg^L + Pd^B$ during battery discharging.

C. Limits to PV Power Increases with MPPT control

In the designed control strategy, the limits to PV power production increases, implemented by operating bellow the MPPT curve, have the following settings:

- $\Delta Pg_{\max}$ (in MW): a ceiling limit to the total PV power production increases, when compared to the registered value in the beginning of each dispatch solution.
- $\partial Pg/\partial t_{max}$ (in %/min): a ramp-up limit to the PV power production variations, defined in percentage of the PV plant rated capacity per minute.

Regarding the presented high-level architecture of the control system (figure 6), these limits are applied to Pg_i, resulting in Pg_i^L. The total daily PV energy curtailment, in MWh, obtained in day d due to these settings is given by:

$$Eg_{loss}(d) = \sum_{i=1}^{N} \left(\int_{t_0}^{T} \left(Pg_i(t) - Pg_i^L(t) \right) \partial t \right), \quad (2)$$

where Pg_i and Pg_i^L are in MW. The values of t_0 and T are the first and last instant (in hours) of daylight in day d, respectively. The obtained annual PV energy curtailment, in percentage values, is given by:

$$(Eg_{loss}/Eg) \cdot 100, \quad (3)$$

with

$$Eg_{loss} = \sum_{d_0}^{D} Eg_{loss}(d), \quad (4)$$

$$Eg = \sum_{d_0}^{D} Eg(d), \quad (5)$$

$$Eg(d) = \sum_{i=1}^{N} \left(\int_{t_0}^{T} \left(Pg_i(t) \right) \partial t \right), \quad (6)$$

where Eg_{loss} is the annual PV energy curtailment in MWh. Eg is the annual PV energy that would be generated without applying limits to PV power production increases (in MWh), and d_0 and D are the first and last day of the year. Active power losses are neglected in this analysis.

D. Combining MPPT control with a BESS

Conditioned by the BESS operational constrains, namely the state of charge (SOC) limits, the charging/discharging efficiency and the inverters power rating, the BESS is used to store curtailed PV generation. Moreover, when PV production is dropping with a ramp-down value violating a pre-defined limit, $\partial Pg/\partial t_{min}$, the BESS discharges to reduce PV power decays to the defined $\partial Pg/\partial t_{min}$ ramp-down rate. Besides smoothing PV power fluctuations, this strategy is also able to further decrease the curtailed PV energy by moving some of the discharged energy for periods of the day where no storage is being required and, therefore, improving the SOC margin for storing more PV energy.

It is assumed that, during daylight, the BESS can only be energized from the PV systems. The battery SOC is supposed to be restored overnight, when no control is being required to the BESS. Therefore, it is assumed that, at sunrise, the SOC has a pre-defined value, SOC_{ini}, which is attained during the preceding hours.

If including the previously described BESS operation, the total daily PV energy curtailment, earlier computed by (2), is now given by (7).

$$Eg_{loss}(d) = \int_{t_0}^{T} \left(Pg(t) - Pg^{Grid}(t)\right) \partial t - Eg_{shift}^{night}, \quad (7)$$

with

$$Eg_{shift}^{night} = \left(\int_{t_0}^{T} \left(Pc^B(t) \cdot \eta_c - \frac{Pd^B(t)}{\eta_d}\right) \partial t\right) \cdot \eta_d, \quad (8)$$

if discharging during the night and with

$$Eg_{shift}^{night} = \left(\int_{t_0}^{T} \left(Pc^B(t) \cdot \eta_c - \frac{Pd^B(t)}{\eta_d}\right) \partial t\right) / \eta_c, \quad (9)$$

if charging during the night. Eg_{shift}^{night} is the PV generated energy shifted by the BESS for the following night. η_c and η_d is the charging and discharging efficiency of the BESS, respectively.

IV. Control Actions for Madeira Island

By following the proposed control strategy described in section III, a set of automatic control actions were designed to mitigate the expected PV power fluctuations in the Madeira power system. These actions were assumed to be applied only on the new PV plants (totalizing 60 MW of installed power), since these will be the cause for requiring those control measures. The adaptation of the defined control strategy to the Madeira use case comprises the sizing of the BESS system (namely, of the total power and energy rating) and the tuning of the following settings:

- ΔPg_{max}: ceiling limit to the total PV power production increases within each 15 minutes;
- $\partial Pg/\partial t_{max}$: ramp-up limit to PV power production variations;
- $\partial Pg/\partial t_{min}$: ramp-down limit to PV power production variations;
- SOC_{ini}: battery SOC at sunrise.

To obtain a feasible BESS sizing and a parameter tuning solution, a comprehensive analysis was performed of the historical daily time series of PV power production already described in section II. The obtained results are described next.

A. Limits to PV Power Increases with MPPT control

As explained in section II, a ceiling limit of 11 MW was defined for the total PV power production increases within each 15 minutes (i.e., ΔPg_{max}=11 MW). Figure 7 presents the expected total PV power production obtained with/without applying this ceiling limit by MPPT control, during a disturbed day (the one illustrated in figure 1). By applying this control, the expected annual PV energy curtailment is only 0.8% (loss of 822 MWh in a total PV production of 108 GWh).

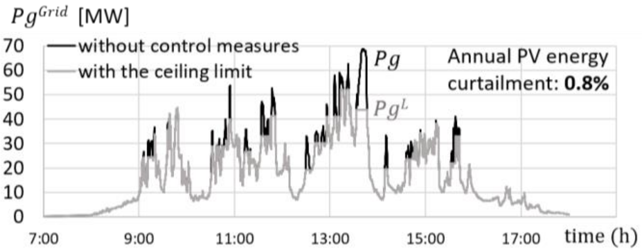


Figure 7. Expected total PV power production in the illustrated disturbed day (with/without ceiling limit = 11 MW in each 15 minutes)

Figure 8 summarizes the expected fluctuations for the total PV power production regarding the defined ramp-rates limits of $\pm$11MW/10s (criteria c1), $\pm$30MW/15min (criteria c2) and the ceiling and floor limits within each 15 minutes of 11 MW and −30 MW, respectively (criteria 3). Here we can see that, apart from the ceiling limit of 11 MW, the expected total PV fluctuations violate all the defined criteria, compromising system security. Therefore, besides performing a ceiling control, a ramp-up limit, $\partial Pg/\partial t_{max}$, was also considered be to contain PV fluctuations.

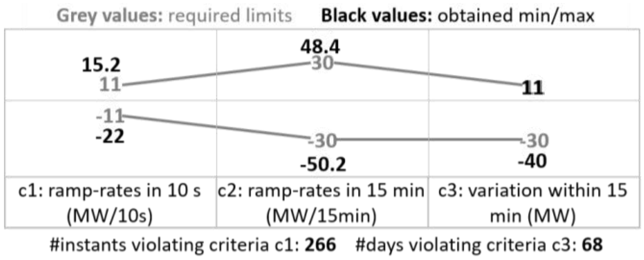


Figure 8. Expected fluctuations for the total PV power production along a year (with a ceiling of 11 MW in each 15 minutes)

From a trial-error procedure, no constant ramp-up limit was found being able to reduce, together with the applied ceiling limit, PV power fluctuations to acceptable limits with a small annual PV energy curtailment. The best trade-off was obtained for a ramp-up limit, $\partial Pg/\partial t_{max}$, of 0.6 MW/min (i.e., of 1%/min applied only to the new PV plants), providing the results summarized in figure 9.

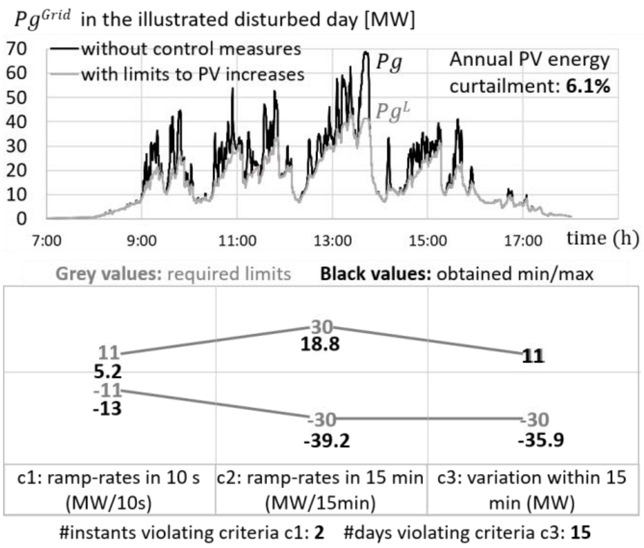


Figure 9. Expected results (ceiling: 11 MW; max ramp-up: 1%/min applied in new PV plants)

The expected annual PV energy curtailment is now about 6.1% and the magnitude of expected downward PV fluctuations within each 15 minutes reaches -35.9 MW (with a maximum ramp-rate of -39.2 MW/15min). PV fluctuations exceeding the floor limit of -30 MW are expected to occur in 15 days spread along the year, which may endanger system security by, frequently, requiring operators to take manual control actions. As described next, by also controlling a BESS with a nominal power around 13% of the total PV installed power (i.e., a BESS of 10 MW for 75 MW of installed PV), it is possible to significantly reduce PV curtailment and smooth PV power fluctuations to acceptable values.

B. Combining MPPT control with a BESS

In this analysis, the following characteristics were assumed for a BESS: a) the battery is allowed to operate between a range of 20% to 90% of the SOC capacity; b) the charging and discharging efficiency is 90% (i.e., $\eta_c = \eta_d = 0.9$). The system operator also defined some boundaries for the investment costs with a BESS, namely, by specifying a maximum value of 10 MW for the BESS total power rating, Pn, and with an energy rating, En, not larger than two times the power rating (i.e., $En/Pn \leq 2$). In this analysis, a Li-ion battery-based storage was assumed. However, the applied methodology is equally valid for any other type of energy storage system.

From a trial-error procedure, the following two control solutions were found:

a) a BESS with a total rating of 5 MW/10 MWh operated with SOC value at sunrise, SOC_{ini}, of 20%;

b) a BESS with a total rating of 10 MW/20 MWh and with a SOC_{ini} of 40%.

Both control solutions apply a ceiling limit of 11 MW in each 15 minutes for the total PV power production (i.e., ΔPg_{max}=11 MW) and ramp-rate limits of $\pm$0.5%/min for the new PV plants (i.e., $\partial Pg/\partial t_{max}$= 0.5%/min obtained with MPPT control and $\partial Pg/\partial t_{min} = -0.5$%/min obtained with BESS discharge). The results when using a BESS of 5 MW/10 MWh are summarized in figure 10. Figure 11 presents the expected results with the BESS of 10 MW/20 MWh.

According to the acceptable limits defined for the PV power fluctuations described in section II, both BESS control solutions provide secure results from an active power balance perspective. However, with a BESS of 5 MW/10 MWh, PV fluctuations still exceed the floor limit of -30 MW, within 15 minutes, and the ramp-rate limits of $\pm 30\mathrm{MW/15min}$. These limits are exceeded only during 3 days in a year, being therefore an acceptable situation. For obvious reasons, the expected annual PV energy curtailment is lower with a BESS of 10 MW/20 MWh (being 3.5% with a BESS of 5 MW/10 MWh and just 1.7% with a BESS of 10 MW/20 MWh). The two identified control solutions can also help in better estimating the Levelized Cost of Energy for the future PV plants in Madeira and, therefore, to provide an initial value for the remuneration of energy obtained from these PV systems.

Here, it is important to remark that if the analyzed PV fluctuations were to be mitigated by only using a BESS (i.e., without MPPT control), this would require a BESS capacity around 40 MW/30 MWh. In fact, this was the obtained BESS sizing, in a scenario of only using this storage system to apply, for the total PV power production, a ceiling limit of 11 MW (i.e., ΔPg_{max} =11 MW) and ramp-rate limits of $\pm$30MW/15min (i.e., of $\pm$2.7%/min for all the PV plants). Figure 12 presents the obtained expected PV fluctuation results if adopting this control solution.

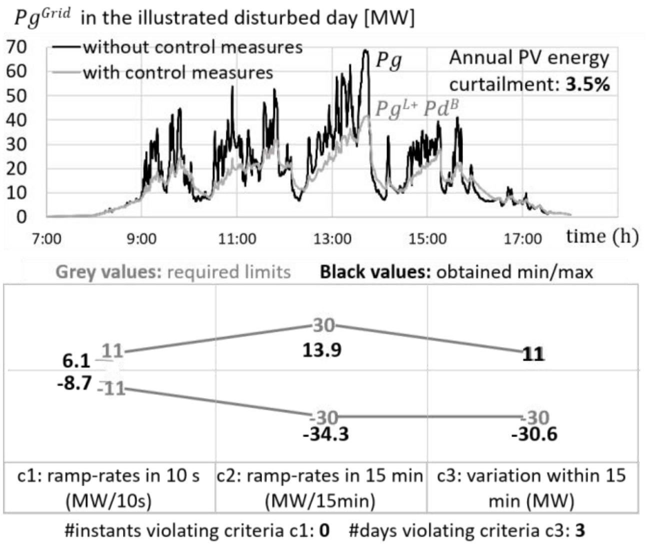


Figure 10. Expected results with a BESS of 5 MW/10 MWh (ceiling: 11 MW; ramp-rate limits +/-0.5%/min applied in new PV plants)

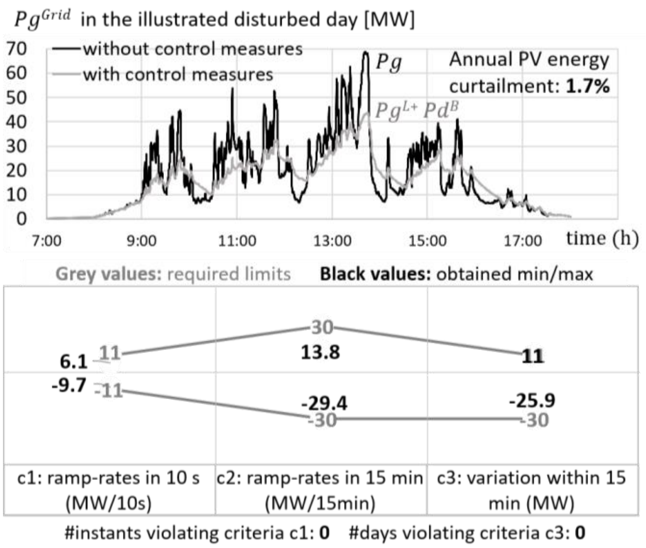


Figure 11. Expected results with a BESS of 10 MW/20 MWh (ceiling: 11 MW; ramp-rate limits +/-0.5%/min applied in new PV plants)

C. Battery Cycle Life Evaluation

A final concern was to evaluate the impact of the intended operation of the BESS in battery cycle life, considering the time-dependency of the PV variability in the Madeira power system. For this analysis, lifetime characteristics were assumed to be similar to the typical ones described by manufactures for Li-ion technology, namely the ones described in [17]. Battery cycle life is expressed as the number of charge/discharge cycles that can be achieved, depending on the depth of discharges (DOD), before reaching its end of life. End of life is reached if obtaining a reduction of 30% from the initial battery SOC capacity. According to [17], around 8 thousand cycles of 80% DOD are allowed before reaching the end of battery cycle life. The number of cycles before reaching the end of life increases with the reduction of the DOD value.

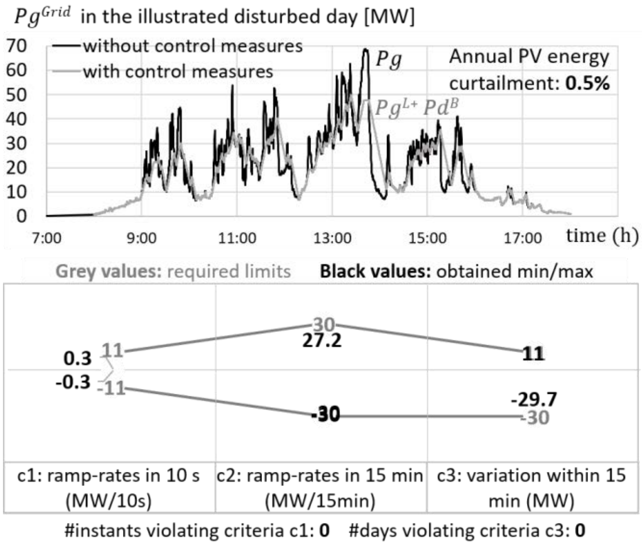


Figure 12. Expected results with a BESS of 40 MW/30 MWh without MPPT control (ceiling: 11 MW; ramp-rate limits +/-2.7%/min applied in all PV plants)

As illustrated in figure 13, in the analyzed study case, the expected depth of each discharge changes significantly, due to the intermittent behavior of the PV power sources. Therefore, to measure the equivalent number of full discharges after a time period, an 80% DOD was set to be one equivalent full discharge. For discharges with a smaller DOD, a proportion of one equivalent full discharge was assigned according to:

$$EFD(DOD) = \#cycles(80\%)/\#cycles(DOD), \quad (10)$$

where $EFD(DOD)$ is the equivalent full discharge for a discharge with a depth DOD $\in]0; 80[\%$; $\#cycles(80\%)$ is the number of cycles before reaching the end of life for a DOD $= 80\%$; $\#cycles(DOD)$ is the number of cycles before reaching the end of life for a DOD $\in]0; 80[\%$.

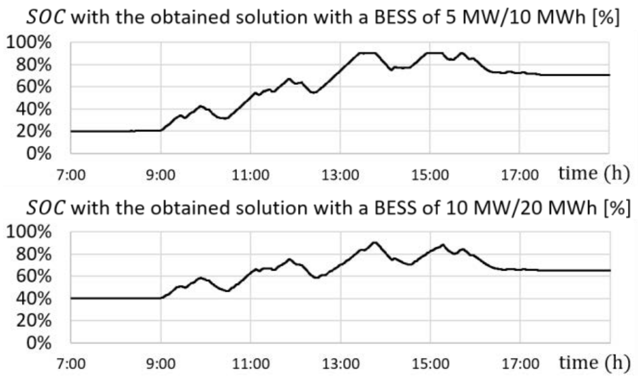


Figure 13. Expected SOC time evolution, in the illustrated disturbed day, if adopting one of the feasible control solutions

By following this EFD measurement procedure with the analyzed historical data, and assuming the intended operation for the BESS with each feasible control solution found, the following total number of equivalent full discharges were obtained after one year of operation: around 522 with a BESS of 5 MW/10 MWh and 400 with a BESS of 10 MW/20 MWh. Assuming that the end of life (i.e., a capacity reduction of 30%) is reached after 8 thousand cycles of equivalent full discharges, the estimated time period for the battery end of cycle life is about 15 years with a BESS of 5 MW/10 MWh and 20 years with a BESS of 10 MW/20MWh. These are usual values for the end of life cycle of Li-ion batteries. Therefore, with the proposed control strategy, an acceptable impact is obtained for the battery life cycle in the Madeira power system.

V. CONCLUSIONS

In this research, a new control strategy was developed to mitigate short- and mid-term PV power fluctuations in a real-case islanded power system with large PV power penetration. Without adopting new control actions, like the ones proposed in this work, the expected increases in PV power fluctuations will surely provoke security loss due to large short-term ramp-rates, leading to large frequency excursions, and to the lack of spinning reserve amount able to restore power balance. The proposed solution combines the use of limits to the magnitude and ramp-rate of PV power increases, by MPPT control, with the use of a BESS. The BESS sizing and parameter tuning of the defined control strategy depend on a trade-off between the investment on the BESS and the operating costs with PV power curtailment. With the presented results for expected scenarios in the Madeira power system, the adopted approach showed that including a BESS with a relatively small power rating, the annual PV energy curtailment can be effectively reduced, while PV power fluctuation magnitudes and ramp-rates are limited to acceptable values from an active power balance and frequency stability perspective.

This approach can be replicated in other isolated systems to allow increased penetration levels of PV power generation, without compromising the active power balancing and also avoiding large frequency excursions in the power system.

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