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Power management strategies and energy storage needs to increase the operability of photovoltaic plants

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This paper analyzes the effect of introducing an energy storage (ES) system in an intermittent renewable energy power plant such as a photovoltaic (PV) installation. The aim of this integration is to achieve an improvement in the operability of these power plants by increasing their production predictability. This will allow a further PV integration within the electrical power system, facilitating the system's load–demand balance. In this manner, the paper proposes two power management strategies (PMSs), each with different configurations, for operating a PV power plant: the first focuses on fixing constant power production and the latter focuses on reducing the high frequency fluctuations of the production. Thereafter, this paper analyzes and quantifies the ratings of the ES system (ESS) required to ensure a reliable performance of the plant on an annual basis for each of the PMSs with their different possible configurations. The resulting ES ratings vary with these PMS configurations. It can be concluded that significant improvements in production predictability are achieved with an ESS energy capacity of approximately 50% of the average daily energy produced by the PV panels and a power rating of around 55% of the plant's rated power. All the results are based on 1-year-long simulations which used real irradiance data sampled every 2 min. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4765696]

I. INTRODUCTION

Thanks to the increased financial stimulus experienced by renewable energies across the planet during the last decade, photovoltaic (PV) systems have emerged as an important power source.[1,2] Nowadays, solar power is rapidly growing as an effective renewable source of electrical energy.[3,4] However, this promising evolution of the PV power capacity faces a challenge in achieving large penetration into the electrical power system (EPS) due to the stochastic nature of the solar resource. In fact, this is an issue for most of the renewable energy sources (RESs), which usually present intermittent production. For PV and other intermittent RESs, a more controllable and nonfluctuating production should be assured to increase their share in the generation mix while offering some ancillary services.[5] This fact also paves the way for the implementation of hybrid generation technologies and the integration of energy storage (ES) systems into PV power plants.[6–8] The first analysis of ES integration into PV power plants dates from 20 years ago.[9] However, the youngness of ES technologies and the small size of the PV power plants at that time made this solution impractical. Subsequently, in the early 2000s, when the renewable experience arose, this topic regained importance. As an example, note the creation of a European Network for Investigation on Storage Technologies for Intermittent Renewable Energies (INVESTIRE),[10] established between 2001 and 2003 under the Fifth EU Framework Program, which made a thorough study of the contribution of ES systems (ESSs) to the integration of renewable generators. The main objective of the Network was to evaluate the maturity of storage technologies and to recommend R&D strategies to improve their use with renewables.

Nevertheless, it was not until recent years that a significant development in most ES technologies (REDOX, Li-Ion and NaS batteries, supercapacitors, etc.) was achieved. This great development coincides in a moment of increasing demands on the operating conditions of large renewable generation systems, which are getting larger and larger. As a result, the possibility of implementing ESSs in PV power plants has become an issue of particular relevance nowadays.[11–18] This research is being further complemented by demonstration projects, like the one started in 2010 as part of the Eurogia + cluster,[19] in which a demonstration PV power plant with 1.1 MW of lithium ion batteries has been developed with the overall objective of reducing the cost of energy, providing ancillary services, improving network stability, and offering back-up functions.

Therefore, the technical interest in introducing ESSs in PV plants is clear and the question that arises is what their energy and power capacities should be and how the combined PV + ES production should be managed. This paper deals with both issues, proposing two different power management strategies (PMSs) and assessing the ESS rating that is required for each of them. The installation of an ESS in a PV power plant introduces a considerable cost increase, apart from the additional space needed for its location, and therefore it is important to optimize both its rating and its exploitation strategy. The analysis conducted in this paper returns some significant figures regarding the ESS power and energy capacity ratings which would guarantee a certain degree of confidence throughout the year when forcing the PV plant to track a particular PMS. This should help PV plant designers to select the optimal ESS rating according to a given expected performance. The structure of the prototype PV + ES power plant considered is represented in Figure 1.

The paper starts by describing and analyzing the characteristics of the power generated by a generic PV plant, discussing the interest of including an ESS, and defining some advanced operational characteristics that can be achieved thanks to the introduction of ES. Then, Sec. III introduces the two different PMSs proposed for use in PV power plants. Section IV focuses on defining the type of analysis performed. The simulation results are presented and discussed in Sec. V. Finally, some concluding remarks are stated in the last section.

II. OPERATION OF PV POWER PLANTS WITH ENERGY STORAGE

A. Characteristic production by PV plants

The characteristic power production of a particular PV plant at a location on the Earth can be derived from the analysis of the solar irradiance and irradiation levels at that location during a particular period of time. This analysis provides information on how much and how frequently the sun's energy strikes a surface. Unlike wind resource, which varies in a stochastic way, with the statistical distribution of wind speed being similar to a Weibull distribution,[20] the solar resource cannot be so clearly assimilated in any statistical model. Nevertheless, knowledge of irradiance levels is needed for effective research into solar energy applications.[21] Due to the cost and difficulty of measuring them, irradiance values are not normally available[22] and many mathematical models have been required to estimate the data of the irradiance that is expected to come into contact with a certain tilted plane at a given location.[23–28]

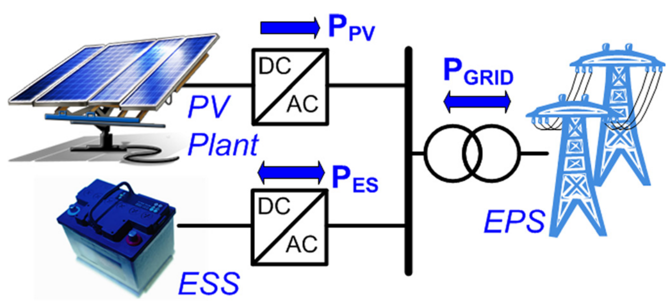

FIG. 1. Prototype grid-tied PV power plant with a generic ESS.

However, since models are locally adapted and depend on different estimations and approximations, none of them can assure an accurate instantaneous irradiance prediction in any place at any time. As a matter of fact, this forecasted value largely varies as a function of the stochastic atmospheric phenomena (clouds) which take place at many orders of magnitude both spatially and temporally.[29] The scales of these phenomena range from local clouds on distance scales of hundreds of meters and timescales of seconds to seasonal variations on global geographic scales.

Modeled global irradiance data approximations can be consulted in several international irradiance databases (SolarGIS, PVGIS, Satel·light, SoDa, ESRA, SOLEMI, etc.) as well as different meteorological agencies and other sources such as NASA or ESA. Most of them are compared and analyzed in Šúri *et al.*[30]

In this paper, the analysis focuses on one specific location in the south of Spain (Sanlúcar la Mayor). Its expected daily irradiance patterns have been extracted from the PVGIS solar database. This database provides the monthly statistically averaged clear and real sky patterns at any location all over Europe throughout a year. These patterns, normally obtained for an optimal tilted plane (around 33° in the location under study), reflect clear differences for fall and winter months, as can be observed in Figure 2, mainly due to the frequent presence of clouds during these two seasons.

Apart from these statistical patterns, actual irradiance values measured at the selected location throughout the year 2009 have been used in this work. These data contain a time series of 365 days' irradiance values sampled every 2 min, which is accurate enough to estimate the effect of the passing clouds and the expected plant energy yield.[31] These values can be used to represent the spectrum of the power produced throughout the year by a PV plant installed at that location. This is represented in Figure 3, where two different sets of data have been introduced: a dispersion of points which represent the spectra of different groups of days and a continuous line which represents the averaged value of the power spectrum. The clear day–night repetition pattern around 86 400 s (24 h) and its harmonics can be seen, as well as the stochastic nature of the variations due to clouds at higher frequencies.

B. ES improvements, characteristics, and selection

The integration of ES will provide PV power plants with advanced control characteristics such as power production predictability improvement (capacity firming[32]) and power production smoothing.[7] Regarding the first, it seems likely that it should be compulsory in the coming future to be able to forecast the amount of power supplied by renewables to be injected into the grid with a certain degree of confidence some hours in advance, as is already the case for other types of generators.[33] This will pave the way not only for an extended penetration of PV installations but also for their access to the electricity markets. On the other hand, although PV production smoothing is not currently a grid requirement for renewables in general, a reduction in the fluctuations of the power generated by PV plants is desirable and could also be demanded

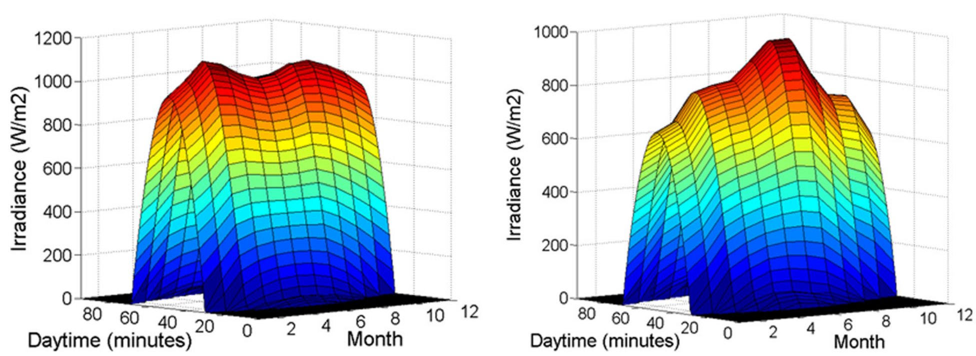

FIG. 2. Standard irradiance for each month on a 33° tilted plane in the south of Spain. (a) Clear sky conditions, ideal irradiance. (b) Real sky conditions, average daily expected irradiance.

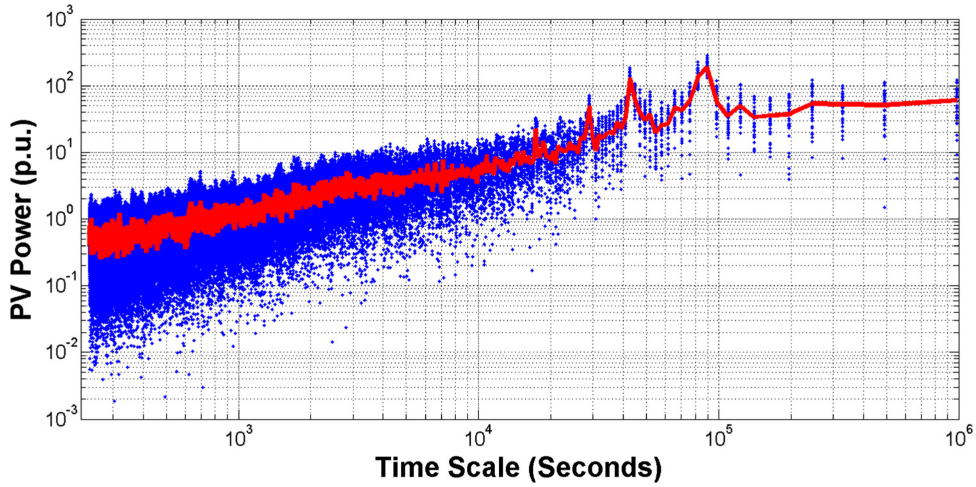

FIG. 3. PV power spectrum on the selected site (Sanlúcar la Mayor, Spain).

in the near future by grid operators to guarantee a stable and balanced operation. This smoothing can be obtained by running the ESS as an energy buffer, that is, by reducing the variability of the production with reference to an average value. The time horizon of such a control strategy would stretch from seconds to hours depending on the size of the ESS. The size or the energy ratings required by the ESS could be reduced if the same PV production smoothing was programmed as a combination of an ESS integration with other techniques that have already been proposed in the literature, for example, with accurate solar forecasting methods[34] and geographic smoothing through aggregation of different power plants.[35,36]

Various reviews can also be found in the literature which analyze the current development status of the most important ES technologies available in the market.[5,6,37,38] Some of these works also classify these ES technologies and examine their corresponding characteristics and possible applications. Among the different classifications proposed, a widely accepted one is that dividing ES technologies between those storing energy in an electromagnetic way (direct storage) and those storing energy in a mechanical or chemical way (indirect storage). In the direct storage group, technologies such as ultracapacitors (UCs) or superconducting magnetic energy storage (SMES) can be highlighted, while in the other group, technologies such as pumped hydro (PHES), compressed air (CAES), or flywheels (FESSs) can be pointed out as mechanical systems and fuel cells (FCs) or batteries (BESS) as chemical ones.

Amongst these ES technologies, few are able to meet the requirements of PV power plant applications. These requirements determine fast reaction time, high efficiency, ability to independently size storage power and capacity, reduced physical size to be placed on the location, ease of maintenance, long lifecycle, and maturity of the technology.[39] According to them, CAES or PHES could not be used due to their geographical dependence and limited modularity, while others present limitations in terms of maturity (SMES) and low efficiency (FCs). Then, although UCs and FESSs could be used for certain high power, low energy applications, batteries arise as the key technology to be integrated within PV power plants. On the one hand, among the different battery technologies, lead-acid battery systems have been mostly used in past applications, mainly due to their maturity and low cost, but performance limitations, short lifecycles, and high maintenance demands have limited their adoption in PV applications. On the other hand, breakthroughs in a new generation of lithium ion based BESSs are entering the market, meeting most of the PV power plants' operation requirements. Moreover, a significant improvement in their performance is expected in the near future due to the large research effort that is taking place in this field, especially focused on its potential application in electric vehicles.[40,41] In this manner, lithium ion batteries are considered to be the candidate technology for use in PV + ES plants in the next years for operation with high energy demand strategies.

However, other ES technologies such as the aforementioned UCs or FESSs could be applied in combination with lithium ion batteries to provide smoothing or other low energy strategies.

III. PROPOSED POWER MANAGEMENT STRATEGIES

The extended operation functionalities that a PV power plant with ES can offer to the grid depend not only on the power and energy rating of the ESS incorporated but also on the PMS implemented in the plant control system. This work proposes two different PMSs to convert the PV instantaneous and stochastic production into a controlled generation useful for the grid. These strategies have been called "constant output" and "fluctuations reduction," and have been designed to cope with two potential grid-connection requirements for renewable energy generators: power capacity firming and output smoothing, respectively.

In any case, the PV power plant production will now track a power reference generated by the control system according to the following equation:

$$P_{ref} = (P_{pv} + P_{ES}), \tag{1}$$

where P_{ref} is the reference power (dependent on the control strategy), P_{pv} is the instantaneous power provided by the PV panels (dependent mainly on time, location, and weather), and P_{ES} is the current power which will have to be delivered or received by the ESS. This is in turn

$$\text{Discharge} : P_{ES} > 0 \rightarrow dE_{ES}/dt = -P_{ES}/\varepsilon_d, \tag{2}$$

$$\text{Charge} : P_{ES} < 0 \rightarrow dE_{ES}/dt = -P_{ES} \times \varepsilon_c, \tag{3}$$

where E_{ES} is the energy stored (available in the ES), while ε_c and ε_d are the charging and discharging efficiencies, respectively.

Thus, P_{ES} is adjusted so as to complement the PV panels' production and therefore achieve control over the power produced by the power plant, hence improving its predictability. The two different PMSs, named constant output power and fluctuations reduction, are presented and analyzed in the following.

A. Constant output power management strategy (COPMS)

This first PMS is based on setting constant values of power (constant power steps) as P_{ref} for the PV power plant. Its main goal is to provide power capacity firming, that is, a more stable and predictable production which could be traded in the electricity markets with high reliability. Electricity markets' configurations are quite diverse worldwide although they are normally run in a continuous way and present constant settlement periods of 1 h or less. For the specific case of the Iberian Electricity Market (MIBEL), which was used as a reference for the analysis presented in this paper, the settlement periods are 1 h long and the production is traded the day before (although it also presents an intraday market with six sessions in which production can be renegotiated).

The number of steps defining the P_{ref} to be tracked in this PMS will be decided by the plant operator as a function of the electricity market conditions. Then, the duration of the steps is adapted to the 1-h settlement periods of the market. Thereafter, the value of the power to be generated during each of the steps is calculated so that over the whole day it will match the PV production defined by the PVGIS clear sky model for that day. Thus, an initial P_{ref} is defined but this is then adjusted by a weather based correction which takes into account the actual weather conditions (Figure 4). This correction will be null for clear days but will modify the reference (reducing it as a function of the weather forecast and using the PVGIS real sky model) during cloudy days.

Figure 5 represents four different energy production reorganization patterns for a clear day (a four-step type, a single 6-h step, a single 10-h step, and a single 14-h step). All of them generate the same amount of energy over the day. It can be noticed that this PMS works very well

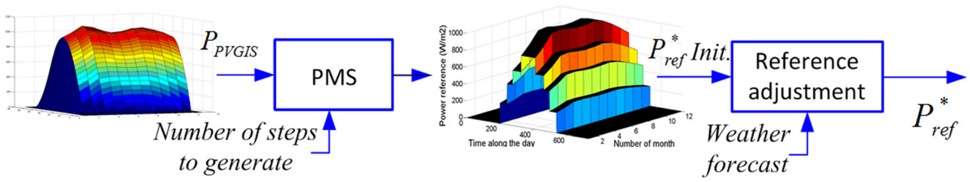

FIG. 4. COPMS steps generation flowchart.

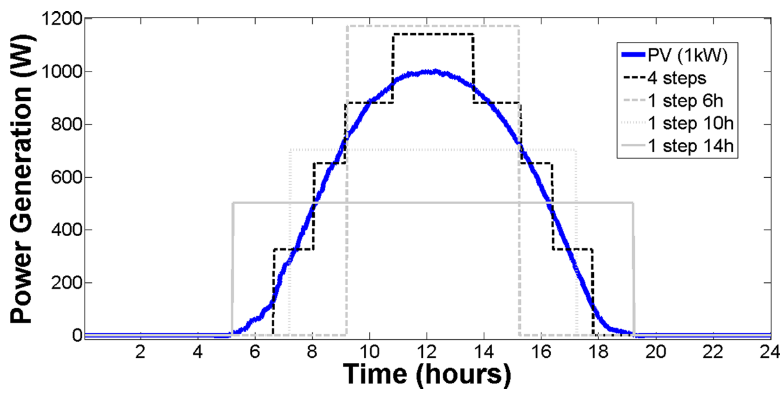

FIG. 5. Resulting P_{ref} for different configurations of the constant power steps PMS for a sunny day.

on clear days when the production pattern extracted from PVGIS fits the actual PV production well. However, this PMS is not so precise for cloudy days when larger amounts of ES capacity will be required to avoid system saturations due to unpredicted sudden PV power variations. This is one of the reasons why, in order to get a reference idea of the ESS requirements for operating the PV plant in this PMS, the sizing analysis has been performed on an annual basis (including clear and cloudy days) and has considered the power generation with the same number of steps every day.

B. Fluctuations-reduction power management strategy (FRPMS)

This second PMS is focused on smoothing out the irregular PV production. Thus, it flattens the power delivered by the PV power plant to the grid using the ESS as an energy filter. In this manner, the goal of this strategy is to remove the high frequency component of the power generated by the PV plant.

Therefore, the input to the control system for this PMS is the instantaneous actual PV production, which is fed to the low-pass first-order discrete filter presented in Eq. (4)

$$Filter_{tf}(z) = \frac{(1-a)}{(1-a/z)}, \quad \text{with} \quad \omega_c = \frac{1}{\tau} = -\frac{\log(a)}{T}, \tag{4}$$

where ω_c is the cutting frequency, τ its time constant, and T the sampling time of the input signal (2 min in this case). The filter characteristic parameter "a" is adapted by choosing the τ value according to the degree of fluctuations in the power to be removed. Then, Eq. (4) provides a smoothed power curve which is used as the new P_{ref} for the PV power plant. Some examples of PV power smoothing can be observed in Figure 6, where a 3-day simulation with a high presence of passing clouds has been represented. Note that, as the degree of filtering increases ("a" becomes closer to 1), a more constant production can be obtained but also a higher ESS capacity will be required. However, PV plant operations with degrees of filtering beyond 0.97 would not deliver significant benefits to the grid but at the same time they require

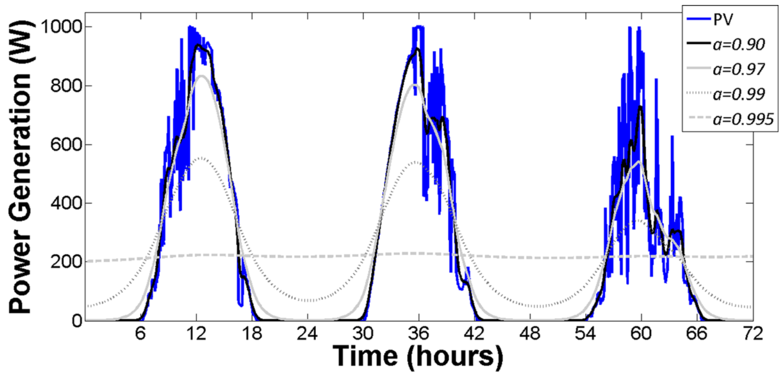

FIG. 6. Resulting P_{ref} for different configurations of the fluctuations-reduction PMS during three cloudy days.

enormous amounts of ES. Thus, these levels of filtering will not normally be considered for practical use.

Unlike the previous strategy, the FRPMS seems inappropriate for clear days with low power fluctuations, being more useful for cloudy days. Therefore, this PMS should be applied for smoothing out the PV production, reducing the intermittent solar power spikes and valleys, and making the operation and planning of the EPS easier. However, it would not enable PV power plants to access the electricity markets with highly predictable production.

IV. RELATIONSHIP BETWEEN THE PMS AND THE ESS RATING

Taking into account its current elevated cost, it is important to define the minimum ESS rating necessary to achieve the objectives of the selected PMS. However, given that the data used to manage the plant are based on statistics and on weather forecasts and that the real operation of the plant is stochastic, the only way to guarantee that the PMS objectives are mostly fulfilled is by assigning the worst case ratings to the ESS. If an ideal estimation of the future PV production was available, the best case ratings for each PMS could be easily calculated. However, in practice there will always be an error in the estimation of the actual production, and consequently the ESS should be overrated to overcome these possible deviations. In this way, if a 100% operation guarantee is required, the ES should be rated to full PV plant power and for the daily maximum produced energy, which would involve installing an enormous, unaffordable ESS. On the contrary, if the error is bounded to a certain margin, the overrating can also be limited although estimation errors can bring situations in which it will not be possible to track the PMS reference either because the ESS is full or because it has run out of energy. In order to minimize these situations, an improved operation of the PV power plant working under any of the PMSs can be achieved by introducing a control loop which continuously monitors the state of charge (SOC) of the ESS. This SOC supervision allows a reference SOC (SOC_{fv}) to be defined that will be regained every time the instantaneous SOC deviates within a defined time period (τ_{SOC}). In this way, saturations of the ESS can be minimized (reducing SOC oscillations) and a smaller ESS can be introduced to properly track the same P_{ref}. Conversely, the production is distorted with regard to the ideally defined P_{ref}. This distortion is due to the power devoted to recovering the SOC_{fv} level within that τ_{SOC}. Thus, the global equation driving the operation of the PV + ES plant, with this complementary control being active, can be defined as

$$P_{ES} = (P_{ref} - P_{pv}) + \frac{(E_{ES} - E_{ES\,\max} \times SOC_{fv})}{\tau_{SOC}}, \tag{5}$$

where

- P_{ref}—current power required at the point of common coupling (PCC),
- P_{pv}—current solar photovoltaic power,

- E_{ES}—current ESS energy,
- E_{ESmax}—energy capacity of ESS,
- SOC_{fv}—reference state of charge, as a percentage of the energy capacity,
- τ_{SOC}—storage charge time constant.

Therefore, Eq. (5) is an evolution of (1) that is focused on tracking the P_{ref} defined by each PMS, which includes a term defining the SOC supervisory complementary control (in charge of keeping the instantaneous SOC as close as possible to SOC_{fv}). As already introduced, note that this new term influences the dynamics of the system by modifying the ideal response of the plant. The tradeoff between the two opposite effects (reducing the need for large ESS energy capacities versus a higher generated power distortion) is mainly defined by the τ_{SOC} value. Generally, this tradeoff value has been fixed to $\tau_{SOC} = 24\,\text{h}$, and this value is used in all those analyses presented in the following where the influence of τ_{SOC} was not subject to analysis.

V. RESULTS AND DISCUSSION

The two PMSs described have been simulated considering a 1-MW-rated PV plant like that in Figure 1. The actual irradiance values presented in Sec. II were used to simulate a whole year of operation of the plant using these values to define the production assigned to the PV panels of the plant. Then, this production was analyzed in combination with the P_{ref}, previously defined according to the PVGIS, to analyze the amount of ES needed to operate the plant according to the different PMSs. This has been done using MATLAB/SIMULINK® and two main types of results have been obtained: those related to the improvement in plant operability and those related to the ESS sizing. Both are introduced and discussed in the following.

A. PV power availability and predictability improvement

First of all, if an ESS large enough to avoid saturations is introduced and the system is considered ideal (no losses while charging or discharging the ESS), the optimal improvement in power availability and predictability that could be achieved with each of the PMS configurations can be statistically determined. This is done by means of the plant's production cumulative distribution function (CDF), which describes the probability that the PV production will be at least equal to or higher than a given percentage of the total PV plant rated power over the year.

Therefore, Figure 7 represents the CDF for the different power production patterns presented in Figures 5 and 6. Note that the CDF of the PV power plant production can be modified enormously by the different PMSs, ranging from a low power value production that is a hardly constant in time (the case which approximately corresponds to the FRPMS with $a = 0.995$ in the figure) to a high power value production that is assured during approximately 35% of the calculated time only (the case of using the constant power strategy with an 8-h step with a

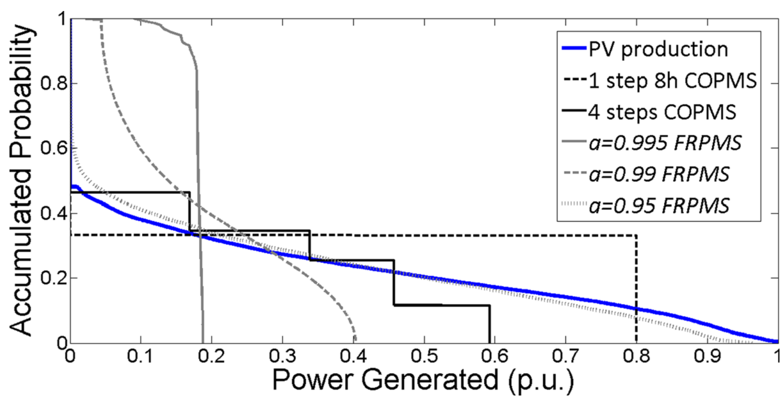

FIG. 7. CDF for the PV + ES power output operating under different PMS.

power value equal to 0.8 p.u. (per unit)). Thus, the fractions of time when high or low power levels are generated can be modified by using the ESS as a function of the PMS implemented. On the contrary, note also how the CDFs resulting for the COPMS are more constant than those obtained for the FRPMS, which could be expected given their different goals.

Finally, it can be concluded from the results represented in Figure 7 that by implementing any of the PMS configurations previously introduced, mainly those of the COPMS, the CDF of the PV plant power production can be made more regular and therefore its predictability can be improved.

B. PV power production smoothing

Similarly, the smoothing effect achieved with the ES introduction is also analyzed. The smoothing out comprehends a general reduction in the fluctuations of the PV power production, that is, it reduces the variability of the instantaneous production with reference to an average value over a period (its standard deviation). This effect makes sense mainly for the fluctuations-reduction PMS, as observed in Figure 6, and is clearly reflected in the frequency spectrum of the curves (Figure 8). This figure represents the comparison between the initial PV power production spectrum, averaged as represented in Figure 3 and the PV + ES power plant production spectrum, also averaged, for a filtering level with "$a = 0.95$." The reduction in the high frequency region can be clearly appreciated.

The amount of reduction in yearly variability can be determined by calculating the standard deviation of the plant production and comparing it with the initial PV production. This comparison is presented in Table I, from which the amount by which the variability is reduced as the filtering level is increased can be deduced. Note that $\tau_{SOC} = 24$ h has been fixed in this case. Also, the timeframe considered in order to determine the standard deviation is the whole year, when the mean actual production value is calculated to be 0.2256 p.u.

Therefore, a clear reduction in the PV power production variability, that is, a smoothing of the production, can be confirmed when a large enough ESS is introduced and the proper PMS is implemented. However, it has been previously mentioned that due to the excessive ESS ratings that will be required and the small contribution to the grid operability of introducing filtering levels beyond "$a = 0.97$," these will not be implemented in real installations.

C. ESS ratings needed to obtain the different operability improvements

From the results for both the improvement in predictability and reduction in variability, it can be concluded that the operability of PV power plants can be improved by using ESS. The

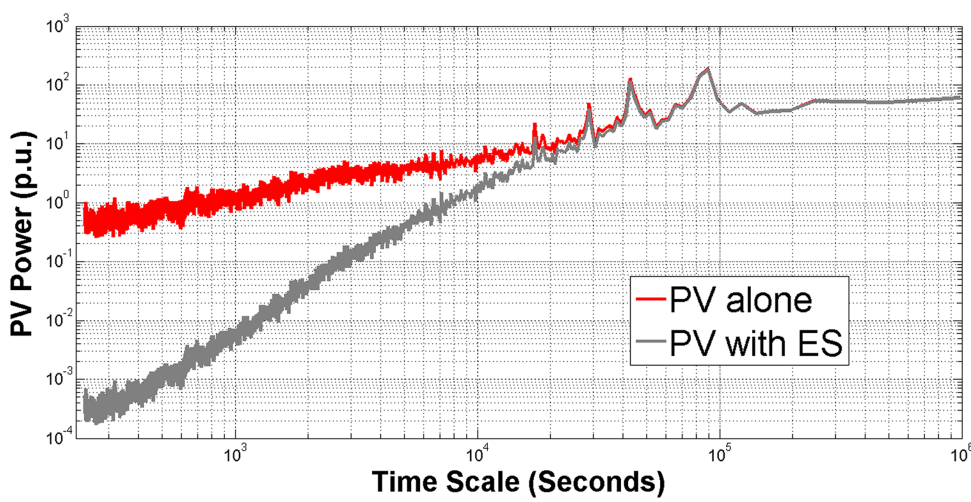

FIG. 8. Power spectrum for the PV power plant with storage under the fluctuations reduction PMS (a = 0.95).

TABLE I. Evolution of production variability as the filtering level is incremented.

Filter parameter value	Filter time constant (min)	Standard deviation (p.u.)
$a = 0$ (PV alone)	…	0.3392
$a = 0.7$	$\tau \approx 5.5$	0.3350
$a = 0.8$	$\tau \approx 9$	0.3336
$a = 0.85$	$\tau \approx 12.3$	0.3322
$a = 0.9$	$\tau \approx 19$	0.3291
$a = 0.95$	$\tau \approx 39$	0.3171
$a = 0.97$	$\tau \approx 66$	0.2959
$a = 0.99$	$\tau \approx 199$	0.1866
$a = 0.995$	$\tau \approx 399$	0.1112

point now is to have a reference for how large the ESS needs to be to achieve this improvement. A sizing analysis has been performed to try to define some reference values for the amount of power and the energy capacity of the ESS that would be needed to properly operate the PV power plant according to each of the PMSs. This analysis has also been developed in a statistical way, calculating on an annual basis the percentage of time that the PV + ES would track the P_{ref} fixed by each PMS, without leading to saturation, for various ES ratings of power and energy.

To do so, a set of parameters of both the power plant characteristics and the PMS configurations have been fixed. These are listed in Table II and define the case study presented in this paper.

Note how, according to the characteristics of the location where the analysis is conducted, the PV plant capacity factor (C_f) is fixed to 4.3 MWh/MW, a typical value in the south of Spain. This C_f is defined as the quotient of the annual average power (P_{AVG}) and the nominal power (P_N) of a PV plant. Thus, given that C_f provides the average PV energy produced per installed MW in a day, it has been used as a base for the p.u. energy calculations. Conversely, the PV plant nominal power (1 MW) is the value used as the base power for the p.u. system.

Finally, the parameters fixed as variable are those which have been systematically modified in each simulation because of their influence on the plant's proper operation. The results for each of the PMSs can be summarized as follows.

1. ESS sizing for the COPMS

Various configurations of the constant power steps PMSs have been simulated. These include single-stepped P_{ref} with step lengths ranging from 4 to 16 h per day. For each of them,

TABLE II. PV + ES plant case study characteristics and values.

PV + ES power plant parameter	
PV plant nominal power (kW)	1000
ES nominal power (kW)	Variable
ES energy capacity (kWh)	Variable
ES charging efficiency (%)	90
ES discharging efficiency (%)	90
Reference SOC, SOC_{fv} (p.u.)	0.5
Capacity factor, C_f (MWh/MW)	4.3
Region where the study is conducted	South of Spain
ES charge time constant (τ_{SOC})	Variable

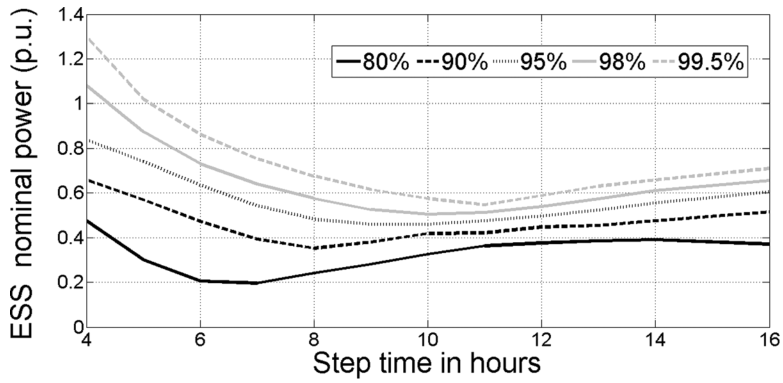

FIG. 9. ESS power needs to guarantee the reference tracking with different degrees of confidence.

the percentage of time with proper operation of the power plant as a function of the ESS ratings has been obtained (Figures 9 and 10).

On the one hand, Figure 9 compiles the power ratings of the ESS (in p.u. referred to the PV plant nominal power) which guarantee that the P_{ref} fixed by the PMS to the hybrid PV + ES plant every 2 min during the year can be tracked with a given degree of confidence. That is, regardless of the PV instantaneous production, the ESS will not be saturated due to power limitations when tracking P_{ref} during that percentage of time in the year. For instance, it can be extracted from Figure 9 that when the PMS configuration defines a 10-h-constant P_{ref}, the ESS nominal power needed to track it without causing saturation with 80% confidence is 0.325 p.u. Similarly, the ESS-rated power needed to track that same P_{ref} with 99.5% confidence is 0.575 p.u. Therefore, a clear and quick comparison of the ESS power ratings needed by the PMS configurations with different constant power steps can be done.

On the other hand, Figure 10 represents the percentage of time with proper operation of the plant when tracking an 8-h-step P_{ref} as a function, in this case, of the energy capacity of the ESS (in p.u.). This is represented for different values of the τ_{SOC} parameter. It stands out in Figure 10 that the lower the value of τ_{SOC}, the smaller the required energy capacity of the ESS, minimizing its cost. The problem is that the lower the value of τ_{SOC}, the more the produced power is distorted and differs from the desired constant reference, as already explained and deduced from Eq. (5). A trade-off among them must be achieved. An analysis of this figure allows the minimum energy capacity which guarantees the compromised production during the year with a certain percentage of probability to be established. For instance, if the plant is operated with a single 8-h constant step P_{ref} and $\tau_{SOC} = 24$ h, an ESS energy capacity of 0.51 p.u. is needed to guarantee that the reference is tracked for 90% of the year and a capacity of 2 p.u. is

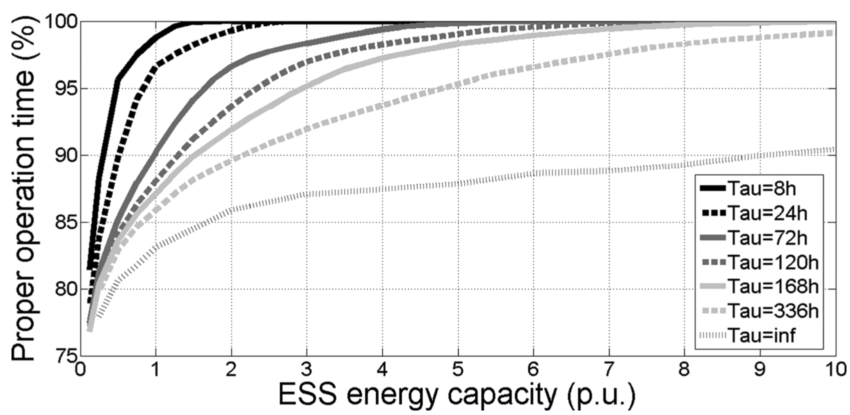

FIG. 10. Percentage of time during the year without SOC saturation as a function of the ESS energy capacity.

required to guarantee this for 99.3% of the time, that is, 2.2 MWh and 8.6 MWh, respectively, for a 1 MW PV plant.

As a conclusion, the storage energy and power requirements derived from the different annual analyses for a significant improvement in the availability during the year (using the COPMS) are found to be between 50% and 200% of the yearly average energy produced in one day and 50% to 60% of the rated power of the plant. This means that, for a 1 MW PV plant, a 500 kW ESS with an energy capacity equal to 2.2 MWh would guarantee tracking of the reference for 90% of the time over the whole year for a daily constant power step lasting 8 h every day with a battery time constant of less than 72 h.

2. ESS sizing for the FRPMS

In this case, a figure representing the degree of confidence of the FRPMS for an annual analysis when the P_{ref} tracking can be effectively guaranteed without saturations is introduced. In this way, Figure 11 lists the calculated percentages of proper operation for different ESS sizes, depending on the values of the filter parameter "a" and for a fixed $\tau_{SOC} = 24$ h. It can be extracted from Figure 11 that with a 0.02 p.u. energy capacity the smoothing level corresponding to "a" = 0.90 can be guaranteed for 97% of the time throughout the year. Equally, with a 0.15 p.u. energy capacity, the smoothing level corresponding to "a" = 0.97 can be guaranteed for 98.7% of the time throughout the year.

Thus, it can be concluded that with an energy capacity ranging from 5% to 30% and around 50% in terms of power, a significant reduction in power variability (using the FRPMS) can be achieved.

D. Expense of the battery life under the different control configurations

Finally, it is important to make some estimates concerning the aging experienced by a battery installed in a PV plant operating under the PMSs defined in this work. In this sense, the same annual simulations were used in order to count the number of charge/discharge cycles for each depth of discharge (DoD), a factor which highly impacts the aging. From that amount of cycles at the different DoDs, equivalent numbers of full cycles were calculated. Thus, Table III summarizes the results obtained for those simulations performed for the two PMSs with various configurations and a battery rated to assure the proper operation of the plant with 95% confidence in a regular year.

Then, depending on the size of the battery and the configuration of the PMS, the aging experienced by the battery will vary greatly. The influence or effect on the aging produced by each PMS can be appreciated when comparing the cycles experienced by the same battery operated under each of the strategies. This is the case for the 0.5 MW/2 MWh battery, which returns 283.3 cycles for the FRPMS with $a = 0.99$ and 375.9 cycles for the COPMS with a 4-h step configuration. Similar results are obtained with a 0.5 MW/0.5 MWh battery which returns 392.5 cycles for

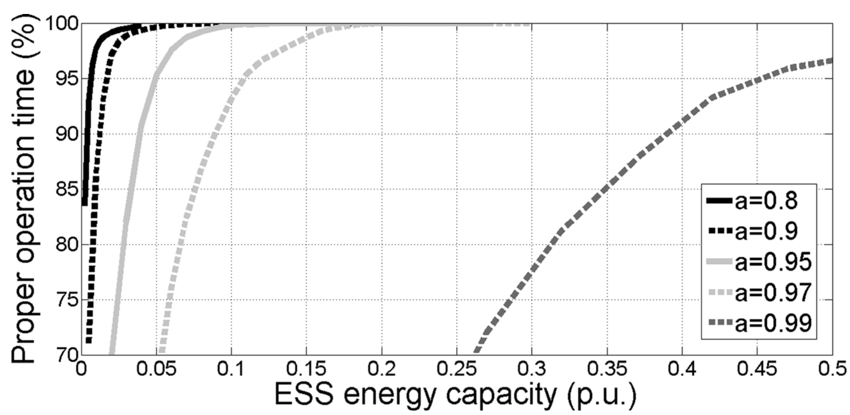

FIG. 11. Percentage of time without ESS SOC saturation operating under the fluctuation-reduction strategy.

TABLE III. Resulting number of battery equivalent full charge/discharge cycles for different operating conditions.

Battery characteristics	PMS and its configuration	Number of full cycles
0.5 MW–37.5 kWh	FRPMS with $a = 0.8$	1314
0.5 MW–75 kWh	FRPMS with $a = 0.9$	964.8
0.5 MW–250 kWh	FRPMS with $a = 0.95$	500.4
0.5 MW–0.5 MWh	FRPMS with $a = 0.97$	392.5
0.5 MW–2 MWh	FRPMS with $a = 0.99$	283.3
0.5 MW–2 MWh	COPMS with 1 step of 4 h	375.9
0.5 MW–1.63 MWh	COPMS with 1 step of 6 h	317.4
0.5 MW–0.75 MWh	COPMS with 1 step of 8 h	363.5
0.5 MW–0.88 MWh	COPMS with 1 step of 10 h	388.3
0.5 MW–1.38 MWh	COPMS with 1 step of 12 h	355.1
0.5 MW–1.88 MWh	COPMS with 1 step of 14 h	347.2
0.5 MW–0.3 MWh	COPMS with 4 steps of 3 h each	444.5

the FRPMS with $a = 0.97$ and 490.25 for the COPMS with a single step of 8 h (case simulated separately because it provides a different degree of confidence in proper operation). Therefore, it seems clear that the COPMS is more aggressive for the battery with regard to life expense.

VI. CONCLUSIONS

The importance of solar photovoltaic technology is already remarkable in many countries and current trends indicate potential massive penetrations in some of them, which could represent an issue for the balance of their grids. Among other techniques, the introduction of energy storage technologies is considered a good solution to solve the intermittency problems associated with the production of PV power plants. The enhanced production achieved by these plants thanks to the storage integration will allow a further degree of penetration of this technology within the grid. In this work, two potential advanced operation modes for PV plants with storage have been defined and analyzed. On the one hand, the constant output power management strategy reorganizes the PV production, making it constant by periods and, hence, predictable and tradable in an electricity market. On the other hand, the fluctuations-reduction power management strategy reduces the high frequency oscillations in the PV power production. Both strategies have been implemented with different configurations in a 1 MW PV plant model and simulated throughout one whole year using actual irradiation data. The results show that important improvements can be achieved in the modification of the cumulative distribution function of the production and in the reduction of the variability, respectively. Moreover, the power and the energy capacities required for the ESS to be installed in such a PV power plant and operated according to each of the power management strategies defined have been calculated. The resultant ratings could be used as a reference for future PV plant developments in places with similar cloud cover characteristics. Finally, some results and comments have been introduced regarding the number of full charge/discharge cycles experienced by the ESS when subject to various configurations of the PMSs presented.

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