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Influence of the State-of-Charge Control on the Size of the Energy Storage Systems to be introduced in PV Power Plants

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Abstract – The usefulness of introducing energy storage (ES) systems (ESS) into PV power plants to make the production less stochastic and even predictable is a fact. Its economic viability is not so clear though, what makes essential the use of an optimally sized ESS. This paper analyses how much the energy ratings required by these ESS can be reduced by varying the values of a control parameter: the ESS reference state-of-charge (SOC) recovery time ($\boldsymbol{\tau_{SOC}}$). This control parameter is introduced to force the plant to recover a given SOC within a certain period of time, thus reducing the SOC variability and allowing the use of smaller ESS. To do the analysis, a generic PV plant with ES is first introduced its main control equations. Then, two energy management strategies are defined to operate it. The analysis shows the $\boldsymbol{\tau_{SOC}}$ impact on the plant performance and also on the change in the ESS ratings obtained by varying the $\boldsymbol{\tau_{SOC}}$ value for each of the strategies is presented. The results obtained in this paper are based on one year long simulations which used actual irradiance data sampled every two minutes.

Key words

Energy storage systems, photovoltaic energy, renewable production planning.

I. Introduction

PV solar power is rapidly growing as an effective renewable source of electrical energy [1]. However, the promising evolution of the PV technology will face up the challenge of massively integrate into the grid with such an stochastic nature of the solar resource, highly dependent on weather conditions. In fact, this is an issue for different renewable energy sources (RES) presenting intermittent production. The power generation variability and limited predictability of the RES has become a handicap which makes the demand balancing difficult to achieve. So, although PV power production represents a low share in most of the electrical markets nowadays, the increment in the installed PV power capacity will force future plants to support the grid services by offering ancillary services and generate in a more predictable way. This opens the way to implement hybrid generation technologies and integrate energy storage systems (ESS) into PV power plants [2-5].

Some research has already been carried out in this way for guaranteeing a more reliable production of PV systems, combining them with different technologies such as: hydrogen fuel cells [6-8], together with wind power [9, 10], or even batteries [11], mainly focusing on small grids or stand-alone PV power plants [12, 13].

This paper is focused on the sizing of ESS integrated in a grid-tied PV power plant with the goal of making the PV production more controllable and predictable. It analyses the variations in the ESS energy capacity requirements produced by the different possible values of an internal control system parameter, the so-called "Reference SOC recovery time", designated by (τ_{SOC}). A generic PV power plant with energy storage (ES) and its main control equations are introduced. Two types of energy management strategy (EMS) to operate this type of plants are defined and analyzed. The study results show what the τ_{SOC} impact on the plant performance is but also how much the ESS ratings can be reduced by introducing and varying the τ_{SOC} value for each of the strategies is presented. All the results obtained in this paper are based on one year long simulations which used real irradiance data sampled every two minutes.

The paper starts with a brief description of the PV power plant with ES and its control equations. Then, a summary on ES technologies is presented in section III. Section IV introduces the proposed EMS and the impact of the τ_{SOC} on their performance. Thereupon, the influence of the τ_{SOC} on the ESS ratings is presented in section V. Finally, some conclusion remarks are introduced in section VI.

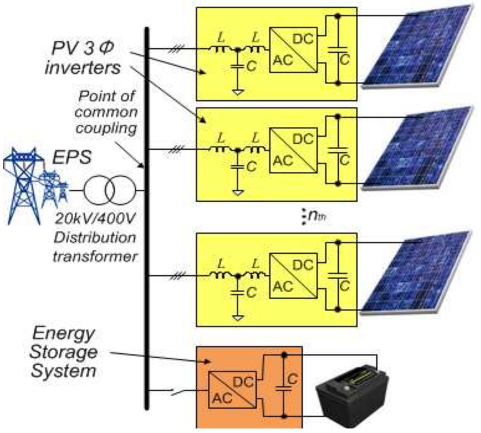


Fig. 1. Schema of the PV+ES power plant under consideration.

II. Proposal PV Plant with Storage

A PV power plant with an ESS integrated on the collector, as the one represented in Fig. 1, is proposed in this work. It consists on a grid connected PV plant which contains a variable number of multi-string PV inverters and a generic ESS, being all of them connected in parallel to the plant point of common coupling (PCC).

As previously introduced, the goal for combining PV with ES is to obtain a further predictable and controllable distributed generation plant regarding its instantaneous energy production. Thanks to the ESS introduction, the PV plant operator will be able to offer, according with the weather forecast and the plant characteristics, a determined amount of power to be delivered to the grid at a given time, and during a certain period, with a high degree of confidence. Besides reducing its stochastic behavior, the ESS will allow the PV plant operator to offer advanced services to the system operator [14] not available nowadays in standard PV plants. In this sense, the PV power plant production will tend to track a power reference, normally to be established in agreement with the system operator, and generated by its control system depending on its EMS. This power setpoint will be accomplished by:

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

Being P_{ref} the power reference, P_{pv} the instantaneous power provided by the PV panels (dependent mainly on time, location and weather) and P_{ES} the theoretically desired received/delivered ESS power:

Discharge: $$P_{ES} > 0 \rightarrow {dE_{ES}}/{dt} = -{P_{ES}}/{\varepsilon_d} \quad (2)$$

Charge: $$P_{ES} < 0 \rightarrow {dE_{ES}}/{dt} = -P_{ES} \cdot \varepsilon_c \quad (3)$$

Where:

- E_{ES} – current stored energy (available energy)
- ε_c – charging efficiency
- ε_d – discharging efficiency

However, the real P_{ES} to be received/delivered by the ESS is modified by a complementary internal control loop which fixes a reference state-of-charge (SOC) value. This value is the SOC level that the ESS should recover within a certain period of time and which is defined as the "reference SOC recovery time", designed as τ_{SOC} and measured in hours. Therefore, the final equation governing the PV+ES power plant when the reference SOC (SOC_{ref}) control is activated is:

$$P_{ES} = \left(P_{ref} - P_{pv}\right) + \frac{\left(E_{ES} - E_{ES\max} \cdot SOC_{ref}\right)}{\tau_{SOC}} \quad (4)$$

Where:

- P_{ref} – power required at the PCC
- P_{pv} – solar photovoltaic power
- E_{ESmax} – capacity of the ES system
- SOC_{ref} – preferred or reference state-of-charge
- τ_{SOC} – reference SOC recovery time (in hours)

The first part in (4) is responsible for the theoretical output P_{ref} tracking, being the second part responsible for maintaining the SOC as close as possible to its preferred value. The balance in the influence produced by those two terms is determined by the τ_{SOC} value which establishes how fast the control should make the ESS to recover its SOC_{ref}, e.g. the time it needs to recover that level of charge once it starts injecting or absorbing power from the PCC. It equally influences the ESS energy and power needs, what is analyzed in this paper.

III. Energy Storage Systems

ESSs convert electric energy to another form of energy that can be stored and released on demand. Some ES technologies have been used for long in electrical applications (pumped hydro, batteries,…) although it has not been till recent years that a significant development has been achieved in most of them due, in part, to the increasing operation requirements on RES. This scenario, together with the huge increase on the installed PV power in many countries, makes the installation of ESS a more and more interesting solution for improving grid-integration of PV power plants [15, 16].

Different ESS classifications can be established nowadays [17, 18], most of them normally 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 (UC) 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 can be pointed out as mechanical systems, and fuel cells (FC), Thermo electric energy storage (TEES) or batteries (BESS) as chemical ones. Within BESS, different technologies are to be noted: Lead Acid, Nickel-Cadmium, Lithium Ion (Li-ion), Sodium Sulphur (NaS) and Redox Flow Batteries. Among them, the choice of a certain ESS for a determined application will depend on factors such as the application power and energy ratings, response time, weight, volume, cost and operating temperature. Fig. 2 represents the characteristic energy ratings for the different ES technologies.

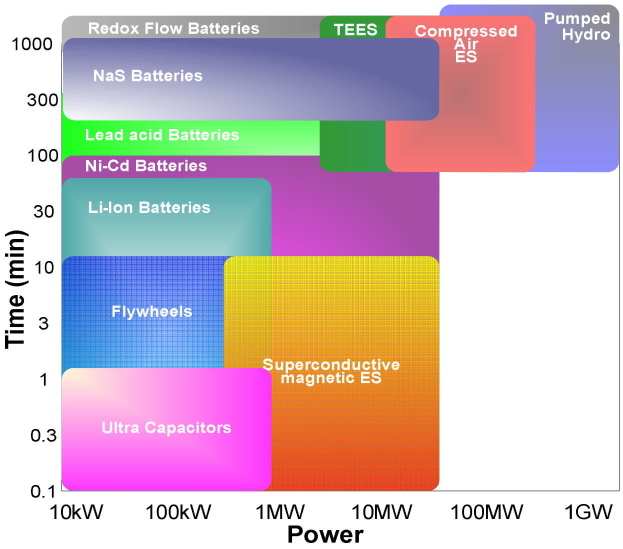


Fig. 2. Operational ranges of the different ES technologies.

According to the ratings defined in Fig 2, few among the different ES technologies commercially available are able to meet the requirements of PV power plants. These include: fast reaction time, high charging and discharging efficiency, low degree of auto discharge, restricted physical size to be placed on the location, easiness of maintenance, long life cycle and maturity of the technology. Thus, batteries are referred to as the key technology to operate integrated within medium power RES power plants. Among them, NaS batteries are already proposed as the solution to connect wind turbines to the grid providing ancillary services. Also, Lead Acid batteries have been used in the past in isolated PV applications (mainly due to their maturity and low cost), but performance limitations (short life cycles and high maintenance demands) have limited their adoption in new isolated and grid-tied PV applications. Another battery technology is entering the market, the Li-ion batteries. These seem a good candidate for grid-tied PV+ES applications meeting most of the PV plants operational requirements. It is noteworthy that a new generation of cutting-edge Li-ion batteries is expected in the near future presenting more and more improved performance characteristics due to the large research effort that is being developed on them, especially focused on its potential application to electric vehicles [19].

IV. Energy Management Strategies

Two main EMS for the control of PV power plant with ES are presented here: the constant output power strategy and the fluctuations reduction strategy. Each of them defines a different P_{ref} to be tracked by the PV+ES power plant and provided to the grid as a combination of the PV instantaneous production plus the ESS energy exchange.

A. *Constant output power strategy*

This EMS is based on redistributing the energy naturally produced by the PV panels by providing to the plant a P_{ref} constant by periods. The duration, number and value of the constant power step used as P_{ref} can be modified every day, adapting it to the expected irradiation. In fact, not only one but several different power steps can be defined along the day as P_{ref}, Fig. 3a), what allows reducing the size of the ESS. This flexibility also enables the plant to adapt its power generation to the market and the grid conditions, given that the production obtained tracking such a P_{ref} will be probably traded on electricity markets. Such an operation mode implies trading and committing the power production with some hours of advance. Since the main goal of this EMS is to provide a constant and predictable production, it will be practical for clear days when the total irradiance can be forecasted and, hence, a guaranteed constant power output easily calculated. Conversely, it will not be so practical for cloudy days. Fig. 3b) shows the distortion introduced by the τ_{SOC} on the overall PV plant generated power when using a 10h constant power step reference. A trade-off between this undesirable effect and the reduction obtained in the profitable ESS size with the τ_{SOC} introduction must be achieved, what is analysed in Section V.

B. *Fluctuations reduction strategy*

This second EMS is based on smoothing the PV power production so as to avoid quick power changes (usually produced by changing or intermittent weather conditions, passing clouds). Hence, this EMS seems appropriate mostly for cloudy days when the total and the instantaneous irradiance strongly depend on clouds and, therefore, the plant output power cannot be guaranteed.

This EMS filters the power generated by the PV panels and allows injecting a flattened production into the grid. The degree of filtering is limited by the energy capacity of the ESS which fixes how much it can flatten the PV panels' production without saturating.

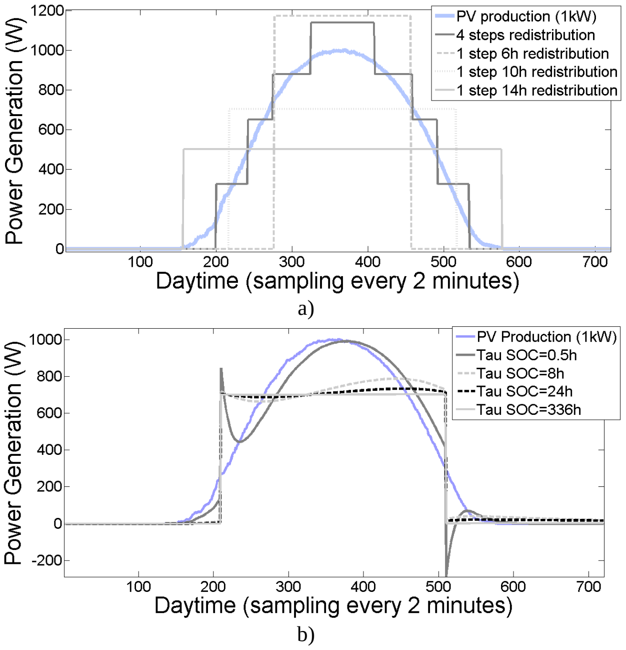


Fig. 3. Constant output strategy: a) examples of redistribution, b) deformation due to the τ_{SOC} influence.

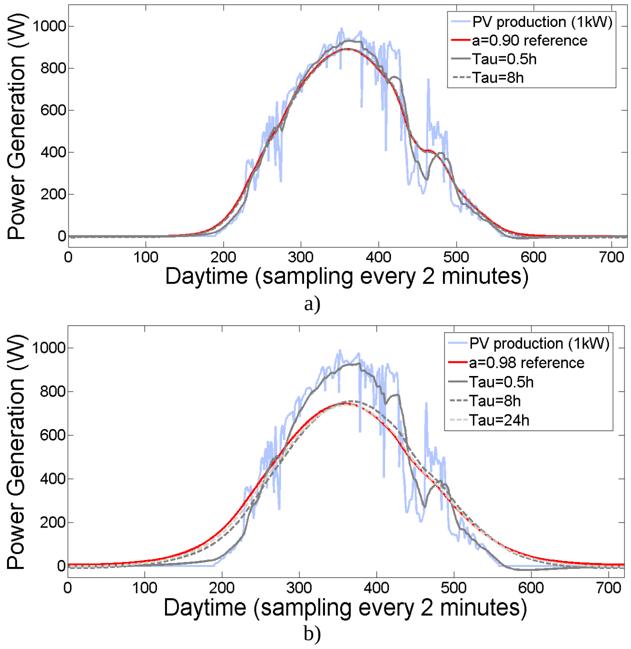


Fig. 4. Fluctuations reduction strategy deformations due to τ_{SOC} effect: a) with a=0.9 filtering, b) with a=0.98 filtering.

The P_{ref} provided to the power plant with this EMS is derived from the following first-order filtering equation:

$$Filter_{tf}(z)=\frac{(1-a)}{(1-a/z)}, \text{with } \omega_c=\frac{1}{\tau}=-\frac{\log(a)}{T} \qquad (5)$$

With ω_c being the cutting frequency of the filter, τ its time constant, and T the sampling time of the input signal. Therefore, the PV panels production is used as input signal (with T = 120 seconds) and (5) returns the smoothed production to be tracked by the PV+ES plant. Note also that the parameter "*a*" of the filter, which defines the degree of smoothing, is adapted by choosing the time constant in accordance to the energy ratings of the ESS introduced in the plant.

The power production pattern registered over a day for a completely intermittent production due to the presence of clouds can be observed on the dim blue line on Fig. 4a) and Fig. 4b). The red continuous line on these figures represents the different P_{ref} obtained by various degrees of filtering: "*a=0.9*" and "*a=0.98*" respectively. Finally, both figures show how the plant operates, for each of the filtering levels, as a function of the τ_{SOC} value. As the filtering level increases ("*a*" gets closer to 1), the time constant of the filter also increases, approaching its value to those assigned to τ_{SOC} and, therefore, the result gets more distorted. This is not desirable and has to eb avoided. Then, although introducing the SOC control allows reducing the ESS size it also introduces distortion in the plant power production. A trade-off value among both effects will have to be achieved.

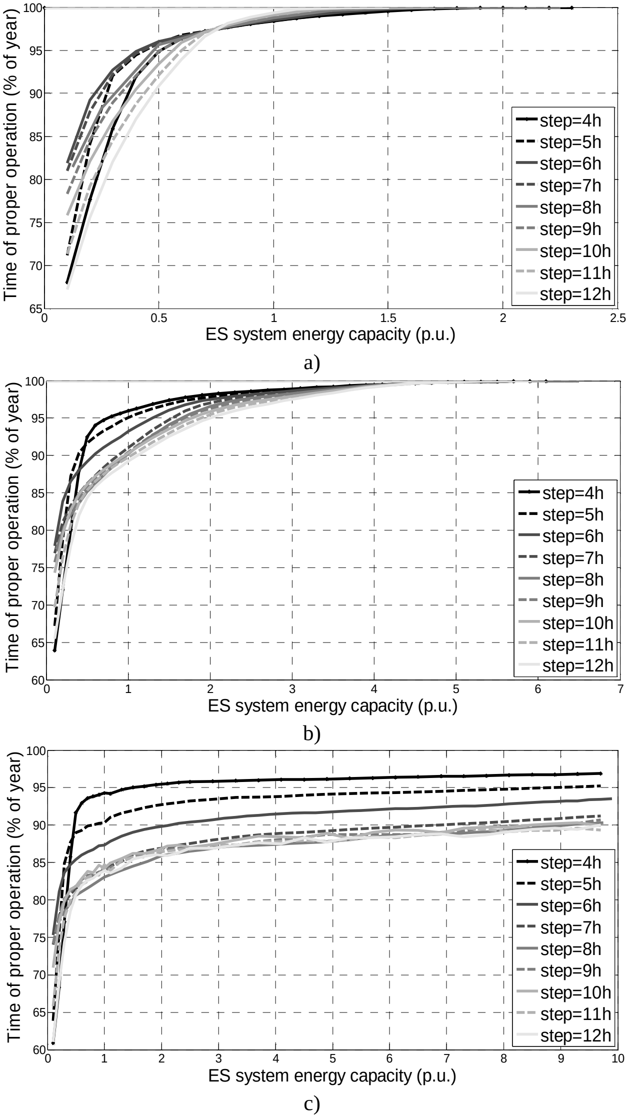
V. Results obtained for the analysis

To analyse the influence of the τ_{SOC} on the ESS ratings, taking into account the distortion introduced to establish the optimal trade-off, a set of simulations considering one year long periods have been performed. Actual solar irradiance data sampled every 120s at an existing PV plant installed in the south of Spain have been used to define the production pattern of a 40 kW PV plant over that year. For each of the EMS, different values of filtering or constant step lengths have been considered, respectively. The ESS energy capacity ratings needed in order to be able to track the P_{ref} without saturation during a certain percentage of time along the year has been estimated, using as base for the energy per unit calculations the average energy produced daily by fix PV installations in the south of Spain (4,3 kWh per installed PV kW). Figures 5 to 8 represent the percentage of time with proper tracking for each EMS configuration and for different values of τ_{SOC}. Its effect can be observed on the figures and is analysed in the following.

A. Results for the constant power output strategy

For this EMS, P_{ref} with just one power step per day, with durations ranging from 4h to 12h per day, and with 7 different τ_{SOC} values have been considered. For the sake of the clarity and shortness of the paper, just a few combinations are reported on Fig. 5 and Fig. 6.

Fig. 5 represents the evolution in the percentage of time along the year when the PV+ES power plant tracks the different lengths power steps without saturation as a function of the ESS energy capacity rating. This is represented for three different values of τ_{SOC}: a) 8h, b)72h, c) infinite. On the contrary, Fig. 6 represents the same evolution but for the case of the 10h constant power step and depicting in this case the variations experienced with the changing τ_{SOC}.



a)

b)

c)

Fig. 5. ESS energy requirements evolution for different power step lengths as a function of τ_{SOC}. a) for 8h, b) for 72h, c) for infinite value.

Some conclusions can be extracted from these figures:

- For a fixed step duration, as τ_{SOC} gets larger, a higher ESS energy capacity is required to be able to track the reference properly the same percentage of time.
- If τ_{SOC} = infinite, no automatic control of the reference SOC level is done. Then, percentages of time without saturation higher than 95% cannot be achieved.
- For a same τ_{SOC} value, if it is over 72h, reference steps under 6h require smaller ESS energy capacities than longer step references. However, if 8h< τ_{SOC} <24h, steps between 5 and 8 hours present similar evolutions.

In general, one should operate the power plant with τ_{SOC} values being around 24h (high deformation for values under it and ESS much bigger from 24h onwards).

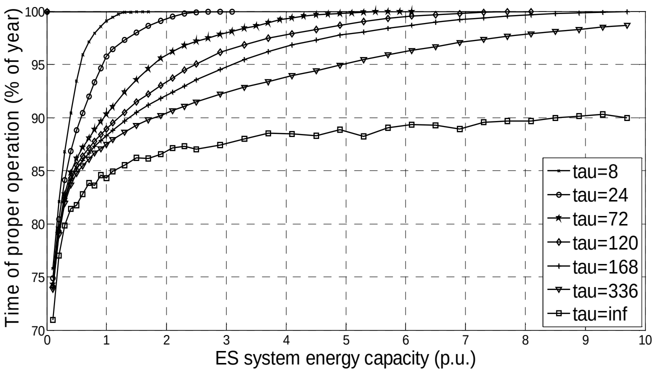


Fig. 6. ESS energy requirements for a 10h power step as a function of τ_{SOC}

For instance, using a τ_{SOC} = 24h instead of 8h represents increasing ESS capacity needs in around the 50%. Besides, for the same change in τ_{SOC}, to achieve times of no saturation up to 95% represents increasing the ESS capacity around two times if one or other lengths of the constant power step are fixed. However, for times of no saturation over 95% of the year, ESS energy capacity variations among the different step lengths get closer, although considering very high energy capacity values, between 0.75pu and 2pu.

B. *Results for the fluctuations reduction strategy*

For the case of the fluctuations reduction EMS, some simplifications have been considered too, given that many different degrees of filtering can be achieved. Then, only seven filtering levels have been considered and analysed. These are: *a* = 0.8, 0.85, 0.9, 0.95, 0.97, 0.99, and 0.995, which have been combined with eight different τ_{SOC} values (0.5h, 8h, 24h, 72h, 120h, 168h, 336h and infinite). Results for some combinations are presented in Fig. 7 and Fig. 8. Fig. 7 represents the evolution in the percentage of time along the year when the PV+ES power plant tracks the different filtering levels references, without saturation, as a function of the ESS energy capacity rating. On the contrary, Fig. 8 represents the variations experienced in the energy needs when varying τ_{SOC} for the case of filtering levels *a*=0.9 and *a*=0.99 respectively. Some conclusions can be also extracted from these figures. These are:

- For a fix filtering level, if τ_{SOC} increases, higher ESS energy capacity is required to track the reference the same percentage of time without saturation.
- For a fix τ_{SOC}, if the filtering level is increased, the ESS energy capacity required to track the reference a percentage of time without saturation increases too.
- On the one hand, to achieve times of proper operation up to the 90% of the year and for any level of filtering, varying τ_{SOC} from 6h to 336h represents that the needed ES energy capacity is increased in the range from 40% to 80%. However, in all these situations, ES energy requirements are kept under 1p.u., hence, no big ES system are required in absolute values.
- On the other hand, for times of proper operation over the 90% of the year, the τ_{SOC} influence is much more important for filtering levels over "*a*=0.9".

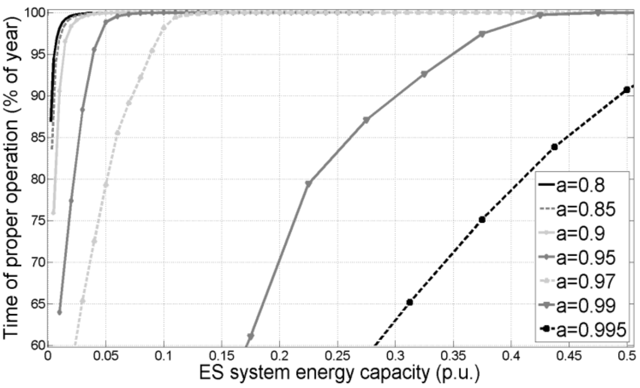
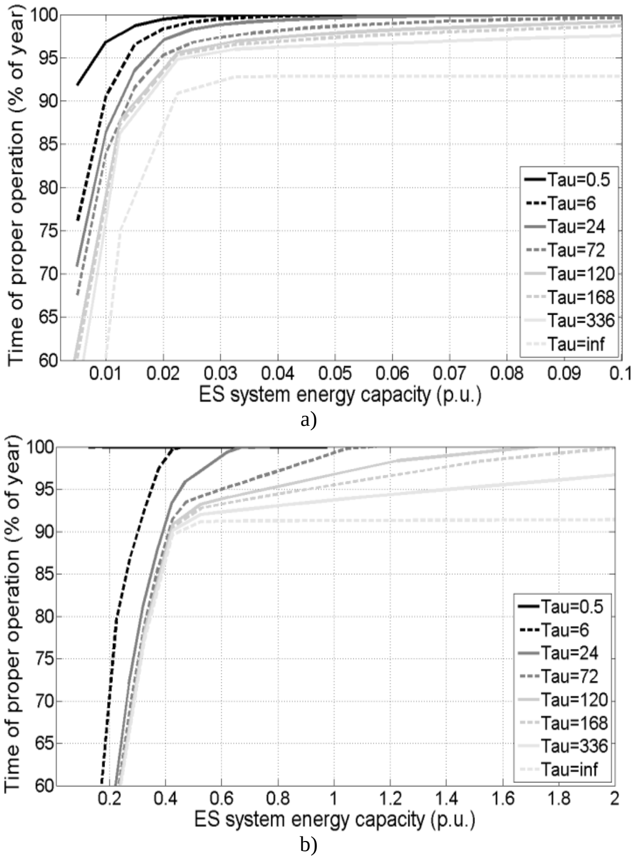


Fig. 7. ESS energy requirements evolution for different filtering levels with τ_{SOC} = 6h.

- Till that filtering level, evolution is similar to that of the previous point, but from there on, ES energy needs are more than doubled varying τ_{SOC} from 6h to 336h.
- For filtering levels over "*a*=0.95", if the time of proper operation is desired to be over 90%, the use of τ_{SOC} values under 24h seem compulsory in order not to avoid huge amounts of energy capacity needs for the ESS. However, as previously introduced, this range of τ_{SOC} values distorts the generated power in great measure. That is due to the fact that the filter time constant for these filtering levels approaches the value of the τ_{SOC} (40 minutes for 0.95, 3h 20min for 0.99 and 6h 40min for 0.995).



a)

b)

Fig. 8. ESS energy requirements as a function of τ_{SOC} for:
a) filtering level "*a* = 0.9", b) filtering level "*a* = 0.99".

So, for high filtering levels, it is reasonable to achieve once again a trade-off between the acceptable deformation in the power injected into the grid (as similar as possible to the P_{ref}) and the value of τ_{SOC} which allows keeping the ESS energy requirements as low as possible.

Nevertheless, one can conclude that, mainly for economic reasons, PV plant operators will tend to work with τ_{SOC} values as small as possible, reducing the ESS energy requirements. In order to avoid the big deformations introduced by low values of τ_{SOC}, as observed in **¡Error! No se encuentra el origen de la referencia.**b), the reference SOC level recovery control should be performed during night hours or during those periods of time when the PV plant has no power tradeoff with the system operator.

VI. Conclusion

Introducing energy storage systems into PV power plants allows making their production less stochastic and even predictable, but this type of installations present the handicap of a marginal economic viability. Thus, the optimal selection of the energy storage system's size which allowed an improved production, while minimally increasing the plant's cost, seems critical for their future deployment. This paper has presented the performance of such a power plant under two different energy management strategies and presents an analysis of the variations experienced in the energy requirements of the storage unit (mainly in the energy capacity needs) as a function of the value assigned to an internal control system parameter named "reference SOC recovery time" (τ_{SOC}).

To perform this analysis, a prototype PV power plant integrating an energy storage system has been first introduced together with its main control equations. And then, the two energy management strategies to operate this type of plant have been described in detail. These show how the PV+ES power plant can achieve an advanced performance (with two different goals), capable in both cases of reducing the PV production variability and improve in this way its predictability. Finally, the τ_{SOC} impact on the generated power patterns, as well as the evolution of the ESS energy capacity requirements when varying the τ_{SOC} value, for each of the two strategies has been presented.

It can be concluded that, as τ_{SOC} gets larger in any of the strategies, a higher ESS energy capacity is required in order to guarantee the same degree of confidence on the proper operation of the system (no saturation of the ESS). But, on the contrary, as τ_{SOC} gets larger, the total final production of the plant is more similar to the theoretical reference imposed by the EMS. A trade-off value between these two divergent trends has been fixed.

Finally, it must be pointed out that, for the sake of the brevity of the paper, just some example figures and values have been introduced in the document. However, the whole work performed allows obtaining a precise idea about the ranges of deformation and/or ESS energy capacity increments introduced by the τ_{SOC} control parameter variation, what is crucial for the proper and viable implementation of these control strategies.

Acknowledgement

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